

Quantum Dash Gain Medium Based Millimeter Wave over Fibre Fronthaul Transmission

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Abstract

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The adoption of millimeter-wave (mmWave) frequencies in 5G and beyond enables high-capacity, low-latency communication but introduces severe propagation loss. Radio-over-fibre (RoF) offers a cost-effective fronthaul solution by transmitting RF signals directly over fibre, reducing complexity and power consumption at the base station. This thesis investigates quantum-dash mode-locked lasers (QD-MLLs) and quantum-dash semiconductor optical amplifiers (QD-SOAs) as key devices for mmWave RoF (mmWoF) links.

This thesis investigates the use of QD-MLLs as multi-wavelength optical sources for mmWoF fronthaul transmission. By generating tens of highly coherent optical comb lines, QD-MLLs enable heterodyne detection to upconvert baseband and intermediate-frequency signals into the mmWave domain with low phase noise. The fundamental mmWoF link was first optimized through architectural improvements, and two enhanced configurations were experimentally demonstrated. The first configuration added a delay line and multiple polarization controllers, while the second configuration will modulate two optical carriers simultaneously. Two configurations can both significantly reduce error vector magnitude (EVM) compared with baseline systems reported in prior work.

Building on this foundation, four distinct frequency-multiplexing techniques employing QD-MLLs were proposed and experimentally validated. By using multiple coherent comb lines

simultaneously, they have different advantages and disadvantages. Technique 1 is the most straightforward and robust in terms of architecture and implementation simplicity, yet it delivers the lowest spectral efficiency and EVM performance, which is up to 8.5%. Technique 2 improves the EVM performance to 8.0% and has better spectral efficiency compared with Technique 1, but at the cost of requiring an I/Q modulator, which increases system complexity. Technique 3 further enhances performance and spectral efficiency³ while maintaining simplicity comparable to Technique 1, as it does not require an I/Q modulator. The EVM performance of Technique 3 is up to 7.6%. Technique 4 achieves the best results in terms of EVM performance and eliminates crosstalk, which is as low as 6.7%. However, it demands more complex hardware, including both an I/Q modulator and a wave shaper or specialized filter. The performance of all four techniques is further verified in a system with up to 50 km of single mode fibre, the EVM performance is consistently below 9.6% even after 50 km of fibre transmission.

This thesis also presents a comprehensive investigation of QD semiconductor optical amplifier (QD-SOA) and their application in mmWoF fronthaul systems. The static performance of QD-SOAs was systematically characterized, including amplified spontaneous emission, gain spectra, optical signal to noise ratio, and noise figure (NF), under varying temperatures, bias currents, and input optical powers. In addition, QD-SOAs with different numbers of stacked QD layers (3, 5, 8, and 12) were compared in detail. The results highlighted distinct trade-offs: an 8-layer QD-SOA provided the highest chip gain (26.4 dB at 1550 nm), the 3-layer device offered a broad bandwidth of 90 nm and low NF of 5.7 dB, while the 12-layer SOA extended operation into the L-band. These measurements establish, for the first time, a comprehensive performance map of QD-SOAs relevant to communication systems.

To evaluate system-level performance, QD-SOAs were integrated into mmWoF fronthaul

links to replace erbium-doped fibre amplifiers (EDFAs). Both single-channel and frequency-multiplexed experiments were carried out. It was demonstrated that QD-SOAs can successfully replace EDFAs without degrading performance, with EVM values consistently below the 5G limits specified by 3GPP. The capability of QD-SOAs to suppress crosstalk in multiplexed configurations was also experimentally verified. Moreover, packaged 8-layer QD-SOAs were employed to enable more practical system integration. These demonstrations confirm the feasibility of QD-SOAs as compact, energy-efficient, and integrable optical amplifiers for 5G fronthaul transmission, representing a significant step toward replacing bulky EDFAs with semiconductor-based solutions.

Overall, the results demonstrate that QD-MLLs and QD-SOAs are compact, energy-efficient, and integrable alternatives to conventional solutions, offering strong potential for scalable mmWoF fronthaul networks in 5G and beyond.

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Dedication

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Table of Contents

List of Figures	xi
List of Tables	xvii
List of Abbreviations	xviii
Chapter 1 Introduction	1
1.1 Evolution of Mobile Communication System.....	1
1.2 Fronthaul Transmission.....	2
1.3 Organization	4
Chapter 2 Background	6
2.1 Traditional RoF Fronthaul Transmission	6
2.1.1 Key Component in RoF Links	7
2.1.2 Challenges in Expanding RoF to the mmWave Band.....	18
2.2 Heterodyne Detected mmWoF system.....	20
2.2.1 Mathematical Explanation of Optical Heterodyne Detection	20
2.2.2 Generation of Optical Carriers in mmWoF system.....	24
2.2.3 The Overview of QD-MLL Based mmWoF System	27
2.3 Quantum Dot and Quantum Dash Gain Medium.....	28
2.3.1 Quantum Dash Mode Locked Lasers	29
2.3.2 Quantum Dash Semiconductor Optical Amplifier	32
2.4 Advantages and Challenges of Current mmWoF System.....	34
2.5 Research Methodology for mmWoF System	35
Chapter 3 Preliminary Improved QD-MLL Based mmWoF System	38
3.1 Improved QD-MLL Based mmWoF System	38
3.1.1 I/Q MZM Based mmWoF Fronthaul Transmission System	38
3.1.2 SSB-MZM based mmWoF Fronthaul Transmission System.....	40

3.2	Bi-directional mmWoF Fronthaul System	42
Chapter 4	Frequency Multiplied mmWoF Fronthaul Transmission Links	45
4.1	Experimentation Setup	45
4.1.1	Setup of <i>Technique 1</i>	46
4.1.2	Setup of <i>Technique 2</i>	47
4.1.3	Setup of <i>Technique 3</i>	48
4.1.4	Setup of <i>Technique 4</i>	49
4.2	mmWoF Experimental Results and Discussion	50
4.2.1	Result of <i>Technique 1</i>	50
4.2.2	Result of <i>Technique 2</i>	52
4.2.3	Result of <i>Technique 3</i>	55
4.2.4	Result of <i>Technique 4</i>	57
4.3	Wireless Experimentation Results	59
4.4	Summary and Discussion of Frequency Multiplexing Techniques	61
Chapter 5	Basic Characterization of Quantum-Dash Semiconductor Optical Amplifier ..	62
5.1	SOA Structure and Measurement Methods.....	62
5.1.1	Structure of QD-SOA.....	62
5.1.2	Measurement Method.....	63
5.2	Results and Discussion of Device Characterization.....	66
5.2.1	Baseline Scenario: 20 °C, 300 mA Biased	66
5.2.2	The Influence of Bias Current.....	69
5.2.3	The Influence of Temperature.....	72
5.2.4	Temperature Stability	75
5.2.5	Discussion of Characterization Results.....	77
5.3	Influence QD Layers	78
5.3.1	Measurement Setup	78
5.3.2	Measurement Results	80

5.3.3	Discussion of the Influence of QD Layers	84
Chapter 6	QD Gain Medium Based mmWave Front Haul Transmission System.....	85
6.1	Step One: One EDFA is Replaced	85
6.1.1	System Setup	85
6.1.2	System Results	88
6.1.3	Discussion of Step One	91
6.2	Step Two: Both EDFAs are Replaced.....	92
6.2.1	QD-SOAs Integrated I/Q MZM Based mmWoF Fronthaul Transmission System ..	92
6.2.2	QD-SOAs Integrated SSB-MZM Based mmWoF Fronthaul Transmission System	94
6.2.3	Discussion of Step Two.....	96
6.3	Step Three: Using QD-SOA in Frequency Multiplexed mmWoF System	97
6.3.1	<i>Technique 3</i> with QD-SOA	98
6.3.2	<i>Technique 4</i> with QD-SOA	99
6.3.3	Discussion of Step Three.....	101
6.4	Summary and Discussion of QD Gain Medium Based mmWave Front Haul Transmission System.....	101
Chapter 7	Conclusions and Future Work	103
7.1	Conclusions	103
7.2	Future Work	105
References		107

List of Figures

Figure 1.1. Comparison between (a) traditional mega base station, (b) D-RAN in 3G, and (c) C-RAN in 4G and above.	3
Figure 2.1. Basic principle of RoF. E/O: electrical to optical, OA: optical amplifier, PA: power amplifier, LNA: low noise amplifier. [16]	7
Figure 2.2. Structure of (a) Fabry-Perot laser, (b) structure of DBR laser, and (c) structure of DFB laser. [17]	8
Figure 2.3. Output spectrum of Fabry-Perot laser.	8
Figure 2.4. Schematic of optical subcarrier modulation.	9
Figure 2.5. Direct modulation method (a) and its mechanism (b) [18].	10
Figure 2.6. Block diagram of the external modulator.	11
Figure 2.7. EAM modulator in a LiNbO ₃ crystal.	11
Figure 2.8. A typical transmission characteristic of EAM. [19]	11
Figure 2.9. Block diagram of I/Q MZM.	12
Figure 2.10. First type Bessel function.	14
Figure 2.11. A sample of ORx. [25]	17
Figure 2.12. Structure of an I/Q coherent receiver. [25]	18
Figure 2.13. Schematic block diagram of optical heterodyne detection.	20
Figure 2.14. Block diagram of mmWoF system with two free-run lasers. [29]	24
Figure 2.15. Simplified schematic of dual self-injection locking system. [30]	25
Figure 2.16. Experimental setup for optical mmWave generation by using external modulator. [32]	25
Figure 2.17. Schematic diagram of the mmWave generation using four-wave mixing. [34] ..	26
Figure 2.18. Block diagram of mmWoF system. [37]	27
Figure 2.19. Evolution of the density of states for (a) bulk material, (b) QW, (c) quantum wire (same as quantum dash) and (d) quantum dots. [41]	29

Figure 2.20. (a) Schematic of a QD Fabry-Perot laser with a cavity length L and ridge width W ; and (b) Geometry of five-layer truncated pyramid InAs QD stacks. [48].....	30
Figure 2.21. (a) Schematic of the cross-section of the laser. SEM images of (b) the top view of the quantum dash layer. [10]	30
Figure 2.22. Measured (a) optical spectrum of the QD-MLL, (b) RF beat linewidth of QD-MLL, and (c) integrated RIN for individual selected channels over a frequency range of 10 MHz to 20 GHz. [38]	31
Figure 2.23. (a) An example of the constellation of signal and (b) the principle of EVM.	37
Figure 3.1. Block diagram of I/Q MZM based mmWoF system. PC: polarization controller.	39
Figure 3.2. the constellation of received signal of (a)16-QAM 4 GBands and (b) 64-QAM 2 GBauds	40
Figure 3.3. Block diagram of SSB-MZM based mmWoF system.	41
Figure 3.4. the constellation of received signal of (a)16-QAM 4 GBands and (b) 64-QAM 2 GBauds	42
Figure 3.5. Block diagram of bi-directional mmWoF fronthaul system.	43
Figure 3.6. The constellation of (a) downlink and (b) uplink with BtB transmission, (c) downlink and (d) uplink with 10 km SMF transmission.....	44
Figure 4.1. Block diagram of proposed multiplexing <i>Technique 1</i> , <i>2</i> , and <i>3</i> is shown on (a), <i>Technique 4</i> is shown on (b).	45
Figure 4.2. (a), (b), (c), (d), (e), (f), (g), (h) and (i) are the spectrum diagram of <i>Technique 1</i> at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.	46
Figure 4.3. (a), (b), (c), (d), (e), (f), (g), (h), and (i) are the spectrum diagram of <i>Technique 2</i> at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.	47
Figure 4.4. (a), (b), (c), (d), (e), (f), (g), (h), and (i) are the spectrum diagram of <i>Technique 3</i> at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.	48
Figure 4.5. (a), (b), (c), (d), (e), (f), (g), and (h) are the spectrum diagram of <i>Technique 4</i> at	

Point A, B, C, D, E, F, G, and H of Figure 4.1(b), respectively.	49
Figure 4.6. The optical spectrum in <i>Technique 1</i> at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1(a).	51
Figure 4.7. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	52
Figure 4.8. The optical spectrum in <i>Technique 2</i> at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1 (a).	53
Figure 4.9. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	54
Figure 4.10. The optical spectrum in <i>Technique 3</i> at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1(a).	55
Figure 4.11. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	56
Figure 4.12. The optical spectrum in <i>Technique 4</i> at (a) Point C, (b) Point D, and (c) Point E of Figure 4.1 (b).	57
Figure 4.13. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	58
Figure 4.14. Block diagram of proposed multiplexing <i>Technique 1</i> , <i>2</i> , and <i>3</i> is shown on (a), <i>Technique 4</i> is shown on (b).	59
Figure 5.1. (a) Top view of QD-SOA chips. (b) Cross-sectional structure of QD-SOA. (c) SEM image of the top view of the QD layer. (d) SEM image of cross-section around QD layers.	62
Figure 5.2. (a) The block diagram of the QD-SOA measurement system (Figure 2 of Ref [63]).	

(b) The picture of the QD-SOA holder and focusers.....	63
Figure 5.3. Reference power of the system without SOA.....	64
Figure 5.4. An example of recorded power spectrum density during gain and NF measurement.	65
Figure 5.5. (a) The overall ASE output of QD-SOA. (b) Closed ASE spectrum around ASE peak.	67
Figure 5.6. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with different input power.	68
Figure 5.7. The (a) FtF gain and (b) NF of QD-SOA versus input laser power at peak gain wavelength (1507.8 nm) and 1550.0 nm.....	69
Figure 5.8. The ASE output of QD-SOA at different bias current.	69
Figure 5.9. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with difference bias current.	70
Figure 5.10. The (a) FtF gain and (b) NF of QD-SOA versus input power at peak gain wavelength.	72
Figure 5.11. The (a) FtF gain and (b) NF of QD-SOA versus input power at 1550.0 nm.	72
Figure 5.12. The ASE output of QD-SOA at different temperature.....	73
Figure 5.13. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with different temperature.	74
Figure 5.14. The (a) FtF gain and (b) NF of QD-SOA versus input power at peak gain wavelength.	75
Figure 5.15. The (a) FtF gain and (b) NF of QD-SOA versus input power at 1550.0 nm.	75
Figure 5.16. ASE spectrum of the 5-layer QD-SOA versus temperature from 17 - 80 °C.	76
Figure 5.17. The (a) ASE peak power spectrum density, (b) ASE peak wavelength, 3-dB bandwidth versus bias current and temperature, and (c) rate of change with temperature of ASE peak power spectrum density, peak wavelength, and 3-dB bandwidth.	77
Figure 5.18. (a) ASE total output power of the SOAs versus bias current for the different	

numbers of QD layers in the active region. (b) The maximum ASE power (left axis) and saturated current (right axis) versus QD layer number. (c) ASE spectra at a bias current of 300 mA and 25 °C with peak powers indicated in dBm. (d) ASE peak wavelength (left axis) and 3 dB bandwidth (right axis) versus number of QD layers.	80
Figure 5.19. (a) SOA chip gain as a function of input optical power for the four different QD devices at 25 °C at the indicated wavelength and current, (b) small-signal chip gain and (c) 3 dB saturated output power vs. number of QD layers.....	82
Figure 5.20. (a) NF as a function of input power for SOAs with different numbers of QD layers at 25 °C and specific measurement wavelengths and bias currents. (b) Small-signal NF at -13 dBm (left axis) and large-signal NF at 7 dBm (right axis) for SOAs versus QD layer number. (c) Spectra of input laser source (yellow) and output SOA (blue) measured at 1532 nm, 300 mA, and 25 °C for a 5-layer SOA.	83
Figure 6.1. The block diagram of the mmWave over fibre system with one QD-SOA.	86
Figure 6.2. The constellation of received signal of (a) 16-QAM 2 Gbaud, (b) 16-QAM 4 Gbauds, (c) 16-QAM 6 Gbauds, (d) 64-QAM 2 Gbauds, and (e) 64-QAM 4 Gbauds....	88
Figure 6.3. The constellation of the received signal of (a) 16-QAM OFDM and (b) 64-QAM OFDM.	89
Figure 6.4. The constellation of received signal of (a) 16-QAM 2 Gbauds, (b) 16-QAM 4 Gbauds, (c) 16-QAM 6 Gbauds, (d) 64-QAM 2 Gbauds, and (e) 64-QAM 4 Gbauds....	90
Figure 6.5. The constellation of the received signal of (a) 16-QAM OFDM and (b) 64-QAM OFDM.	90
Figure 6.6. Packaged 8-layer QD-SOA in 14-pin butterfly form.	92
Figure 6.7. The constellation of received signal of (a) 16-QAM 1 Gbauds, (b) 16-QAM 2 Gbauds.....	93
Figure 6.8. Block diagram of QD-SOAs integrated SSB-MZM based mmWoF system.....	94
Figure 6.9. Optical spectrum at the ORx.....	95
Figure 6.10. The constellation of received signal of (a) 16-QAM 1 Gbauds, (b) 16-QAM 2	

Gbauds.....	95
Figure 6.11. The constellation of received signal of (a) 16-QAM 1 Gbaud, (b) 16-QAM 2 Gbaud.	96
Figure 6.12. Block diagram of QD-SOA integrated frequency multiplexing <i>Technique 3</i> is shown on (a), <i>Technique 4</i> is shown on (b).	97
Figure 6.13. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	99
Figure 6.14. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.	100
Figure 7.1 Photonic wire bonding between QD-MLL and optical fibre.	106

List of Tables

Table 1.1 Summary of the evolution of the mobile communication system.....	1
Table 1.2 mmWave frequency definition in NR [3]	2
Table 4.1. Comparison of with and without wireless link in EVM (%).....	60
Table 4.2. Comparison of four multiplexing techniques in EVM (%)	60
Table 5.1. The peak gain wavelength and 3-dB bandwidth are shown at different bias current.	71
Table 5.2. The peak gain wavelength and 3-dB bandwidth at different temperature.....	73
Table 6.1 The EVM (%) of the received signal in different QD-SOA based mmWoF system	97

List of Abbreviations

ADC	Analog-to-digital converter
ASE	Amplified spontaneous emission
BBU	Baseband unit
BtB	Back-to-back
C-RAN	Centralized radio-access network
CW	Constant wavelength
DAC	Digital-to-analog converter
DBR	Distributed Bragg reflector
DFB	Distributed feedback
D-RAN	Distributed radio-access network
E/O	Electrical-to-optical converter
EAM	Electro-absorption modulator
EDFA	Erbium-doped fibre amplifier
EML	Electro-absorption modulated laser
EVM	Error vector magnitude
FP	Fabry-Pérot
FtF	Fibre-to-fibre
FWM	Four-wave mixing
I/Q	In-phase and quadrature
IF	Intermediate frequency
MLL	Mode-locked laser
mmWave	Millimeter wave
mmWoF	mmWave RoF
MZM	Mach-Zehnder modulator
NF	Noise figure

NR	New radio
O/E	Optical-to-electrical converter
OBPF	Optical band-pass filters
OC	Optical coupler
ORx	Optical receiver
OSNR	Optical signal to noise ratio
OTx	Optical transmitter
QD	Quantum dash
QW	Quantum well
RF	Radio frequency
RIN	Relative intensity noise
RoF	Radio-over-fibre
RRH	Radio remote head
SEM	Scanning electron microscope
SMF	Single-mode fibre
SOA	Semiconductor optical amplifier
SSB	Single side-band
SUL	Supplementary uplink

Chapter 1 Introduction

Mobile communication has undergone remarkable advancements over the past few decades. Driven by the growing demand for higher data rates and lower latency, each new generation has introduced significant improvements, particularly in fronthaul transmission. Section 1.1 provides a brief review of the evolution of mobile communication systems. Section 1.2 then focuses on fronthaul transmission as a key component of mobile networks, discussing its development in detail. Finally, Section 1.3 outlines the organization of this thesis.

1.1 Evolution of Mobile Communication System

Table 1.1 Summary of the evolution of the mobile communication system

	1G	2G	3G	4G	5G
Year	1980s	1990s	2000s	2010s	2020s
Technique	AMPS, NMT, TACS, C-Netz	GSM, D-AMPS, IS-95A	WCDMA, TD-SCDMA, CDMA2000	LTE	NR
Technique Improvement		GPRS, EDGE, IS-95B	HSPA+, EVDO	LTE A LTE Pro	
Peak Data Rate	N/A	384 kbps (EDGE) Real:150kbps	42.2 Mbps (HSPA+) Real:8Mbps	3Gbps (LTE Pro) Real:100Mbps	20Gbps
Carrier Frequency	450 MHz - 960 MHz	850 MHz - 1800 MHz	850 MHz - 2100 MHz	410 MHz - 5900 MHz	450 MHz - 71 GHz
Carrier Bandwidth	30 kHz	1.25 MHz	5 MHz	20 MHz	1 GHz
Latency		~500 ms	~100 ms	~50 ms	~1 ms

In the early 1980s, Motorola and several other companies introduced the first-generation mobile-phone system, essentially a landline-integrated, standardized walkie-talkie that used analog modulation and could transmit only voice [1], [2]. Mobile networks have since evolved rapidly.

Second-generation (2G) systems brought digital data transmission; third-generation (3G) systems further increased data rates and standardized both backhaul and fronthaul; and fourth-generation (4G) systems adopted orthogonal frequency-division multiplexing to combat burst noise. The current state of the art, fifth-generation (5G) technology, pushes data rates up to 20 Gb/s while reducing latency to roughly ms [1], [3]. Table 1.1 summarizes this progression.

As transmission rates have climbed, the required channel bandwidth has widened, driving carrier frequencies ever higher. By the time 5G was proposed, the traditional sub-6 GHz spectrum was overcrowded; for example, the 1.7-1.8 GHz band is shared by mobile communication, radiolocation, aeronautical radionavigation, amateur radio, and various fixed services [4]. Consequently, 5G New Radio (NR) extends wireless service into the millimeter-wave (mmWave) region, assigning new bands between 26 and 71 GHz [1], [5], as listed in Table 1.2.

Table 1.2 mmWave frequency definition in NR [3]

NR operating band	Uplink (UL) and Downlink (DL) operating band BS transmit/receive UE transmit/receive $F_{UL,low} - F_{UL,high}$ $F_{DL,low} - F_{DL,high}$	Duplex mode
n257	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	TDD
n259	39500 MHz – 43500 MHz	TDD
n260	37000 MHz – 40000 MHz	TDD
n261	27500 MHz – 28350 MHz	TDD
n262	47200 MHz – 48200 MHz	TDD
n263	57000 MHz – 71000 MHz	TDD

However, mmWave also introduces challenges in fronthaul transmission, which will be discussed in the following section.

1.2 Fronthaul Transmission

Fronthaul transmission is a comparatively recent element in mobile-network architecture.

In 1G and 2G systems, the concept did not exist. Every baseband and radio frequency (RF) module sat beneath the tower, and the modulated RF signal reached the antenna through a short coaxial cable run, as illustrated in Figure 1.1 (a). The idea of a fronthaul link first appeared in 3G [6], [7], where it served simply as the connection between a remote radio head (RRH) on the mast and a baseband unit (BBU) in a distributed radio-access network (D-RAN), as shown in Figure 1.1(b). With 4G, the architecture evolved into centralized RAN (C-RAN), in which multiple BBUs are pooled in a central office [3]. This step entirely separated the fronthaul from the backhaul, as shown in Figure 1.1(c).

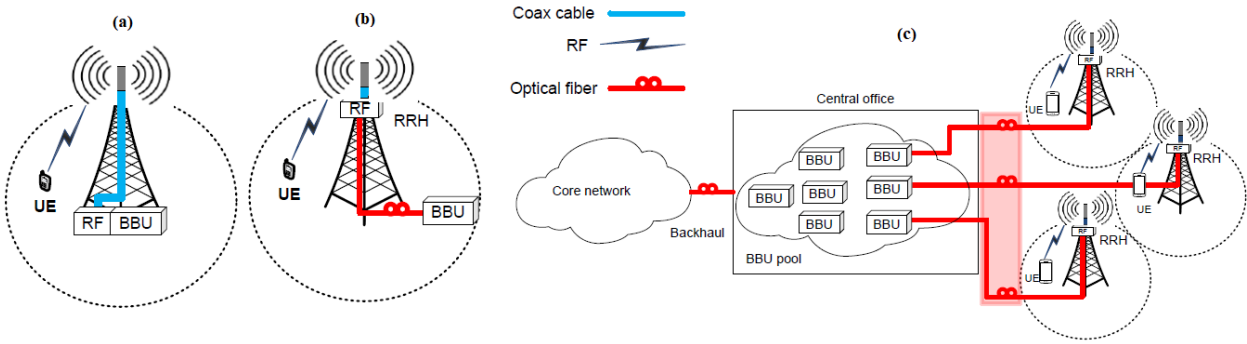


Figure 1.1. Comparison between (a) traditional mega base station, (b) D-RAN in 3G, and (c) C-RAN in 4G and above.

In 4G networks, fronthaul links are still predominantly digital baseband optical paths that carry in-phase and quadrature (I/Q) baseband signals to the RRH. As 5G pushes signal bandwidth even wider, however, the RRH becomes increasingly complex and power-hungry. To ease this burden, radio-over-fibre (RoF) has been adopted for fronthaul transmission, allowing analog RF signals to be delivered directly to the RRH [5], [8]. At that point, only optical-to-electrical (O/E) conversion and amplification are needed in RRH, while most modulation circuitry is centralized in the core office. In 5G NR, operating in the mmWave regime also raises significant fronthaul challenges. Achieving the required high bit rates and carrier frequencies forces every component,

including digital-to-analog and analog-to-digital converters (DACs/ADCs), to function at tens of gigahertz [6], [7], [9], [10]. Such hardware is inherently complex, expensive, and power-hungry. To alleviate these constraints, researchers have turned to RoF solutions, with a particular focus on millimetre-wave RoF (mmWoF) systems [1], [6], [11], [12].

In an mmWoF fronthaul system, the baseband signal is up-converted to the mmWave band by heterodyne detection at the optical receiver (ORx) [7], [9], [10], [12]. This architecture relaxes the performance demands on both ADCs and modulators. A key technology that can streamline mmWoF even further is the quantum-dot/quantum-dash mode-locked laser (MLL), which is introduced in Section 2.3.1.

Furthermore, future 5G fronthaul transmission systems may be deployed at the room or hall level to compensate for the inherently high attenuation of mmWave signals. This naturally raises the requirement for compact BBUs and RRUs. One potential solution is the use of integrated electro-optical chips [13], while another promising approach is photonic wire bonding [14], [15]. However, both approaches require an optical amplifier with a compatible size. Traditional erbium-doped fibre amplifiers (EDFAs) typically employ tens of meters of doped fibre. The long fibre in EDFAs make them unsuitable for integration into photonic chips or for wire bonding with other components. In this context, the QD semiconductor optical amplifier (SOA), introduced in Section 2.3.2, represents a promising candidate due to its compact size and adequate performance.

1.3 Organization

This report is organized into 7 chapters. Chapter 1 introduces the study, presenting a concise history of mobile-communication systems and fronthaul transmission, the challenges posed by 5G NR, especially in the mm-wave bands. Chapter 2 supplies the research background, analyzes the

limitations of existing RoF fronthaul systems, and the mathematical explanation of heterodyne detection and an overview of state-of-the-art QD gain medium. The challenge of current mmWoF system and further research methodology is also presented in this chapter. Chapter 3 proposes the preliminary improved mmWoF systems, and outlines the study methods. Chapter 4 further expanded mmWoF system by proposing four different frequency multiplexing techniques. In Chapter 5, basic characterization of QD-SOA is measured and analyzed. In Chapter 6, a QD gain medium based mmWoF system is proposed and verified in experimentation that shows the potential and flexibility of using QD-MLLs and QD-SOAs in 5G fronthaul transmission system. Finally, in Chapter 7, the conclusion and future works are discussed in detail.

Chapter 2 Background

In this chapter, the background of mmWoF fronthaul transmission systems is presented in detail. Section 2.1 introduces traditional RoF fronthaul links and discusses the challenges of extending them to state-of-the-art mmWave fronthaul systems. Section 2.2 describes the heterodyne-detected mmWoF link, which leverages RoF principles for mmWave fronthaul transmission. In Section 2.3, the QD gain medium is introduced in depth, highlighting its advantages, particularly those relevant to mmWoF systems. Finally, the chapter concludes with a discussion of the overall benefits and challenges of current mmWoF systems, guiding the research presented in the following chapters.

2.1 Traditional RoF Fronthaul Transmission

Over the past two decades, RoF technologies have attracted significant attention as a promising solution for the delivery and distribution of broadband RF signals. By employing analog optical transmission and optical subcarrier modulation, RoF systems enable the direct distribution of RF signals over optical fibres. In RoF systems, the RF signals are carried in their analog form without requiring digital conversion, which distinguishes RoF systems from conventional digital optical transmission.

RoF offers several key advantages that make it particularly relevant for emerging wireless networks. Optical fibres provide extremely high bandwidth and very low transmission loss, enabling the seamless distribution of high-frequency signals over long distances. In addition, optical transmission is immune to electromagnetic interference, ensuring reliable signal delivery even in environments with intense electrical noise. RoF also allows for the centralization of signal

processing at the BBU, while keeping RRH simple, compact, and cost-efficient, a critical requirement for dense deployments in 5G and beyond.

With the rapid development of mmWave and terahertz technologies for next-generation mobile communication, RoF has emerged as an enabling technology for fronthaul networks. It provides a scalable solution for transporting broadband signals between BBUs and RRUs, addressing key requirements such as high capacity, low latency, and cost-effectiveness. However, several challenges remain in traditional RoF systems that hinder their direct integration into mmWave fronthaul transmission. These challenges are also discussed in this section.

2.1.1 Key Component in RoF Links

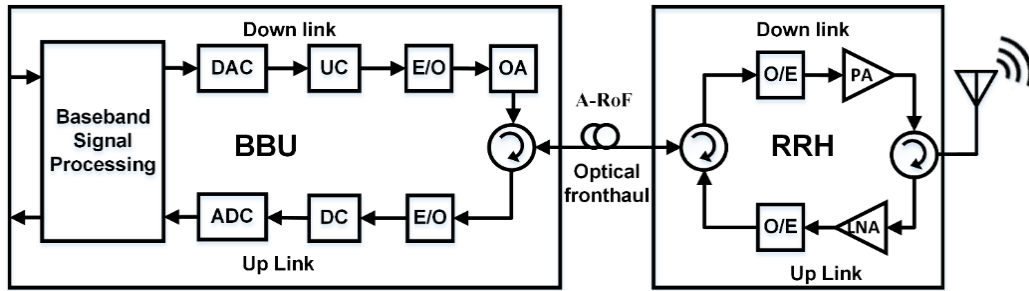


Figure 2.1. Basic principle of RoF. E/O: electrical to optical, OA: optical amplifier, PA: power amplifier, LNA: low noise amplifier. [16]

Figure 2.1 shows the basic structure of a RoF link, which reflect its principal function. A continuous-wave (CW) laser generated by the laser source is first modulated with an RF signal using an optical modulator, thereby converting the electrical signal into the optical domain. After the signal is modulated, it is transmitted through optical fibre, usually a single-mode fibre (SMF). When the transmission distance is long, it is usually necessary to introduce an optical amplifier to compensate the loss. At the RRH, the ORx restores the transmitted optical signal to RF signal, so as to complete the link transmission. Thus, a traditional RoF link consists of four key components:

the laser source, the optical modulator, the optical amplifier, and the ORx. In this section, each of these components is discussed in detail.

a) CW Laser

In optical communication systems, lasers are often used to generate stable optical carriers. Among them, distributed feedback (DFB) lasers are the most widely used. Compared with traditional Fabry Perot (FP) laser and distributed Bragg reflector (DBR) laser, DFB laser can maintain single longitudinal mode output and is superior to DBR laser in efficiency. Its typical structure is shown in Figure 2.2 [17]. In contrast to DFB lasers, the output spectrum of FP laser contains multiple side modes, which seriously weakens its application value in the field of high-performance communication.

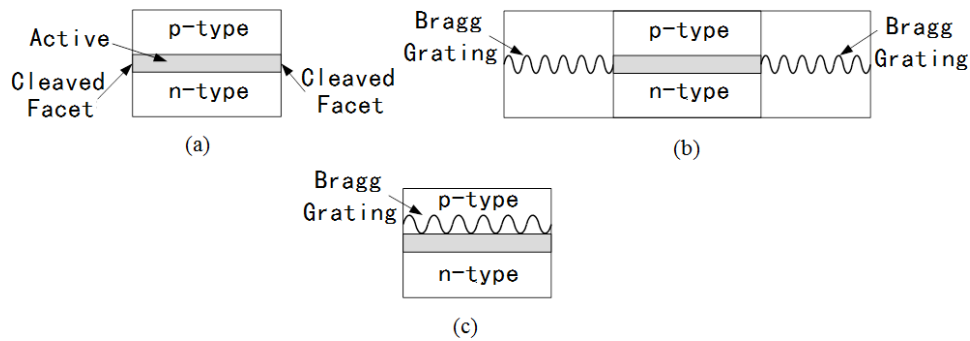


Figure 2.2. Structure of (a) Fabry-Perot laser, (b) structure of DBR laser, and (c) structure of DFB laser. [17]

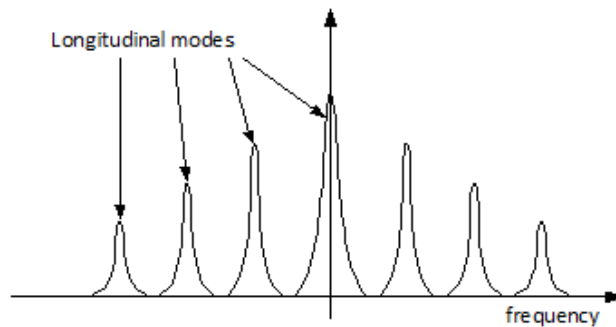


Figure 2.3. Output spectrum of Fabry-Perot laser.

DFB lasers, in contrast, exhibit high spectral purity, narrow linewidth, and stable single-mode operation, all of which are crucial for RoF and mmWoF systems. These properties help minimize phase noise and dispersion penalties, thereby enabling reliable high-capacity transmission in advanced fronthaul networks.

b) Optical Modulator

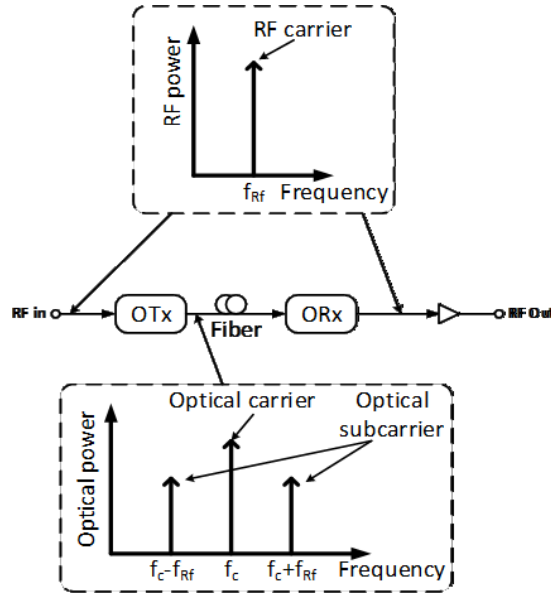


Figure 2.4. Schematic of optical subcarrier modulation.

As the CW laser carrier is generated, its modulation process is called optical subcarrier modulation. The principle of double-sideband (DSB) optical subcarrier modulation and demodulation is shown on Figure 2.4. In this process, the original RF signal is upconverted by the optical transmitter (Otx) at the frequency f_{RF} to achieve its shift to the optical carrier frequency in the frequency domain. In the digital optical modulation scheme, the modulation directly acts on the carrier frequency f_c , while in the analog system, the modulated signal is loaded on the subcarrier offset f_{RF} relative to f_c . This method makes the analog system occupy a wider bandwidth than the

digital system, reflect lower bandwidth efficiency. Because the three components at $f_c - f_{RF}$ and $f_c + f_{RF}$ exist and transmit at the same time, the influence of RoF link on optical nonlinearity is particularly significant.

The optical subcarrier modulation methods of laser carrier are generally divided into direct modulation and external modulation. Direct modulation is realized by changing the driving current of the injection laser, which change the laser intensity. A simplified direct modulation model is shown in Figure 2.5(a), while Figure 2.5(b) [18] shows its working mechanism. Direct modulation devices are typically compact and straightforward, but they are highly sensitive to chirp [17]. Moreover, when the input electrical power falls below the threshold level, the system experiences severe distortion, further limiting the applicability of direct modulation in high-performance communication systems.

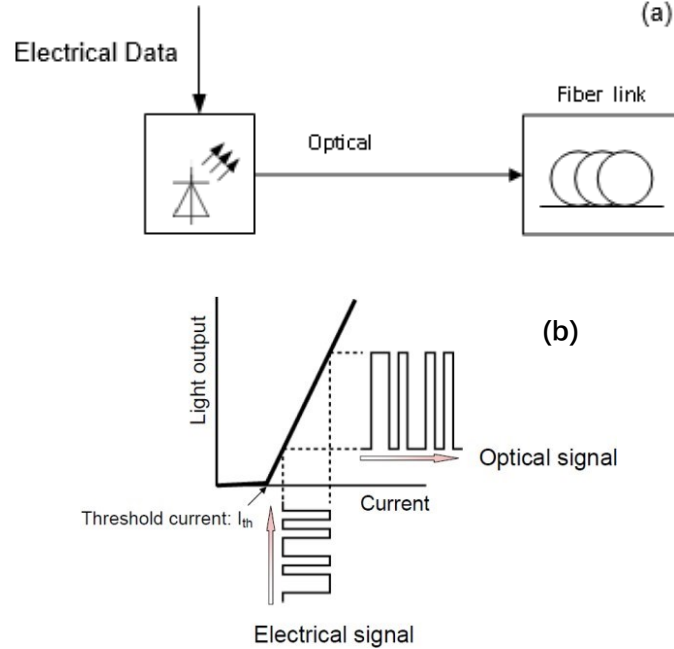


Figure 2.5. Direct modulation method (a) and its mechanism (b) [18].

In external modulation, the optical signal is modulated by an independent device rather than

directly through the laser current. There are many kinds of external modulators are used widely in communication systems, including electro-absorption modulators (EAMs) and Mach-Zehnder modulators (MZMs). These external modulated RoF links usually shares similar structure as shown in Figure 2.6.

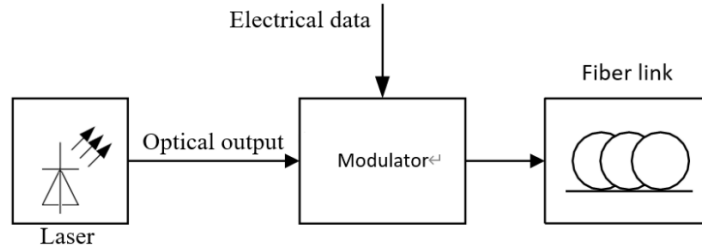


Figure 2.6. Block diagram of the external modulator.

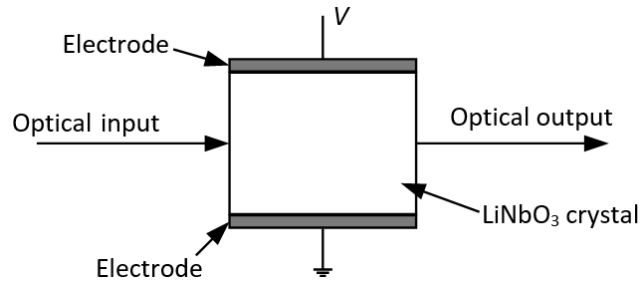


Figure 2.7. EAM modulator in a LiNbO₃ crystal.

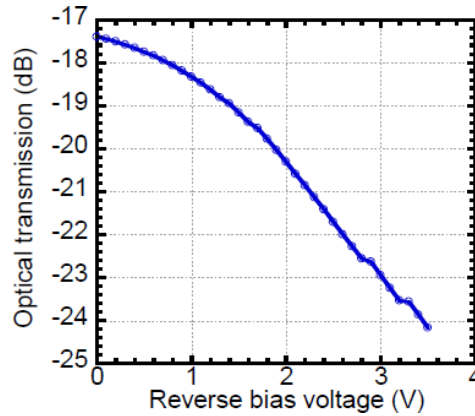


Figure 2.8. A typical transmission characteristic of EAM. [19]

EAMs employ a semiconductor waveguide to control the intensity of the laser. The structure of a typical EAM is shown in Figure 2.7. EAMs can provide a compact size, low bias voltage, and non-threshold modulator to modern RoF links. In practice, most EAMs are integrated with a laser

diode on a single chip, forming an electro-absorption modulated laser (EML). The three dimensions of an EML is comparable to that of a direct modulator. Compared with direct modulation, the EMLs also supports higher bandwidth while keeping a low chirp.

Another essential feature of EAMs is their fast absorption recovery time, typically less than 10 ps under high reverse-bias operation [20]. Their characteristics have been extensively studied and reported in the literature [21], [22]. Because the absorption of the semiconductor is controlled by the applied reverse bias voltage, the modulation performance of the EAM is directly determined by this parameter. A representative transmission characteristic is shown in Figure 2.8.

MZMs are another widely used class of external modulators and, in fact, are more commonly adopted than EAMs. A single MZM can be used to modulate a CW laser into DSB or single sideband (SSB). If two MZMs are connected in parallel, they can be used to modulate an I/Q signal. As these I/Q MZMs support multiple modulation formats and can be operated with near-zero chirp, making them highly suitable for advanced optical communication systems. Despite their relatively large physical size, MZMs are favored because of their versatility and superior performance. The general structure of an I/Q MZM is shown in Figure 2.9.

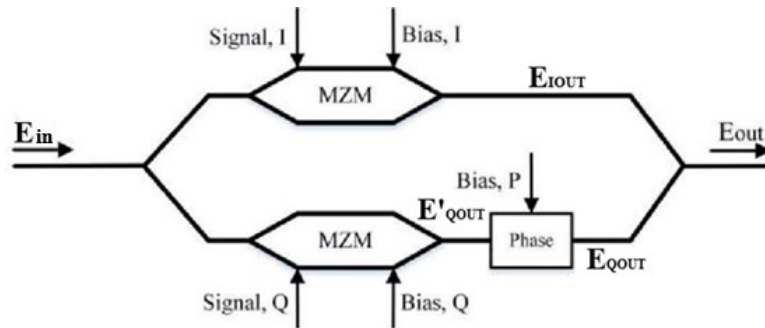


Figure 2.9. Block diagram of I/Q MZM.

Here is a mathematical explanation of I/Q MZM. It is assumed input of the MZM is defined

as $E_{in}(t)$:

$$E_{in}(t) = A_o(t) \exp\{j(\omega_o t + \varphi_o(t))\} \quad (2-1)$$

where $A_o(t)$ is the optical amplitude noise, $\varphi_o(t)$ is the optical phase noise, and ω_o is the wavelength of the laser.

In I/Q MZM, optical carrier $E_{in}(t)$ will be divided into in-phase and quadrature branches. In the I branch, the input electrical signal $I(t)$ and a constant bias will change the reflection index of the waveguide material, which will lead to a phase change. In this setup, bias is set to the null point, which leads to a phase change of π . Therefore, the E_{Iout} of Figure 2.9 will be:

$$E_{Iout}(t) = \frac{A_o \left(t + \frac{I(t) + \pi}{\omega_o} \right)}{2} \exp \left\{ j \left(\omega_o t + \varphi_o \left(t + \frac{I(t) + \pi}{\omega_o} \right) + I(t) + \pi \right) \right\} + \frac{A_2(t)}{2} \exp\{j(\omega_o t + \varphi_o(t))\} \quad (2-2)$$

where $I(t)$ is the in-phase baseband electrical signal. Here we assume the two branches have equal power divided and no loss. In the formular, $\frac{I(t)+\pi}{\omega_o}$ is about 3 fs, which is way below the coherent time. Therefore, we could also assume $A_o \left(t + \frac{I(t)+\pi}{\omega_o} \right) = A_o(t)$ and $\varphi_o \left(t + \frac{I(t)+\pi}{\omega_o} \right) = \varphi_o(t)$. Thus, the Equation (2-2) can be simplified as:

$$\begin{aligned} E_{Iout}(t) &= \frac{A_o(t)}{2} \exp\{j(\omega_o t + \varphi_o(t) + I(t) + \pi)\} + \frac{A_o(t)}{2} \exp\{j(\omega_o t + \varphi_o(t))\} \\ &= \frac{A_o(t)}{2} \exp\{j(\omega_o t + \varphi_o(t))\} \{ \exp\{j(I(t) + \pi)\} + 1 \} \\ &= \frac{A_o(t)}{2} \exp\{j(\omega_o t + \varphi_o(t))\} \{ -\exp\{j(I(t))\} + 1 \} \end{aligned} \quad (2-3)$$

Expand $\exp\{j(I(t))\}$ of Equation (2-3) with Bessel function:

$$E_{Iout}(t) = \frac{A_o(t)}{2} \exp\{j(\omega_o t + \varphi_o(t))\} \left\{ 1 - \sum_{n=0}^{+\infty} j^n J_n[I(t)] \right\} \quad (2-4)$$

where J_n is the n^{th} order first type Bessel function. Figure 2.10 shows the first type Bessel function.

In general, $I(t)$ is always low enough (less than 0.4), hence it is assumed $J_0[I(t)] \approx 1$. The first

order Bessel function $J_1[I(t)]$ is also assumed linear, which means $J_1[I(t)] = I(t)$. For higher orders, the $J_n[I(t)]$ is low enough which can be ignored and consider as harmonic distortion. The $\sum_{n=0}^{+\infty} j^n J_n[I(t)]$ in Equation (2-4) can be simplified as:

$$\sum_{n=0}^{+\infty} j^n J_n[I(t)] = I(t) \quad (2-5)$$

Therefore, after substitute Equation (2-5) into (2-4), the output $E_{Iout}(t)$ can be express as:

$$E_{Iout}(t) = \frac{A_o(t)}{2} I(t) [-j \cos(\omega_o t + \varphi_o(t)) + \sin(\omega_o t + \varphi_o(t))] \quad (2-6)$$

Here, the distortion caused by the MZM is ignored, which is located far from the passband of the system.

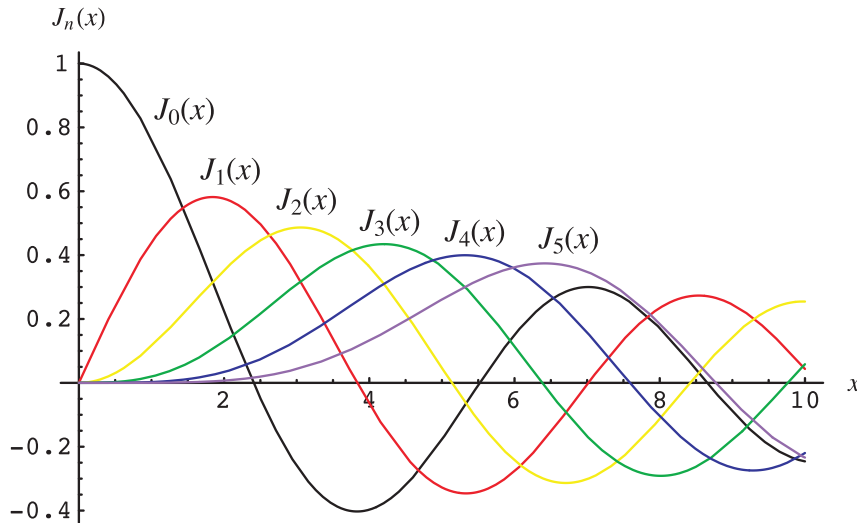


Figure 2.10. First type Bessel function.

Similar to Equation (2-6), in the quadrature branch, the $E'_{Qout}(t)$ in the Figure 2.9 can be expressed as:

$$E'_{Qout}(t) = \frac{A_o(t)}{2} Q(t) [-j \cos(\omega_o t + \varphi_o(t)) + \sin(\omega_o t + \varphi_o(t))] \quad (2-7)$$

where $Q(t)$ is the quadrature baseband electrical signal, $A_o(t)$ and $\varphi_o(t)$ is the amplitude and

phase noise of optical carrier, respectively.

Signal $E'_{Qout}(t)$ will then pass-through a phase modulator to shift the phase by $\pi/2$. The signal $E_{Qout}(t)$ of Figure 2.9 will be:

$$E_{Qout}(t) = \frac{A_o(t)}{2} Q(t) [j \sin(\omega_o t + \varphi_o(t)) + \cos(\omega_o t + \varphi_o(t))] \quad (2-8)$$

The output of I/Q MZM $E_{out}(t)$ will be the summation of Equation (2-6) and (2-8), which will be:

$$\begin{aligned} E_{out}(t) &= Real(E_{Iout} + E_{Qout}) \\ &= \frac{A_o(t)}{2} (I(t) \sin(\omega_o t + \varphi_o(t)) + Q(t) \cos(\omega_o t + \varphi_o(t))) \end{aligned} \quad (2-9)$$

If $I(t)$ and $Q(t)$ are generated specifically, I/Q MZM can be converted to DSB-MZM or SSB-MZM.

c) Optical Amplifier

After the RF signal is modulated onto a CW laser carrier, the resulting optical signal is fed into a fibre link for transmission. If the transmitted signal power is insufficient, an optical amplifier is required to maintain adequate signal strength. Among the available technologies, EDFAs and SOAs represent the two most widely adopted solutions in optical communication systems. They are discussed in detail.

EDFAs have been the dominant optical amplifier technology in long-haul and metro optical communication systems since their introduction in the late 1980s [23], [24]. They are based on the principle of doping silica fibres with erbium ions (Er^{3+}), which provide optical gain when pumped by a 980 nm or 1480 nm laser source. This configuration enables efficient amplification in the C-

band (1530-1565 nm), coinciding with the low-loss transmission window of silica fibres, and can be extended to the L-band (1565-1625 nm) with appropriate design [25].

The key advantages of EDFAs include high gain (>40 dB), low noise figure (as low as 4-5 dB), broad bandwidth, polarization insensitivity, and the ability to simultaneously amplify multiple wavelength channels in dense wavelength-division multiplexing (DWDM) systems [26], [27]. These characteristics have made EDFAs the backbone of optical communication infrastructure for decades, supporting high-capacity, long-distance transmission with minimal signal regeneration.

However, EDFAs also have inherent limitations. Their large physical size, reliance on long stretches of erbium-doped fibre, and relatively high-power consumption restrict their suitability for integration into chip-scale systems [28]. In addition, nonlinear effects such as four-wave mixing and gain saturation can degrade performance under high input power or dense channel loading. As a result, while EDFAs remain indispensable in backbone networks, alternative solutions such as SOAs are being explored for applications where compactness, integration, and low power consumption are critical, such as mmWoF fronthaul systems.

SOAs are also widely used in communication systems. SOAs are compact, electrically pumped devices that amplify optical signals through stimulated emission in a semiconductor gain medium. Unlike EDFAs, which require long lengths of doped fibre, SOAs are chip-scale devices that can be fabricated using standard semiconductor processes, making them highly suitable for integration with other photonic and electronic components. SOAs can operate across a broad wavelength range, offer fast gain dynamics on the order of picoseconds, and support functions beyond amplification, such as switching and wavelength conversion. However, they typically exhibit higher noise figures and nonlinearities compared with EDFAs, which can limit performance

in long-haul systems. Nevertheless, their small footprint, low operating power, and potential for photonic integration make SOAs a promising solution for short-reach, cost-sensitive, and next-generation applications such as mmWoF fronthaul systems. The detail of SOA is also discussed in Section 2.3.2.

d) Optical Receiver

An ORx converts optical signals into electrical signals, with the core component being a photodiode. In its simplest form, a single photodiode, such as a PN or PIN photodiode, can function as an ORx. However, most practical receivers include additional circuitry, such as a preamplifier and signal processing components, to improve sensitivity and overall performance. A typical and simplified ORx is illustrated in Figure 2.11. The signal processing stage can consist of an analog filter or other electronic circuits designed to optimize the recovered signal for subsequent processing.

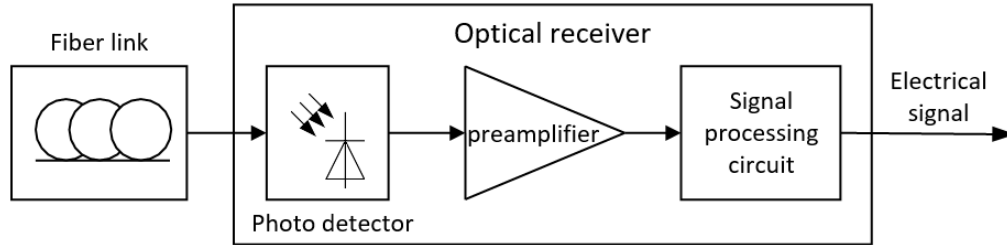


Figure 2.11. A sample of ORx. [25]

In RoF systems, the direct receiver shown in Figure 2.11 primarily functions as an amplitude demodulator. This approach is sufficient for analog signals but becomes inadequate in modern digital optical communication, where phase rather than amplitude is often the modulated parameter. Direct, or incoherent, receivers cannot capture phase or frequency variations, limiting their ability to process advanced modulation formats. To overcome this restriction, coherent

detection techniques have been developed by researchers. As shown in Figure 2.12, an optical I/Q coherent receiver shares a similar architecture with a microwave I/Q demodulator. By mixing the received optical signal with a local oscillator, the receiver simultaneously extracts amplitude and phase information. This capability enabling the detection and demodulation of complex modulation schemes such as n -QAM, making coherent receivers indispensable in state-of-the-art digital optical communication systems.

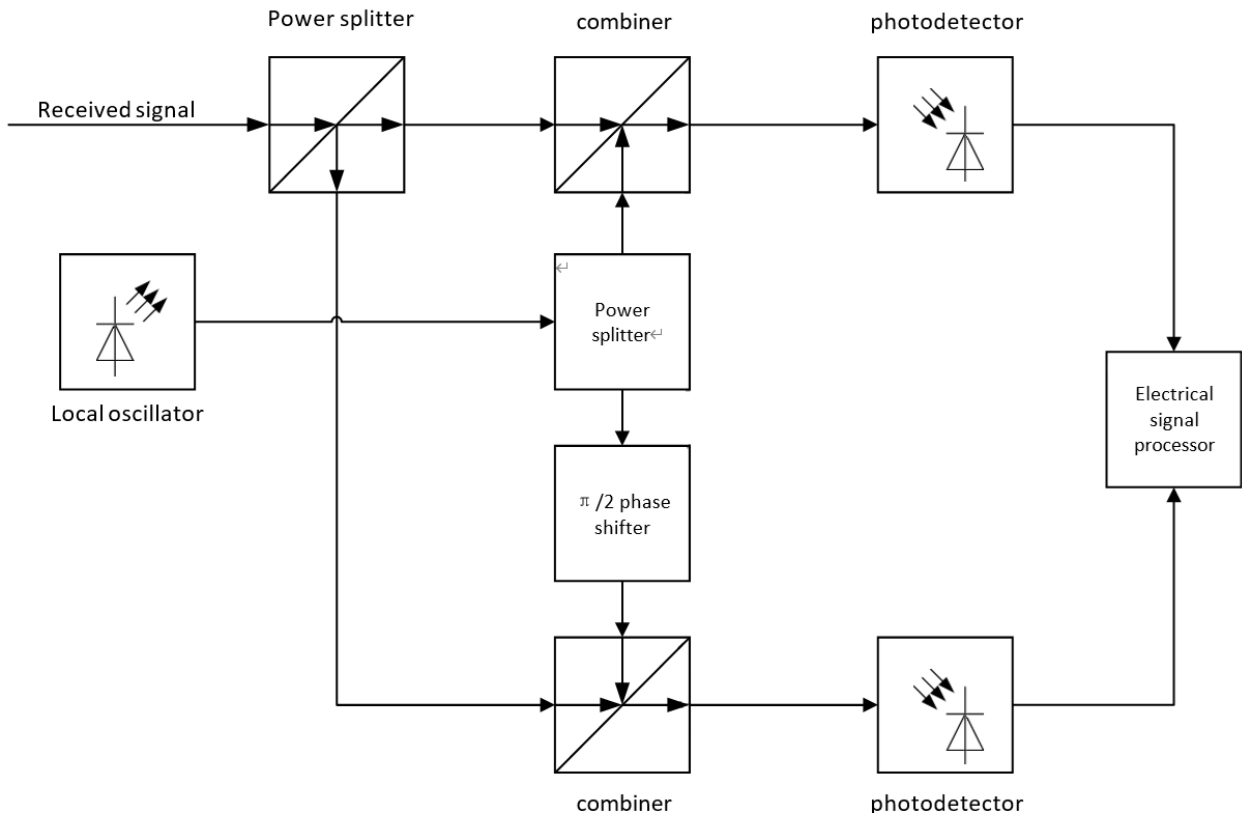


Figure 2.12. Structure of an I/Q coherent receiver. [25]

2.1.2 Challenges in Expanding RoF to the mmWave Band

In 5G and beyond, mmWave bands are adopted to further increase transmission rates. However, due to the inherently high attenuation of mmWave signals, their propagation distance is

much shorter than that of traditional sub-6 GHz signals. To compensate for this limitation, a denser deployment of base stations is required, potentially extending to every room or hall. Naturally, RoF is expected to play an essential role in fronthaul transmission systems thanks to its simple RRH design and low power consumption. Nevertheless, two major challenges hinder the direct expansion of traditional RoF systems into the mmWave band.

In conventional RoF systems, digital signals must be converted into analog RF signals by a high-speed DAC before being modulated onto the optical carrier, as shown in Figure 2.1. At mmWave frequencies, however, the required sampling rates and resolution for DACs become extremely demanding. State-of-the-art DACs capable of generating wideband mmWave signals consume significant power and are very costly, making them unsuitable for large-scale deployment in dense fronthaul networks. This cost and energy barrier greatly limits the scalability of traditional RoF architectures in the mmWave band. To overcome this, a heterodyne-detected mmWoF fronthaul transmission system is proposed [16], which will be discussed in Section 2.2.

Another challenge lies in the reliance on EDFA for optical amplification. As explained in the previous section, EDFAs require long lengths of erbium-doped fibre, resulting in bulky devices that cannot be easily integrated into compact or chip-scale systems. Additionally, their relatively high power consumption makes them impractical for deployment in large numbers of RRHs, where both space and energy efficiency are critical. While EDFAs remain essential for long-haul backbone networks, their size and power demands are major obstacles for mmWave fronthaul applications.

These challenges highlight the limitations of traditional RoF systems and motivate the exploration of alternative solutions such as SOA, and in particular QD-SOA, which combine

compact size, lower power consumption, and compatibility with photonic integration. The details of QD-SOA will be introduced in Section 2.3.2.

2.2 Heterodyne Detected mmWoF system

When transmitting mmWave signals through a traditional RoF system, as shown in Figure 2.1, the requirement for high-speed DACs and high-bandwidth E/O modulators becomes a major barrier to further development. To overcome these limitations, researchers have proposed an alternative approach in which the baseband or intermediate-frequency (IF) signals are optically upconverted to the mmWave band at the ORx, a technique known as heterodyne detection. A schematic block diagram of optical heterodyne detection is shown in Figure 2.13. This approach removes the need for ultra-high-speed DACs at the transmitter. It reduces the bandwidth requirements of optical modulators, thereby simplifying the system architecture while enabling direct mmWave generation at the receiver.

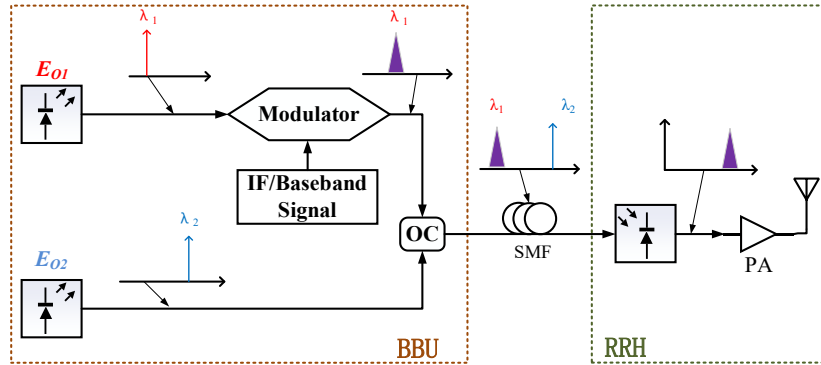


Figure 2.13. Schematic block diagram of optical heterodyne detection.

2.2.1 Mathematical Explanation of Optical Heterodyne Detection

Traditionally, electronic heterodyne detection is a well-established technique in microwave communication systems, where a high-frequency signal is mixed with a locally generated oscillator

signal to down convert it to IF [2]. This architecture enables the use of lower-frequency electronic components for signal processing, reducing system complexity and cost while maintaining access to high carrier frequencies. Electrical heterodyne receivers have been widely deployed in radar, satellite communications, and broadband wireless systems due to their superior sensitivity and frequency selectivity compared with direct detection architectures.

Although optical heterodyne detection is based on the same fundamental concept as electrical heterodyne detection, mixing two frequencies followed by power detection, its function in mmWoF systems is different. Specifically, optical heterodyne detection in this context is employed to upconvert baseband or IF signals generated at the BBU to the desired mmWave band at the RRH. In optical heterodyne systems, two optical carriers are mixed at the photodetector. The power detection, also known as beating, of these carriers directly produces a mmWave or terahertz electrical signal, effectively transferring the heterodyne principle from the electrical to the optical domain [16]. This approach bypasses the need for ultra-high-speed DACs at the transmitter and directly generates mmWave signals at the ORx, making it especially attractive for next-generation fronthaul systems. Here is a detailed mathematical explanation of optical heterodyne detection.

Firstly, two optical carrier, as shown in Figure 2.13, $E_{O1}(t)$ and $E_{O2}(t)$ is defined as:

$$E_{O1}(t) = A_{O1}(t)\exp\{j(\omega_{O1}t + \varphi_{O1}(t))\} \quad (2-10)$$

$$E_{O2}(t) = A_{O2}(t)\exp\{j(\omega_{O2}t + \varphi_{O2}(t))\} \quad (2-11)$$

where $A_{O1}(t)$ and $A_{O2}(t)$ is the amplitude noise, $\varphi_{O1}(t)$ and $\varphi_{O2}(t)$ is the phase noise, and ω_{O1} and ω_{O2} is the wavelength of two carrier. In some cases, the phase noise contains a common noise and differential noise follow the rule:

$$\varphi_{O1}(t) = \varphi_c(t) + \varphi_d(t) \quad (2-12)$$

$$\varphi_{O2}(t) = \varphi_c(t) \quad (2-13)$$

where $\varphi_c(t)$ represents the common noise that both carriers are the same. $\varphi_d(t)$ represent the phase difference between carrier 1 and 2.

As shown in Figure 2.13, one of the optical carriers will be modulated. Here it is assumed that optical carrier 1, $E_{O1}(t)$, is modulated by an I/Q modulator. Therefore, substitute Equation (2-10) to Equation (2-9), the output of the modulator will be:

$$E_{out}(t) = \frac{A_{O1}(t)}{2} (I(t) \sin(\omega_{O1}t + \varphi_{O1}(t)) + Q(t) \cos(\omega_{O1}t + \varphi_{O1}(t))) \quad (2-14)$$

where $E_{out}(t)$ is the output modulated optical signal, $I(t)$ and $Q(t)$ is the I/Q baseband or IF band signal.

Then, the modulated optical signal $E_{out}(t)$ will combined with reference signal $E_{O2}(t)$ and transmitted through SMF. At the receiver side, the received optical signal $E_{Rx}(t)$ will be:

$$\begin{aligned} E_{Rx}(t) &= E_{out} + E_{O2} \\ &= \frac{A_{O2}(t)}{2} \cos(\omega_{O1}t + \varphi_{O1}(t)) \\ &\quad + \frac{A_{O1}(t)}{2} (I(t) \sin(\omega_{O1}t + \varphi_{O1}(t)) + Q(t) \cos(\omega_{O1}t + \varphi_{O1}(t))) \end{aligned} \quad (2-15)$$

The photo detector only detects the power of the optical signal, known as power detection. Therefore, the detected electrical signal $Y(t)$ will be:

$$\begin{aligned} Y(t) = E_{Rx}^2(t) &= \left\{ \frac{A_{O2}(t)}{2} \cos(\omega_{O2}t + \varphi_{O2}(t)) \right. \\ &\quad \left. + \frac{A_{O1}(t)}{2} (I(t) \sin(\omega_{O1}t + \varphi_{O1}(t)) + Q(t) \cos(\omega_{O1}t + \varphi_{O1}(t))) \right\}^2 \end{aligned} \quad (2-16)$$

Further expand Equation (2-16), $Y(t)$ will be:

$$\begin{aligned}
Y(t) = & \left\{ \frac{A_{02}(t)}{2} \cos(\omega_{02}t + \varphi_{02}(t)) \right\}^2 \\
& + \left\{ \frac{A_{01}(t)}{2} (I(t) \sin(\omega_{01}t + \varphi_{01}(t)) + Q(t) \cos(\omega_{01}t + \varphi_{01}(t))) \right\}^2 \\
& + \left\{ \frac{A_{02}(t)}{2} \cos(\omega_{02}t + \varphi_{02}(t)) \right\} \left\{ \frac{A_{01}(t)}{2} (I(t) \sin(\omega_{01}t + \varphi_{01}(t)) \right. \\
& \left. + Q(t) \cos(\omega_{01}t + \varphi_{01}(t))) \right\}
\end{aligned} \tag{2-17}$$

After expand all the terms in the Equation (2-17), many components appear around $2 * \omega_0 t$, which can be neglected. The signal located within the pass band, $Y_F(t)$, will be:

$$\begin{aligned}
Y_F(t) = & \frac{A_{02}^2(t)}{8} + \frac{A_{01}^2(t)}{8} (I^2(t) - Q^2(t)) \\
& + \frac{A_{01}(t)A_{02}(t)}{8} \{ I(t) \sin((\omega_{01} - \omega_{02})t + \varphi_{01}(t) \\
& - \varphi_{02}(t)) + Q(t) \cos((\omega_{01} - \omega_{02})t + \varphi_{01}(t) - \varphi_{02}(t)) \}
\end{aligned} \tag{2-18}$$

After substitute Equation (2-12) and (2-13) into Equation (2-18), only the difference of phase noise $\varphi_d(t)$ will remain. The final signal can be expressed as:

$$\begin{aligned}
Y_F(t) = & \frac{A_{02}^2(t)}{8} + \frac{A_{01}^2(t)}{8} (I^2(t) - Q^2(t)) \\
& + \frac{A_{01}(t)A_{02}(t)}{8} \{ I(t) \sin((\omega_{01} - \omega_{02})t \\
& + \varphi_d(t)) + Q(t) \cos((\omega_{01} - \omega_{02})t + \varphi_d(t)) \}
\end{aligned} \tag{2-19}$$

It is found that the signal contains DC component $\frac{A_{02}^2(t)}{8}$ and the power of baseband or IF band signal, $\frac{A_{01}^2(t)}{8} (I^2(t) - Q^2(t))$. These two components can be removed in RF amplifier and antenna designed to work at mmWave band, or by adding a bandpass filter (BPF).

The third term of Equation (2-19) contains the I/Q modulated RF signal, $Y_{mmWave}(t)$,

located at mmWave, which will be:

$$Y_{mmWave}(t) = \frac{A_1(t)A_2(t)}{8} \{I(t) \sin((\omega_{o1} - \omega_{o2})t + \varphi_d(t)) + Q(t) \cos((\omega_{o1} - \omega_{o2})t + \varphi_d(t))\} \quad (2-20)$$

It is clear that the baseband I/Q signal is upconverted to the mmWave band, where the central frequency is determined by the frequency (or wavelength) difference between the two optical carriers. The dominant phase noise that remains is the phase noise difference between two optical carriers, as shown in Equation (2-20).

Therefore, the key challenge of the heterodyne detected mmWoF system is to produce two or more optical carriers that have either low phase noise or have highly coherent phase noise.

2.2.2 Generation of Optical Carriers in mmWoF system



Figure 2.14. Block diagram of mmWoF system with two free-run lasers. [29]

As explained in Section 2.2.1, the major challenge in mmWoF systems lies in identifying laser sources that either exhibit ultra-low phase noise or possess highly coherent phase noise characteristics. Several approaches have been proposed to generate such carriers. The most straightforward method is to employ two free-running lasers with ultra-low phase noise [29], as shown in Figure 2.14. However, this approach requires two highly stable and expensive lasers, typically with linewidths below 10 kHz, which makes the solution cost-prohibitive.

To make two free-running lasers coherent with each other, an injection locking mechanism

can be employed [30], [31]. As shown in Figure 2.15, part of the laser output is injected back into the original laser through a micro-FP cavity [30]. This feedback loop forces the two free-running lasers to become highly coherent. In other implementations, such as [31], a master-slave configuration is used, where only a portion of the master laser's output is injected into the slave laser. Although the configurations differ, the underlying principle remains the same: injecting light from one laser into another induces coherence between them. Compared with simply using two independent free-running lasers, injection locking increases system complexity and suffers from limited stability, as it is highly sensitive to the injected power level. However, this approach avoids the need for costly ultra-low-noise lasers, making it a more practical solution in many cases.



Figure 2.15. Simplified schematic of dual self-injection locking system. [30]

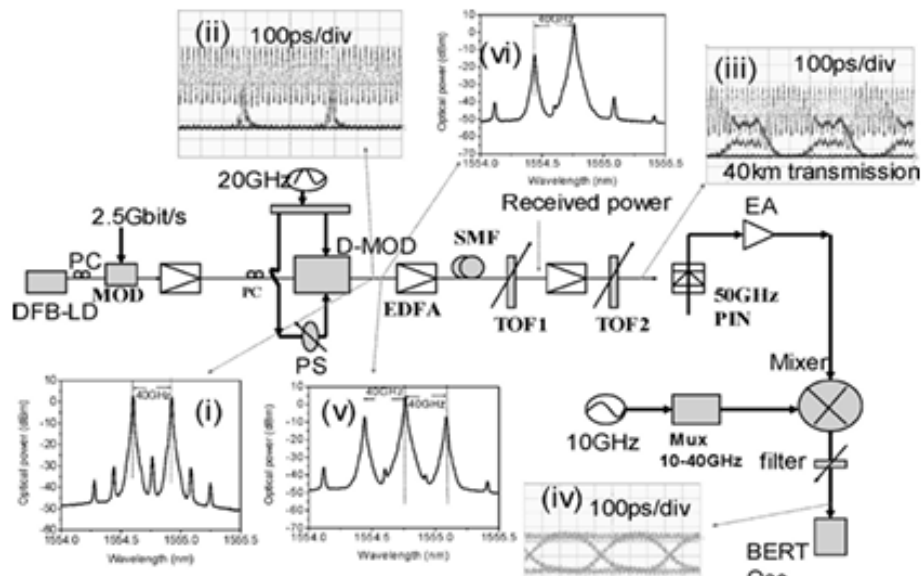


Figure 2.16. Experimental setup for optical mmWave generation by using external modulator. [32]

Another popular solution is to employ an external modulator to generate two or more coherent optical carriers [32], [33]. The block diagram presented in [32] is shown in Figure 2.16, where an external modulator (D-MOD in Figure 2.16) is used to create the carriers. Since the carriers generated by the same modulator share identical phase noise, this noise is effectively canceled during heterodyne detection. Although this approach introduces additional complexity due to the inclusion of an extra modulator, and the attenuation of the MZM can degrade performance, it remains a more cost-effective solution compared with using two independent free-running lasers.

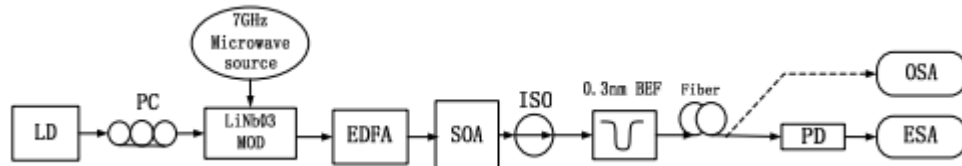


Figure 2.17. Schematic diagram of the mmWave generation using four-wave mixing. [34]

Nonlinear effects can also be exploited to generate coherent optical carriers [34], [35]. In [34], the authors use four-wave mixing (FWM) in SOAs to produce optical carriers, as shown in Figure 2.17. In this scheme, a laser diode generates a single-wavelength optical signal, which is then modulated by an IF signal. After amplification by an EDFA, the modulated signal enters the SOA. Since the EDFA raises the signal power above the SOA's saturation level, strong four-wave mixing and other nonlinear effects occur, generating the desired mmWave optical carrier inside the SOA. Because both the modulated optical signal and the FWM-generated carrier originate from the same laser source, they remain highly coherent with one another. As a result, at the ORx, their phase noise contributions cancel effectively.

Beyond the above solutions that rely on additional components to generate multiple optical carriers, MLL have also been investigated, as they can inherently provide numerous highly

coherent optical carriers simultaneously. Previous studies have explored two-section quantum well (QW) MLLs [31], quantum dot MLLs [36], and quantum dash (QD) MLLs [16] as sources for mmWoF systems. In this work, QD-MLLs are selected for future research due to their superior performance, and they are introduced in detail in Section 2.3.1. Given that employing QD-MLLs in heterodyne-detected mmWoF systems is a highly promising approach, this solution will be discussed in depth in the following section.

2.2.3 The Overview of QD-MLL Based mmWoF System

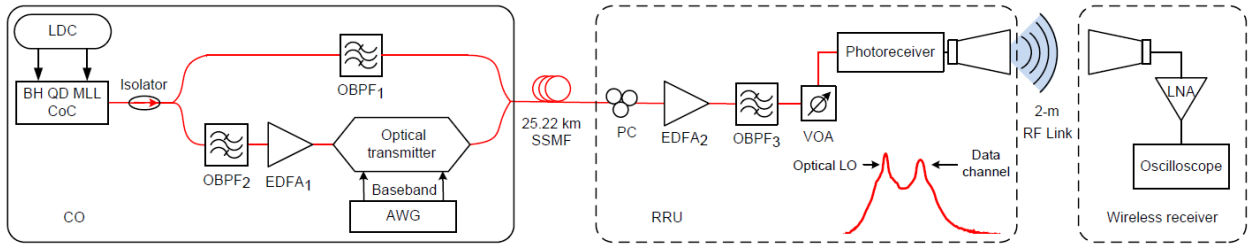


Figure 2.18. Block diagram of mmWoF system. [37]

As shown in Table 1.1, the 5G standard extends into the mmWave spectrum to widen signal bandwidth and boost data-transmission rates. Generating mmWave carriers, however, is technically demanding, so mmWoF has emerged as a practical, robust alternative [12], [38]. Figure 2.18 shows a representative mmWoF architecture [37].

A QD-MLL provides tens of highly coherent optical carriers [38]. After passing through an optical coupler (OC), two wavelengths are isolated by optical BPFs (OBPFs). One carrier is intensity-modulated by an optical transmitter, while the other remains unmodulated as a reference. The two optical signals are then recombined and sent down SMF.

At the RRU, the composite signal is amplified, and a second OBPF suppresses amplified-spontaneous-emission noise from the erbium-doped fibre amplifier (EDFA). A photonic

receiver performs optical-to-electrical conversion; the heterodyne beat between the two carriers simultaneously recovers the data and up-converts it to the mmWave band. The operation and performance of this mmWoF system are analyzed in Chapter 3.

Compared with other multi-carrier generation techniques, QD-MLLs offer distinct advantages for mmWoF systems. Methods such as using two ultra-low phase noise free-running lasers provide excellent phase performance but suffer from prohibitive cost and complexity. Injection locking of free-running lasers reduces cost but is highly sensitive to operating conditions and lacks long-term stability. External modulation approaches can generate coherent carriers at lower cost, but the added insertion loss and extra components reduce overall system efficiency. Nonlinear techniques, such as four-wave mixing in SOAs, provide carrier generation from a single source but often introduce significant noise and require high input power. In contrast, QD-MLLs naturally generate tens of highly coherent carriers with low phase noise, high stability, and good compatibility with WDM architectures, making them a highly attractive and scalable solution for heterodyne-detected mmWoF fronthaul transmission systems, therefore, the detail of QD-MLL is given in Section 2.3.1

2.3 Quantum Dot and Quantum Dash Gain Medium

Semiconductor quantum-dot or QD gain medium were first proposed in 1976 [39], with the initial theoretical treatment of carrier confinement following in 1982 [40]. Quantum confinement occurs when one or more structural dimensions approach the carrier de Broglie wavelength (≈ 10 nm), producing quantization of the density of states, continuous in bulk (3D), step-like in QWs (2D), and discrete (δ -like) in quantum dots (0D), as shown in Figure 2.19 [41]. Because carriers are confined in all three spatial dimensions in QDs, these devices exhibit distinctive optical

properties: high material gain, wavelength tunability, ultrafast carrier dynamics, ultralow threshold current density, improved temperature stability, a low linewidth-enhancement factor, and high spectral purity [42]. As a result, QD-based lasers can achieve substantially narrower spectral linewidths and lower relative-intensity noise (RIN) than their quantum-well counterparts [36].

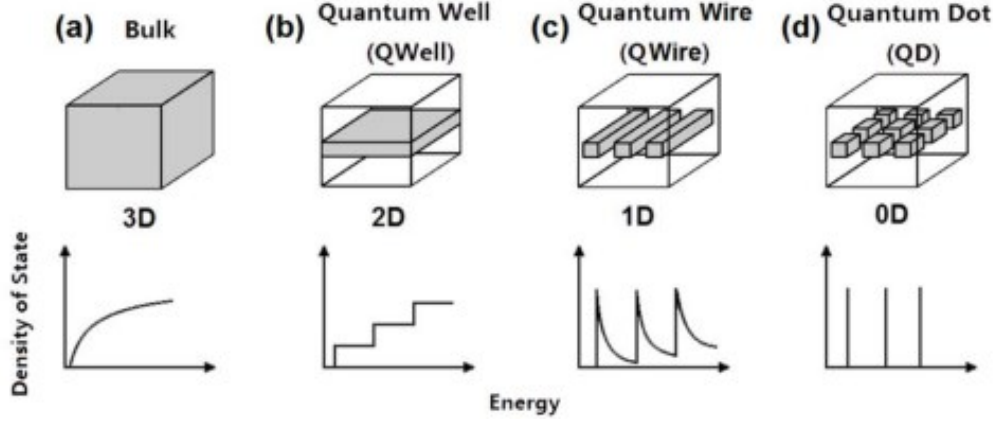


Figure 2.19. Evolution of the density of states for (a) bulk material, (b) QW, (c) quantum wire (same as quantum dash) and (d) quantum dots. [41]

QD gain medium can be used in general DFB lasers [39], multi-wavelength lasers [43], MLLs, or semiconductor optical amplifiers (SOAs). In this work, QD-MLL and QD-SOA are investigated in depth and verified in 5G fronthaul transmission system. This two specific QD based optical devices will be introduced in the following sections.

2.3.1 Quantum Dash Mode Locked Lasers

Quantum dot and quantum dash lasers are now well understood theoretically [38], [44], [45], [46], [47]. Figure 2.20 presents a schematic of an InAs/InP QD laser. Each dot or dash traps carriers in all three dimensions, creating discrete energy levels that are more stable than those in conventional quantum-well devices. As a result, QD lasers exhibit narrower linewidths and lower phase noise [43], [48], [49], [50]. Because fabricating true dots is difficult, quantum dash lasers

were developed as a practical compromise [43], [50], [51]. Their performance is slightly inferior to that of ideal quantum dot devices yet remains superior to traditional quantum-well sources [43], [50], [51]. Figure 2.21(a) illustrates an InAs/InP QD-MLL. A dash is elongated in one dimension, so its carrier confinement is weaker than that of a dot, explaining the modest performance penalty, but the relaxed fabrication tolerances make quantum dash devices attractive for production. InAs/InP QD-MLLs are typically realized by standard photolithography followed by a combination of dry- and wet-etching steps and contact metallization.

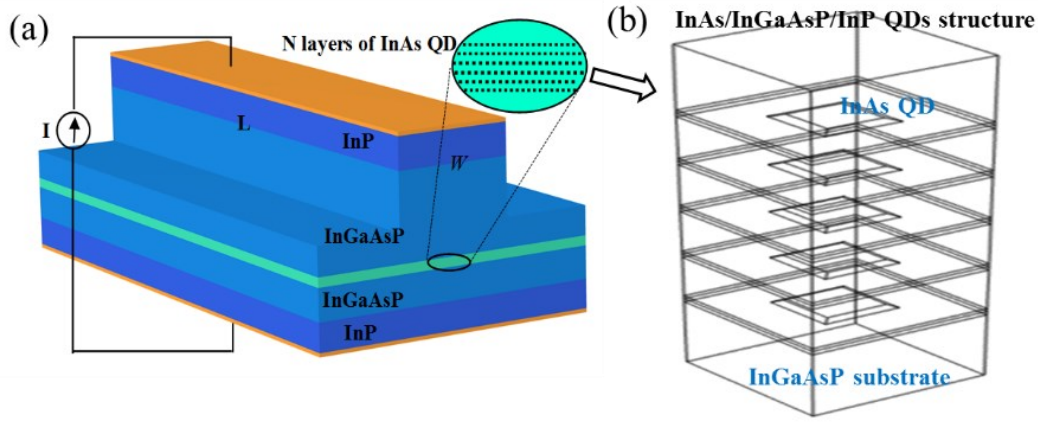


Figure 2.20. (a) Schematic of a QD Fabry-Perot laser with a cavity length L and ridge width W; and (b) Geometry of five-layer truncated pyramid InAs QD stacks. [48]

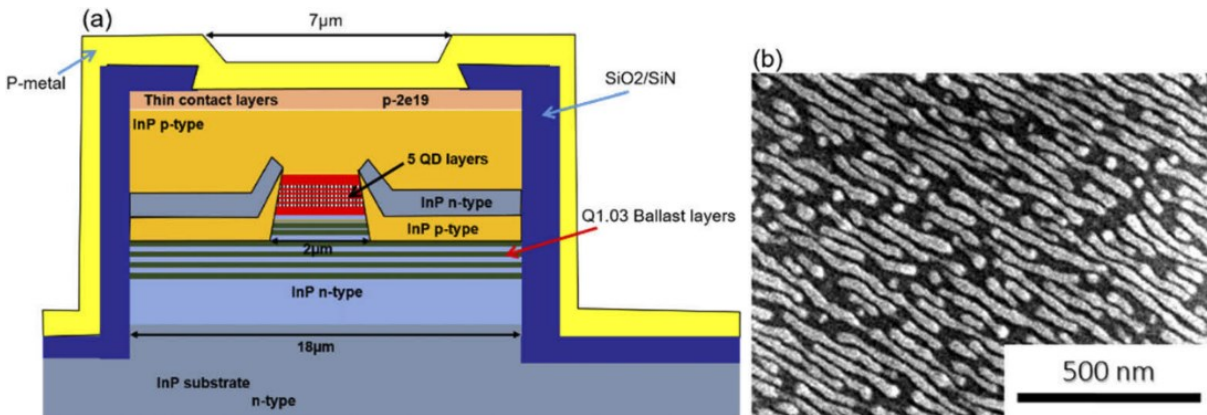


Figure 2.21. (a) Schematic of the cross-section of the laser. SEM images of (b) the top view of the quantum dash layer. [10]

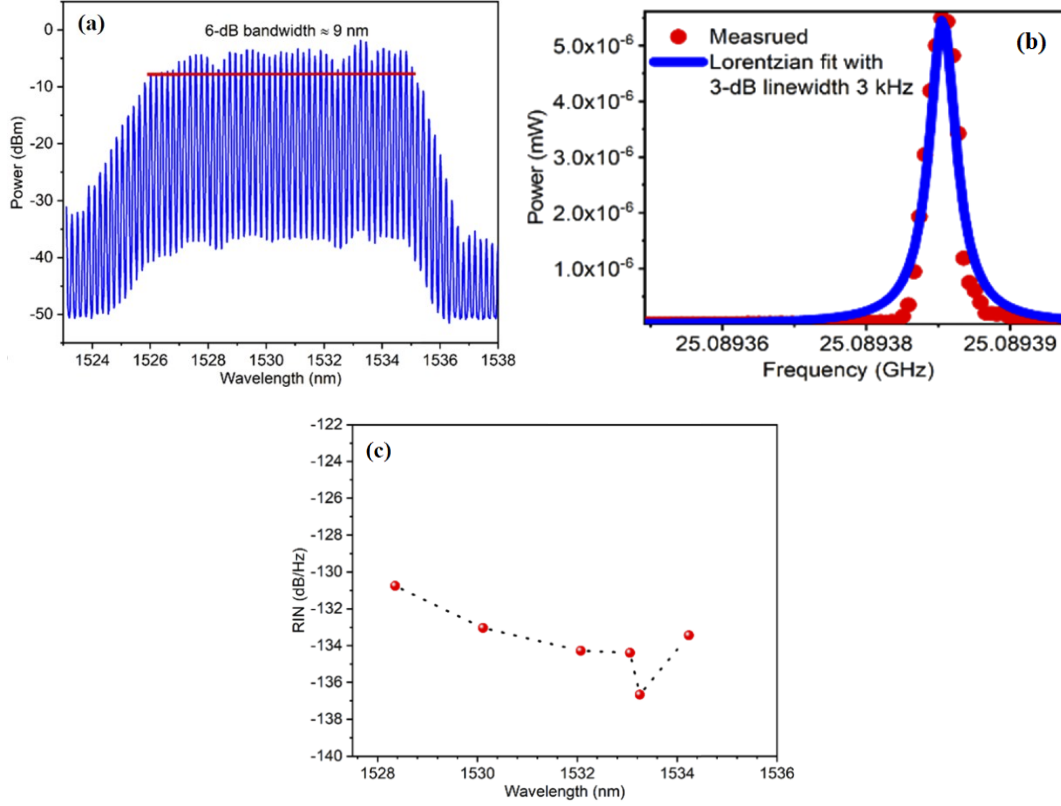


Figure 2.22. Measured (a) optical spectrum of the QD-MLL, (b) RF beat linewidth of QD-MLL, and (c) integrated RIN for individual selected channels over a frequency range of 10 MHz to 20 GHz. [38]

In this work, quantum dash MLL is used instead of quantum dot due to manufacture issues. The active gain region of QD-MLL is a 170 nm thick InGaAsP waveguide with 10 nm $\text{In}_{0.816}\text{Ga}_{0.184}\text{As}_{0.392}\text{P}_{0.608}$ (1.15Q) barrier layer which containing five layer of QD [52]. The 10 nm barrier layer is introduced to make sure there are no coupling between QD layers while thin enough to allow strain fields build up a correlated vertical stacking of dashes. Outside the active gain region, n- and p-type InP semiconductor material is used as cladding layers. To reduce cavity loss and coupling of spontaneous emission, a n-type cladding containing 1.03Q ballast layers is introduced, which force the optical mode generating in the n-type material. The average QD density is $3.5 \times 10^{10} \text{ cm}^{-2}$ in each QD layer. The top view of the quantum dash layer under scanning electron microscope (SEM) is shown on Figure 2.21(b). The whole core region is covered inside a 2- μm

wide waveguide mesa and pnp blocking layer. The whole laser core and waveguide cover is surrounded by a p-type metal as anode contact layer and n-type semiconductor material as cathode contact layer, separated by a silicon isolation layer.

The QD-MLL simultaneously generates tens of highly coherent optical carriers, known as comb lines [36], as shown in Figure 2.22(a) [38]. It also delivers excellent phase-noise and relative intensity noise (RIN) performance, as shown in Figure 2.22(b) and (c) [38]. After heterodyne detection, the resulting RF linewidth can be as narrow as 3 kHz, making the QD-MLL a highly promising source for optical mm-wave signal generation. The principles of heterodyne detection are explored in Section 2.2.

Apart from communications, QD-MLL has many other applications, like data center [46] and ADC [53], [54], shows a huge potential on QD-MLL. To further improve the performance of QD-MLL, self-injection method is employed, which can further reduce the linewidth of the beating signal down to sub-kilohertz [55], [56], [57].

2.3.2 Quantum Dash Semiconductor Optical Amplifier

Similar to QD-MLLs, QW technology was first applied to SOAs. Over the past few decades, numerous QW-SOAs have been reported for both the S-band and C-band. However, in a QW-SOA, photons within only a narrow wavelength range, determined by the energy separation of the QW, can efficiently interact with carriers. This phenomenon, known as homogeneous broadening, leads to strong phase fluctuations and inter-channel crosstalk [58], [59], [60], [61]. To mitigate these drawbacks, QD-SOAs have been extensively studied. In a QD gain medium, stimulated carriers are confined in all three spatial dimensions, with a typical radius of about 5 nm [62], [63]. A QD of a given size still exhibits homogeneous broadening; however, because QDs within the gain

medium vary in size, photons of different wavelengths can interact with QDs of corresponding dimensions. This phenomenon, known as inhomogeneous broadening [59], [64], [65] and sometimes described as “atom-like” optical gain [66], offers several advantages: it increases the gain bandwidth, reduces phase noise, mitigates pattern effects, and lowers crosstalk [59], [64], [65], [66]. As a result, QD-SOAs are particularly well-suited for 5G and beyond photonic-integrated-circuit applications, especially in multichannel transmission systems.

With these advantages, QD-SOAs have triggered many researchers to further explore its theory and applications. Theoretical studies on QD-SOAs have investigated carrier dynamics [58], gain/noise saturation [64], nonlinear effect [67], gain-clamping [68], and emission characteristics [69]. In addition, extensive research on the physics of QD gain media has been conducted over the past decades [70], [71], [72]. Building on these theoretical insights into QDs and QD-SOAs, many devices have been fabricated and experimentally characterized. For example, in [73], researchers reported an O-band QD-SOA with an ultra-wide gain bandwidth of 100 nm, achieving a chip gain of 20 dB. In [74], a small-signal chip gain of 25 dB was demonstrated at 1450 nm, with a minimum noise figure (NF) of 6.1 dB. In [75], a QD-SOA was demonstrated with a minimum polarization-dependent chip gain of 25 dB over a 110 nm wavelength range centered at 1520 nm. A more recent study [76] presented a QD-SOA with a polarization-independent fibre-to-fibre (FtF) gain of 22 dB centered at 1550 nm. The highest reported chip gain was achieved in [77], where a 35 dB gain was measured at a 400 mA bias current with a coupling loss of 15 dB per facet, and the calculated NF was 4.59 dB. Temperature stability has also been investigated; for instance, in [78], a QD-SOA measured at 82 °C exhibited a small-signal gain of 20 dB at 1599 nm.

QD-SOA has also been widely used in different application. It can be used as a traditional wave-guide amplifier [72], or reflective SOA [79], [80]. Similar to other SOAs, QD-SOA can also

be used as wavelength shifter [81]. Furthermore, QD-SOA is also reported to be used in digital-to-analog conversion [82], optical logical component [83], [84], and variable optical delay [85]. In communication system, QD-SOA is proposed to be integrated with MZM [86] and QD laser [79]

2.4 Advantages and Challenges of Current mmWoF System

As noted in Section 2.2.3, a QD-MLL based mmWoF system produces the mmWave signal through heterodyne detection. This architecture offers two principal advantages.

First, it is inherently simple. Most of the components shown in Figure 2.18 operate below 6 GHz, so there is no need for ultra-high-speed DACs or very-high-frequency modulators. This greatly reduces system complexity, cost, and power consumption. The only elements that must handle mmWave frequencies are the ORx, power amplifier, and antennas, components that are unavoidable in any case [36], [38], [51], [87].

Second, the QD-MLL provides tens of highly coherent optical carriers. When two of these carriers beat in the photonic receiver, as described in Equation (2-18), their phase noise largely cancels each other, yielding a clean mmWave tone [12], [87], [88]. By contrast, a scheme that uses multiple free-running QW lasers would require injection-locking or other phase-stabilization techniques to attain comparable coherence, adding significant complexity [89], [90].

Beyond these two primary advantages, the mmWoF fronthaul system is remarkably flexible. By choosing non-adjacent comb lines, heterodyne detection can up-convert a signal to much higher frequencies, potentially into the terahertz range [91], [92]. Furthermore, a QD-MLL occupies far less chip area than a bank of free-running lasers with phase-locking circuitry, giving it a significant edge for photonic integration [13], [37].

Despite its advantages, the mmWoF architecture faces a significant challenge: each optical carrier produced by the QD-MLL has low power. Although the laser's total output can reach about 23 mW, that power is divided among dozens of comb lines, leaving each with only ~ 0.3 mW [36]. To compensate, the system incorporates multiple stages of optical amplification [9].

Another key challenge is polarization. In an mmWoF fronthaul link the wavelength separation between the reference and the modulated carriers is much larger than in a conventional sub-6 GHz RoF system, so the two tones experience different polarization evolution as they propagate through the SMF. By the time they reach the photonic receiver their states of polarization can be misaligned, lowering the O/E conversion efficiency and introducing polarization-dependent distortions [37]. This issue is mitigated by inserting multiple polarization controllers along the link and replace SMF with polarization maintain fibre.

The future of QD gain medium is optical integrate circuit. However, as shown in Figure 2.9, there are multiple EDFAs in the mmWoF system, which contains 30-40 m of erbium doped fibre inside. To reduce the size of the system and further integrate the whole system in to a photonic silicon chip, SOAs should be used instead of fibre amplifiers. Thanks to the inherit in-homogeneous broadening in QD-SOA, it can be used as a promised solution in the further photonic silicon chips.

2.5 Research Methodology for mmWoF System

Firstly, the mmWoF system [37] is re-implemented in order to build familiarity with equipment, devices, and overall configuration. Efforts are then focused on improving the existing setup, for example, by adding components such as an optical delay line and additional polarization controllers. After the system has been optimized, preliminary simulations will be carried out to extend the architecture and provide an initial validation of the proposed schemes. Finally, the new

designs will be verified experimentally.

For QD-SOA, basic characteristics, including ripple, amplified spontaneous emission, gain, and NF, are measured. A test bed has been built for the measurement. After the performance of QD-SOAs is measured and analyzed, the best QD-SOA devices have been packaged.

Finally, QD-SOA is deployed to the QD-MLL based mmWoF system, replacing the EDFAs in the system. Different structures are verified in an experiment to show the advantage of the QD gain medium.

System performance in this work is evaluated using error vector magnitude (EVM). In mmWoF systems, phase noise and other distortions have a direct impact on non-constant envelope signals generated by linear modulation schemes, where both amplitude and phase are modulated simultaneously. These impairments introduce amplitude and phase distortions that alter the constellation diagram, potentially shifting points into adjacent decision regions and causing bit errors. EVM provides a quantitative measure of such degradations by representing the vector distance between the ideal and measured signal points. In other words, EVM indicates the extent to which received constellation points deviate from their theoretical locations. An example of EVM of a 16-QAM signal is illustrated in Figure 2.23. The EVM value is calculated as:

$$EVM = \sqrt{\frac{\frac{1}{N} \sum_{i=1}^N |S_{ideal,i} - S_{meas,i}|^2}{\frac{1}{N} \sum_{i=1}^N |S_{ideal,i}|^2}} \quad (2-21)$$

where $S_{ideal,i}$ and $S_{meas,i}$ represent the ideal power and measured power of the i^{th} point of the recorded signal. N is the total number of points in the recorded signal. Communication systems must maintain adequate EVM performance to ensure accurate signal demodulation. If the EVM exceeds acceptable limits, constellation points may drift into neighboring decision regions,

resulting in symbol errors. In practical implementations, EVM is typically measured using a vector signal analyzer, which provides a direct assessment of modulation quality. However, in this paper, the EVM is calculated from a recorded signal using an oscilloscope. In the 3GPP standard, it is stipulated that the EVM should be less than 17.5% with QPSK modulation, and less than 12.5% with 16-QAM modulation [1].

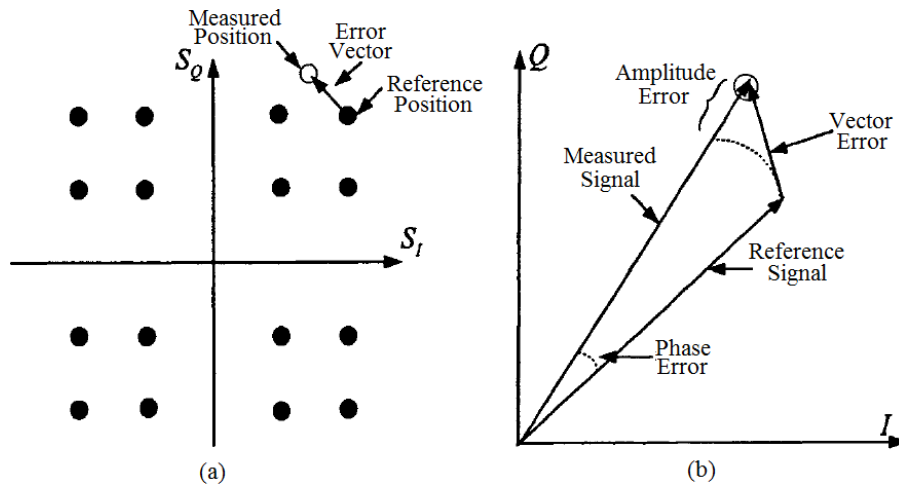


Figure 2.23. (a) An example of the constellation of signal and (b) the principle of EVM.

Chapter 3 Preliminary Improved QD-MLL Based mmWoF System

As mentioned in Section 2.4, current QD-MLL based mmWoF has several challenges. To overcome these challenges, two mmWoF structures are proposed. The details of these two structures are discussed in Section 3.1. Based on the improved QD-MLL structure, a bi-directional mmWoF fronthaul transmission system is also proposed and verified in an experiment to prove the performance of the improved structure.

3.1 Improved QD-MLL Based mmWoF System

In general, there are two methodologies to improve the performance of a transmission system. The first approach is to add more devices to the system to overcome each challenge. The structure using this methodology is called I/Q MZM based mmWoF fronthaul transmission system, which is introduced in Section 3.1.1 in detail. The second approach is to simplify the system, thereby reducing the significance of the challenges. The structure using this methodology is called SSB-MZM based mmWoF fronthaul transmission system, which is introduced in Section 3.1.2 in detail.

3.1.1 I/Q MZM Based mmWoF Fronthaul Transmission System

To enhance the mmWoF system, additional polarization controllers, a wave shaper, and an optical delay line were incorporated, as shown in Figure 3.1. Compared with the baseline in Figure 2.18, the OC and two OBPFs have been replaced by a single wave shaper, reducing overall insertion loss by about 3 dB. A polarization controller has been placed after the EDFA in the MZM branch to align the amplifier output with the modulator's slow axis, improving modulation efficiency.

Another controller in the reference branch matches the state of polarization between the modulated and reference carriers. An optical delay line in the reference branch equalizes the optical paths of the two branches. Without this compensation, excessive path-length mismatch would degrade carrier coherence, leading to higher phase noise and poorer system performance.

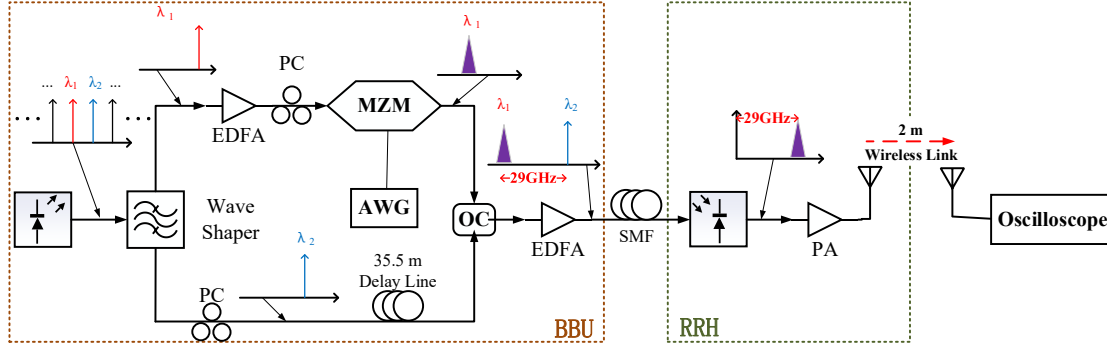


Figure 3.1. Block diagram of I/Q MZM based mmWoF system. PC: polarization controller.

The optimized system, shown in Figure 3.1, was verified experimentally. Optical carriers are generated by a QD-MLL, and two adjacent lines are selected and split into reference and modulator branches by a II-VI 16000A wave shaper. In the modulator branch, an EDFA first amplifies the carrier, its polarization is rotated to the slow axis with a polarization controller, and it is then modulated by an SHF-46215B I/Q modulator driven by baseband signals from a Keysight M8195A AWG. The reference branch contains a variable optical delay line to equalize the path lengths. An OC recombines the two branches, and the composite signal travels through 20 km of SMF, is boosted by a second EDFA, filtered by an OBPF, and detected by a New Focus 1014 photoreceiver. The resulting mmWave signal is amplified, transmitted over a 2 m wireless link, and finally captured and analyzed with a Tektronix DPO73304SX oscilloscope.

Figure 3.2 summarizes the results. The optimized mmWoF system achieves EVM of 5.6% for a 16-QAM 2 Gbaud signal and 6.0% for a 64-QAM 2 Gbaud signal. Compared with earlier work, the EVM for the 16-QAM 4 Gbaud signal has improved from 8.4 % [37] to 5.6 %. These

results show that the optimized system delivers markedly better performance than previous implementations and provides a solid foundation for further expansion.

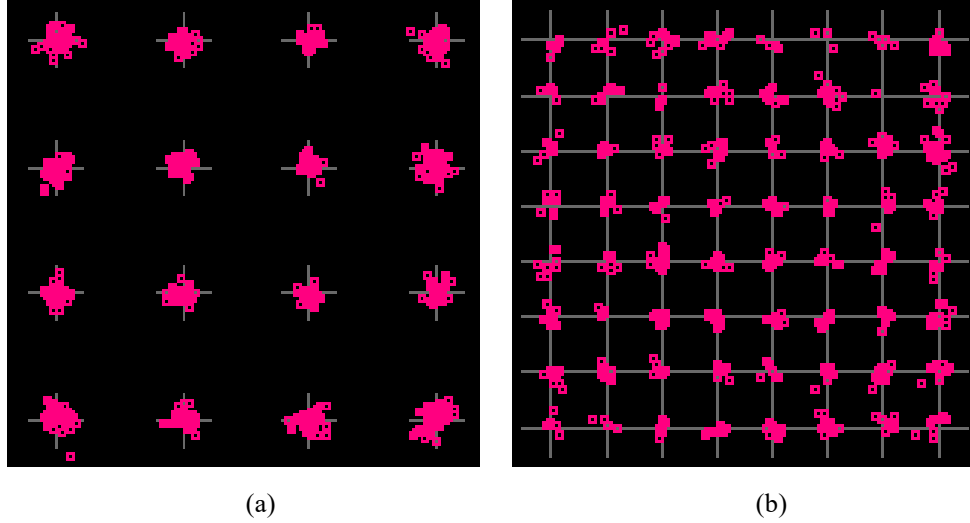


Figure 3.2. the constellation of received signal of (a)16-QAM 4 GBands and (b) 64-QAM 2 GBauds

3.1.2 SSB-MZM based mmWoF Fronthaul Transmission System

Another methodology to improve the performance of the QD-MLL based mmWoF fronthaul transmission system is replacing the I/Q MZM with an SSB-MZM, as shown in Figure 3.3. In this mmWoF structure, two optical carriers, 1535.09 nm and 1535.28 nm, are modulated as SSB by MZM simultaneously. By using this structure, the reference branch of Figure 2.9 is totally removed, and two OCs are also removed. Besides, the attenuation of SSB-MZM is about 4 dB lower than that of I/Q MZM. The total attenuation of the optical parts can be reduced by 9 dB. The overall system is more robust, and it contains fewer devices.

However, in this structure, many unneeded optical carriers and signals remain in the signal, which significantly reduces the power efficiency. Since the maximum power of the ORx is limited, the converted RF power is lower than that of the I/Q MZM-based mmWoF structure, which reduces

the performance. Besides, as shown in Figure 3.3, the RF signal contains a converted optical carrier at 28.951 GHz. An RF BPF is necessary in a commercial environment due to device limitations; however, it has not been added to the system at this time.

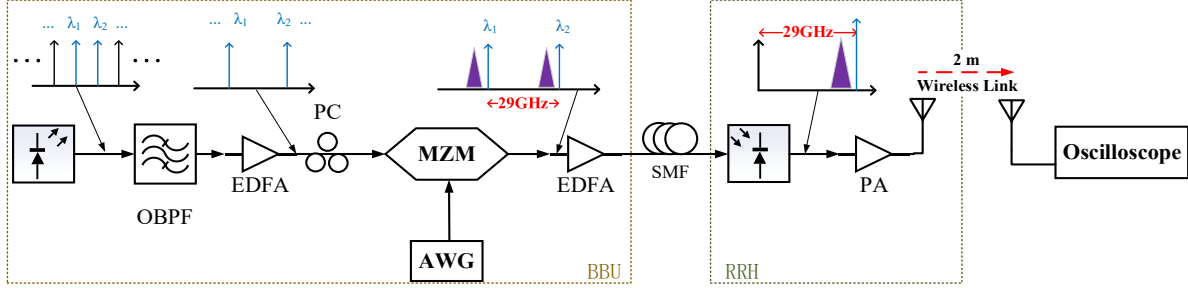


Figure 3.3. Block diagram of SSB-MZM based mmWoF system.

This simplified structure is also verified in experimentation. Similar to I/Q based mmWoF system, the optical carriers are also generated by a QD-MLL, and two adjacent lines are selected by an OBPF. Two carriers are first amplified by an EDFA, their polarization is rotated to the slow axis with a polarization controller, and it is then modulated by Sumitomo T-DKH1.5-40PD SSB-MZM driven by a Thorlabs MX40A driver with baseband signals from a Keysight M8195A AWG. The composite signal travels through 20 km of SMF, is boosted by a second EDFA, filtered by an OBPF, and detected by a New Focus 1014 photoreceiver. The resulting mmWave signal is amplified, transmitted over a 2 m wireless link, and finally captured and analyzed with a Tektronix DPO73304SX oscilloscope.

Figure 3.4 summarizes the results. The optimized mmWoF system achieves EVM of 7.5 % for a 16-QAM 4 Gbaud signal and 7.9 % for a 64-QAM 2 Gbaud signal. Compared with earlier work, the EVM for the 16-QAM 4 Gbaud signal has improved from 8.4 % [37] to 7.5 %. The SSB-MZM is also much simpler than the original structure [37]. The performance of SSB-MZM based mmWoF system is worse than that of the I/Q MZM based mmWoF system, mainly caused by the lower optical power efficiency. Besides, the performance of SSB-MZM (Sumitomo

T-DKH1.5-40PD) is worse than that of the I/Q MZM (SHF-46215B), which also contributes to the difference.

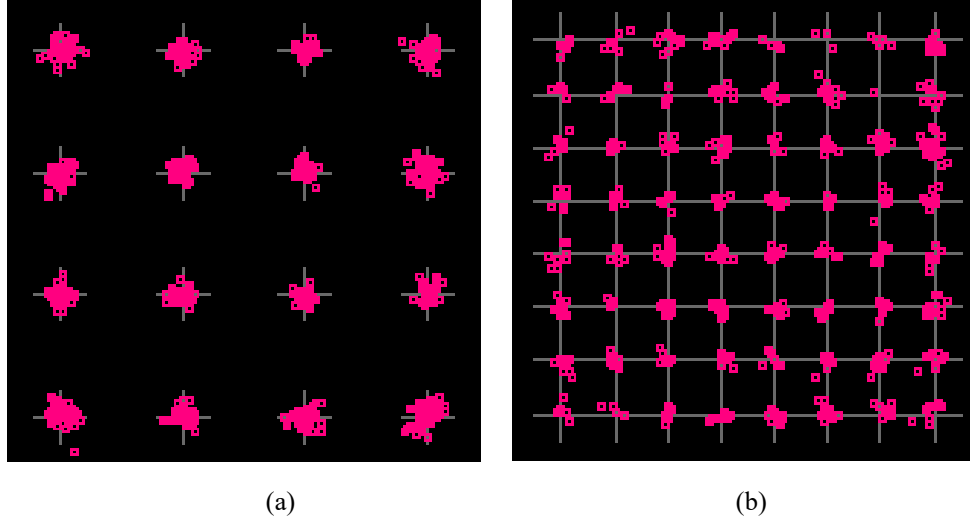


Figure 3.4. the constellation of received signal of (a)16-QAM 4 GBands and (b) 64-QAM 2 GBauds

3.2 Bi-directional mmWoF Fronthaul System

To further investigate the flexibility of QD-MLL based mmWoF fronthaul transmission system, a bi-directional mmWoF fronthaul transmission system is proposed and verified in experimentation. In comparison to conventional bands (sub-6 GHz), mmWave signals experience much higher propagation loss. To address this limitation, 3GPP Release 17 [3] introduced the supplementary uplink (SUL) technique, in which the downlink of 5G NR operates in the mmWave band while the uplink remains in sub-6 GHz. Leveraging the large number of channels provided by the QD-MLL, up to 46 in this work, a third optical carrier can be allocated specifically for SUL. In this way, both uplink and downlink use a single QD-MLL as laser source, further simplifying the architecture of the proposed bidirectional fronthaul transmission system. Figure 3.5 illustrates the proposed bi-directional 5G fibre-wireless fronthaul architecture. The red and blue paths denote the downlink and uplink, respectively. A single C-band QD-MLL operating at a 24.951 GHz

repetition rate serves as the only optical source. Two wavelengths, 1535.09 nm and 1535.28 nm, are SSB modulated with a 16-QAM 2 Gbaud downlink signal centered at 4 GHz. Accordingly, the frequency offset between the lower carrier and the upper sideband of the higher carrier is 28.951 GHz.

After the signal is modulated, an SMF spans of either 0 km (back-to-back) or 10 km is added between BBU and RRH. At the remote unit, the downlink light is separated from the uplink carrier by an OC and BPF. After heterodyne detection, the downlink signal is converted to a mmWave RF tone and propagated across a 2-m wireless link. An oscilloscope is used to analyze the received RF waveform.

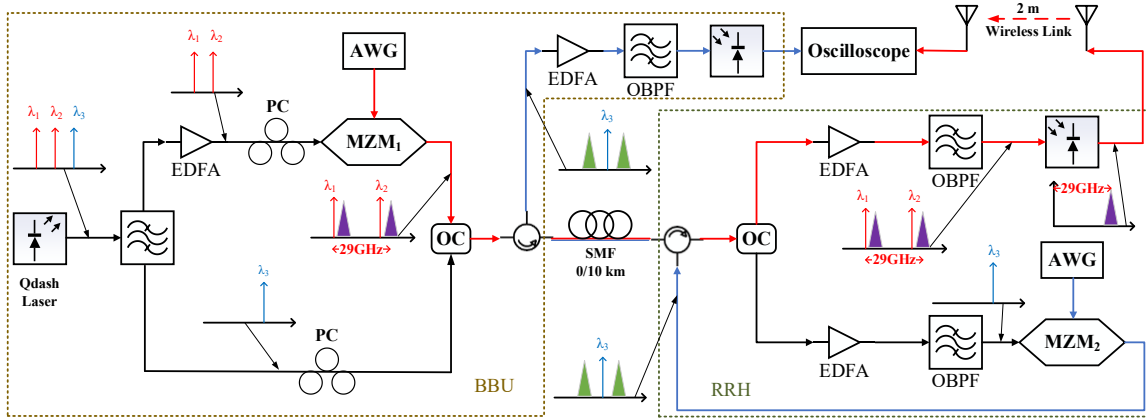


Figure 3.5. Block diagram of bi-directional mmWoF fronthaul system.

For the uplink, QD-MLL also generates a 1535.47 nm carrier, which is then launched into the SMF. At the remote unit, it is separated from the downlink signal and modulated in double-sideband format with a 16-QAM 2 Gbauds uplink signal. The modulated light then traverses the same fibre back to the central unit, where a circulator directs it to a second photodetector. The recovered electrical waveform is captured and analyzed on an oscilloscope.

Figure 3.6 presents the received constellations for both back-to-back (BtB) and 10 km transmissions. In the BtB case, the EVMs are 8.7% for the downlink and 6.7% for the uplink. After propagating through 10 km of SMF, the EVMs increase slightly to 7.9% for the downlink and 9.5 % for the uplink.

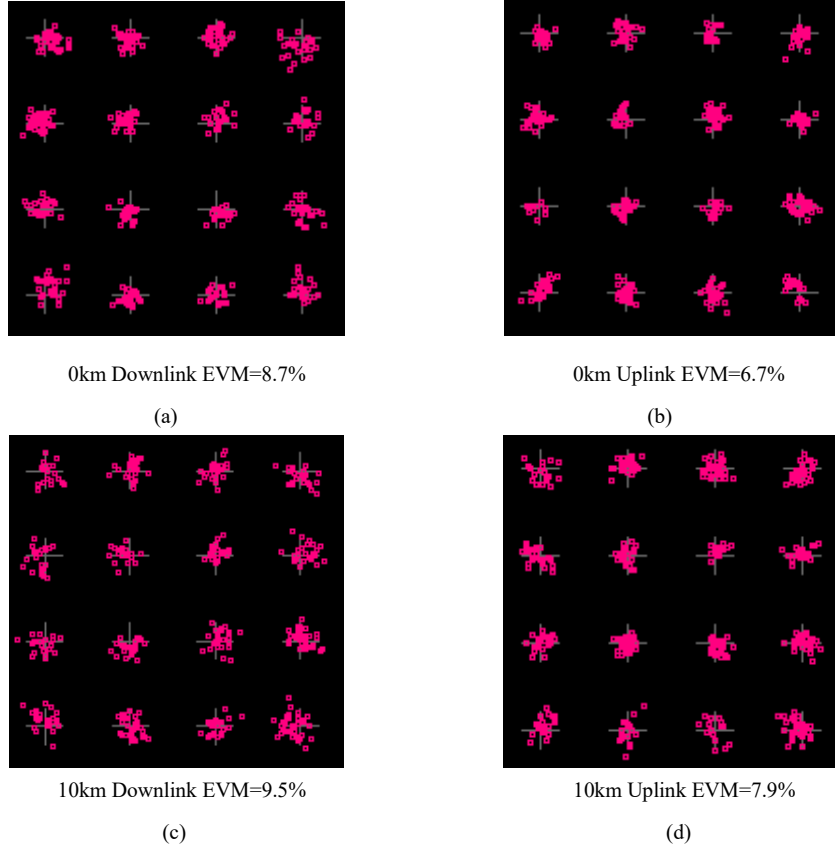


Figure 3.6. The constellation of (a) downlink and (b) uplink with BtB transmission, (c) downlink and (d) uplink with 10 km SMF transmission.

Chapter 4 Frequency Multipled mmWoF Fronthaul Transmission Links

Previous mmWoF implementations have used only two or three adjacent optical carriers from the QD-MLL, even though the laser can provide 47 coherent lines. To exploit this untapped flexibility, two expanded mmWoF architectures and four multiplexing techniques are proposed. Each scheme employs three or four comb lines, thereby boosting the system's overall capacity.

4.1 Experimentation Setup

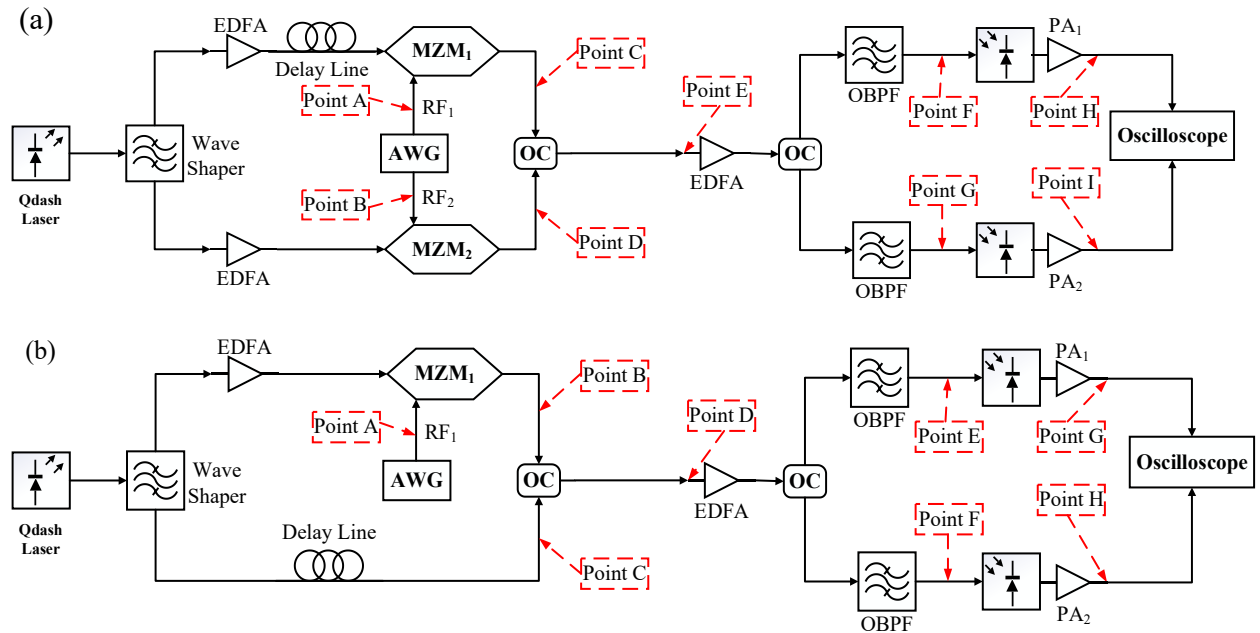


Figure 4.1. Block diagram of proposed multiplexing *Technique 1, 2, and 3* is shown on (a), *Technique 4* is shown on (b).

Figure 4.1 shows the experimental setup used to evaluate frequency multiplexing techniques. A single C-band QD-MLL delivers 28 mW spread across 47 highly coherent comb lines with 28 GHz spacing. Up to four lines, λ_1 (1547.032 nm), λ_2 (1547.256 nm), λ_3 (1547.480 nm), and λ_4 (1547.708 nm), are selected for the trials. Optical routing and filtering are performed by a II-VI

16000A wave shaper, while Amonics AEDFA-series EDFAs provide amplification. Baseband waveforms are generated by a Keysight M8195A AWG operating at 64 GS/s. Modulation is applied with an SHF SHF-46215B as MZM₁ and a Sumitomo T-DKH1.5-40PD SSB as MZM₂ driven by a Thorlabs MX40A driver; a Marki QH0R518 quadrature hybrid supplies the required RF phase shifts. Optical detection is performed with New Focus 1014 photodiodes. RF amplification is provided by an SBP-3335034520-2F2F-S1 power amplifier (PA₁, 33–50 GHz) and an RLNA20G50G01BEV amplifier (PA₂, 20–50 GHz). Captured signals are analyzed with a Tektronix DPO73304SX oscilloscope.

The detailed structures of all four techniques are elaborated as follows:

4.1.1 Setup of *Technique 1*

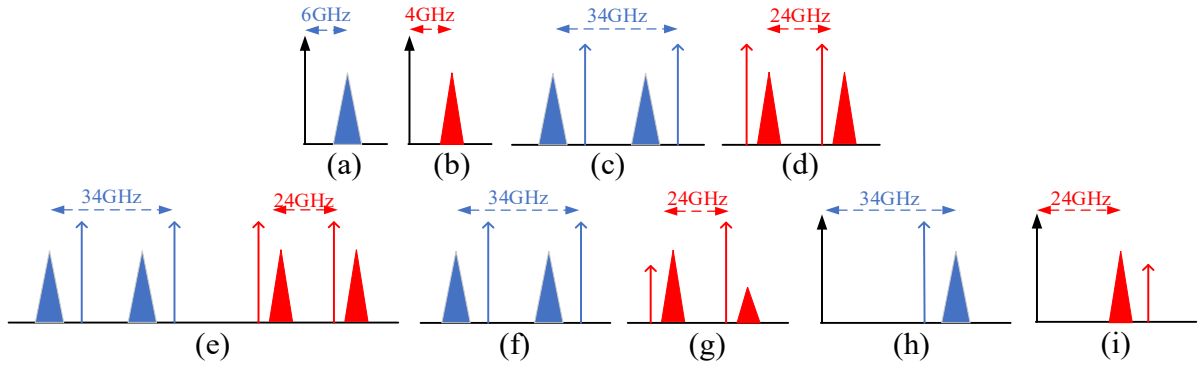


Figure 4.2. (a), (b), (c), (d), (e), (f), (g), (h) and (i) are the spectrum diagram of *Technique 1* at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.

Technique 1 is the most straightforward multiplexing method. For channel 1, comb lines λ_1 and λ_2 are selected and SSB modulated with RF signal 1 (RF₁) in MZM₁, as shown in Figure 4.2(c). RF₁ is a QAM waveform centered at 6 GHz, as shown in Figure 4.2(a). For channel 2, the adjacent comb lines λ_3 and λ_4 are chosen and single-sideband-modulated with a different RF signal 2 (RF₂) in MZM₂, as shown in Figure 4.2(d). RF₂ is another QAM waveform centered at 4 GHz, as shown

in Figure 4.2(b).

At the remote end, the combined optical signal is first split by an OC and then passed through two separate optical filters, as shown in Figure 4.2(f) and (g). A comparison of these traces shows that the filters also remove some unwanted carriers and duplicate tones. The two filtered signals are subsequently heterodyne-detected, as shown in Figure 4.2(h) and (i). Because the selected comb lines are spaced by 28 GHz, the ORx up-converts the baseband signals to 34 GHz and 24 GHz, respectively. Power-amplifier bandwidth limits further suppress out-of-band components, as evident in Figure 4.2(h) and (i). Finally, the two RF signals are analyzed independently on the oscilloscope.

4.1.2 Setup of *Technique 2*

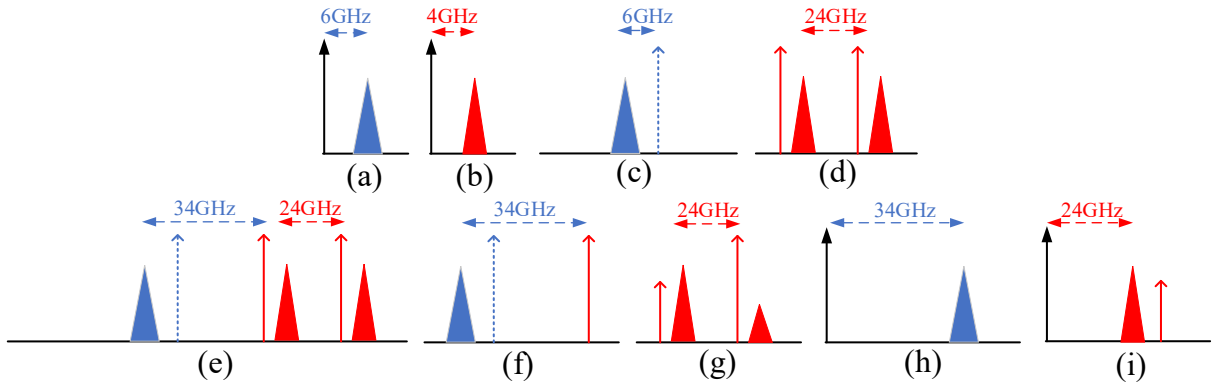


Figure 4.3. (a), (b), (c), (d), (e), (f), (g), (h), and (i) are the spectrum diagram of *Technique 2* at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.

A second, more wavelength-efficient multiplexing scheme, *Technique 2*, was also proposed and experimentally verified. It employs only two optical carriers, λ_2 and λ_3 . Each carrier is SSB modulated by RF₁ and RF₂, respectively, as shown in Figure 4.2(c) and (d). RF₁ and RF₂ are identical to those used in the previous method, as shown in Figure 4.2(a) and (b). The two modulated tones are then combined as shown in Figure 4.2(e) and later separated again by two

optical filters, as depicted in Figure 4.2(f) and (g).

Similar to the previous techniques, the optical filters partially suppress unwanted carriers and duplicate sidebands, though some residual cross-talk remains, a notable drawback of the scheme. After heterodyne detection, two mmWave signals are produced, as shown in Figure 4.3(h) and (i). These RF waveforms are then captured and analyzed on an oscilloscope.

4.1.3 Setup of *Technique 3*

Technique 3 aims to further improve spectral efficiency by reusing both carriers. In this approach, only two carriers, λ_2 and λ_3 , are employed. Each carrier is modulated using SSB with RF_1 and RF_2 , respectively, as illustrated in Figure 4.4(b) and (c). The RF signals (RF_1 and RF_2) are the same as those used in *Techniques 1* and 2, shown in Figure 4.4(a) and (b). The combined optical signal is then transmitted through an SMF, as shown in Figure 4.4(e), and subsequently demultiplexed using two optical filters, shown in Figure 4.4(f) and (g).

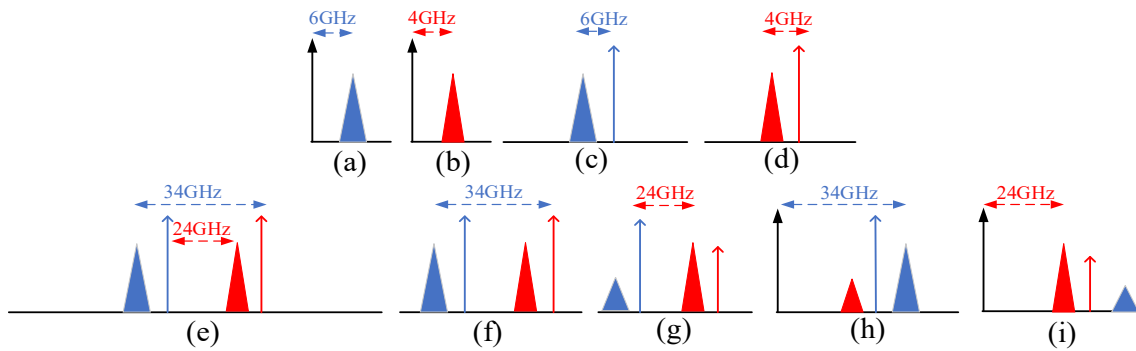


Figure 4.4. (a), (b), (c), (d), (e), (f), (g), (h), and (i) are the spectrum diagram of *Technique 3* at Point A, B, C, D, E, F, G, H, and I of Figure 4.1(a), respectively.

Similar to the previous techniques, the optical filters can partially remove unnecessary carriers and signals, although some cross-talk may persist. This cross-talk represents a significant drawback of this technique. Following heterodyne detection, two mmWave signals are generated,

as illustrated in Figure 4.4(h) and (i). Finally, the two signals are analyzed using an oscilloscope. However, due to some of the unnecessary frequency components being too close to the passband of the PAs, cross-talk may persist.

4.1.4 Setup of *Technique 4*

Technique 4 differs from the other approaches because it requires only a single modulator. However, it necessitates the use of an optical wave shaper or a specially designed filter to isolate two non-adjacent comb lines. As illustrated in Figure 4.5(c), the two solid blue lines represent the selected non-adjacent comb lines, while the dashed line indicates the intermediate comb lines that are suppressed. This type of comb line selection cannot be accomplished with a standard optical filter; instead, it requires a customized fibre Bragg grating or a wave shaper.

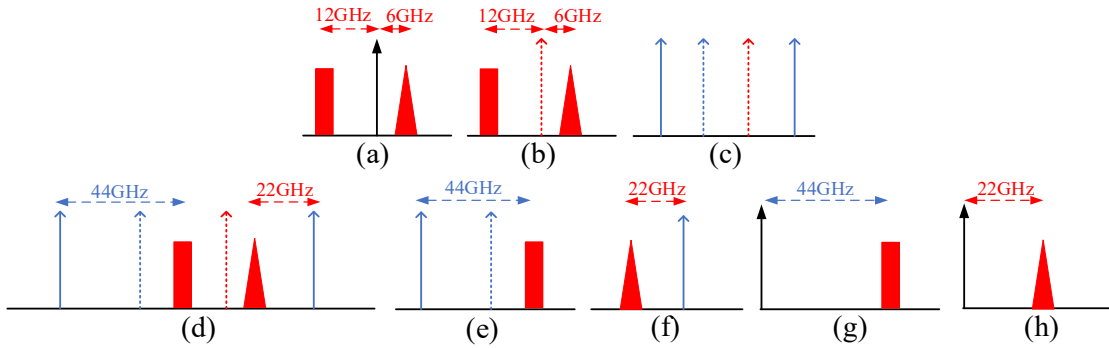


Figure 4.5. (a), (b), (c), (d), (e), (f), (g), and (h) are the spectrum diagram of *Technique 4* at Point A, B, C, D, E, F, G, and H of Figure 4.1(b), respectively.

Additionally, in *Technique 4*, MZM_1 must be configured as an I/Q modulator. The RF_1 signal consists of two QAM signals at 6 GHz and 12 GHz, as shown in Figure 4.5(a). These two RF signals are combined into an I/Q format and then modulated by MZM_1 , as illustrated in Figure 4.5(b). The resulting modulated signal is subsequently combined with the optical carrier and transmitted through an SMF.

At the receiver side, an OC and an optical filter are used to separate the two demultiplexed optical signals, as illustrated in Figure 4.5(e) and (f). Since the two signals are spaced by 18 GHz, cross-talk is effectively eliminated. After heterodyne detection, the corresponding electrical spectra are obtained, as shown in Figure 4.5(g) and (h). Finally, the recovered signals are analyzed using an oscilloscope.

4.2 mmWoF Experimental Results and Discussion

It should be noted that in the experimental setup, there is often a trade-off between the performances of the two channels. Optimizing the system for one channel can lead to degraded performance in the other. Consequently, the optical power allocated to each channel varies across different techniques, and the corresponding results are discussed in detail in the following sections.

4.2.1 Result of *Technique 1*

First, we consider *Technique 1*. Among the four techniques, this approach features the most robust structure. It essentially combines two independent heterodyne-detected mmWave channels. Since the two channels are separated by 28 GHz, they can be effectively isolated using optical filters, ensuring the absence of cross-talk. Furthermore, in *Technique 1*, both signals are modulated as SSB without carrier suppression, eliminating the need for an I/Q modulator. Although an I/Q modulator is employed as MZM₁ due to component availability, it can be readily replaced with a standard SSB MZM, similar to MZM₂.

Figure 4.6 presents the optical spectra corresponding to Points E, F, and G in Figure 4.1(a). Despite its straightforward and robust structure, *Technique 1* exhibits relatively poor overall performance. As shown in Figure 4.6(b) and (c), multiple spurious frequency components remain

at the ORx. Because the receiver limits the optical power, the power spectral density of the mmWave signal is relatively low. In the experiment, the received optical power of Channel 1 (34 GHz) was measured at 1.07 mW, while Channel 2 (24 GHz) achieved 1.21 mW. However, a significant portion of the optical power is carried by duplicated signals and unnecessary carriers, which degrade the quality of the desired mmWave signal. Moreover, since the output optical power of the EDFA is higher in *Technique 1* than in the other techniques, it suffers from the strongest nonlinear distortions.

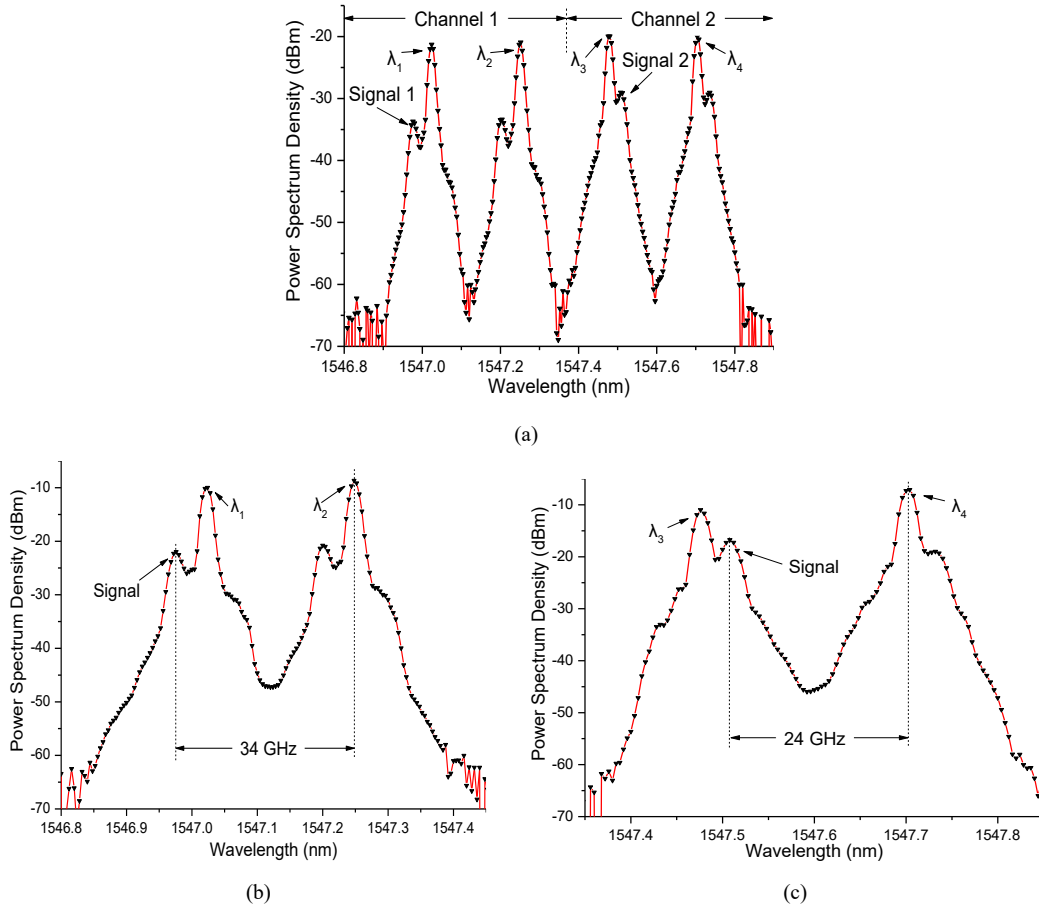


Figure 4.6. The optical spectrum in *Technique 1* at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1(a).

In a BtB optical setup, the EVM of Channel 1 and Channel 2 was measured at 7.4% and 8.2%, respectively. The corresponding eye diagrams and constellation plots are shown in Figure

4.7. The performance of Channel 2 is inferior to that of Channel 1, primarily due to the relatively poorer performance of MZM_2 compared with MZM_1 .

In brief, *Technique 1* is robust and straightforward, with no crosstalk between the two channels. However, it exhibits the lowest spectrum efficiency since all four carriers are utilized. Besides, the redundant optical signals and carriers significantly reduce the power of the desired signal after heterodyne detection and lead to higher nonlinearity, resulting in the poorest performance among all four techniques.

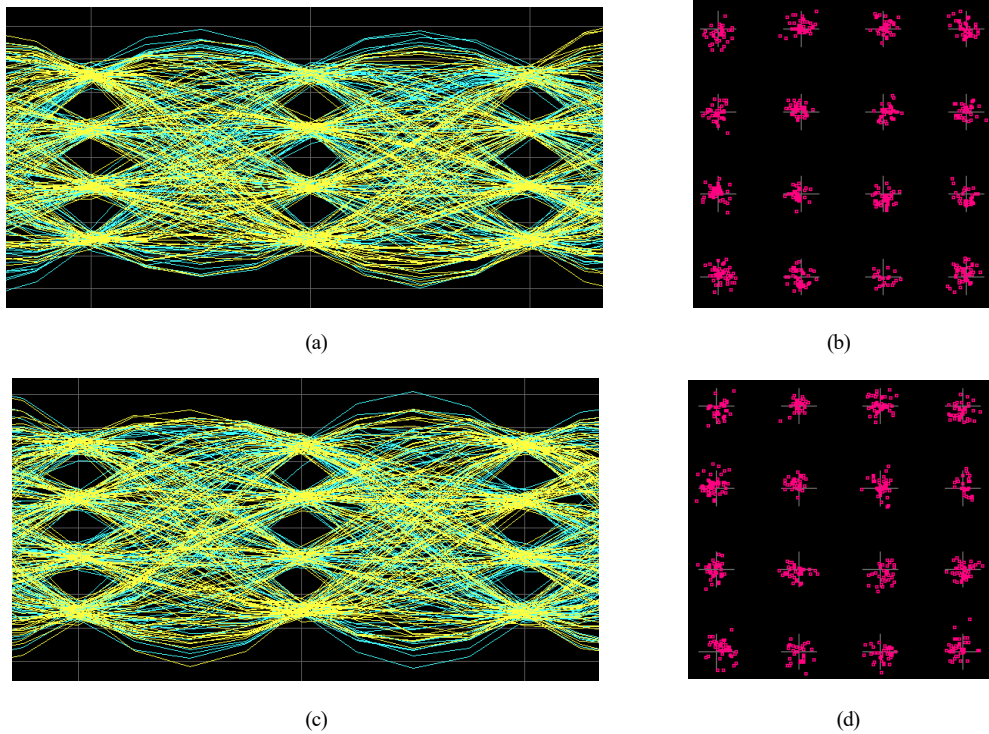


Figure 4.7. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

4.2.2 Result of *Technique 2*

Technique 2 employs three comb lines, with one comb line (λ_3) reused in both channels during heterodyne detection. Compared with *Technique 1*, this approach improves spectral

efficiency, as shown in Figure 4.3(e) and Figure 4.8(a), where three comb lines are utilized. In this configuration, one carrier (λ_2) is carrier-suppressed SSB (CS-SSB) modulated by RF₁ in MZM₁, while the other two carriers (λ_3 and λ_4) are simultaneously SSB modulated by RF₂ in MZM₂. However, CS-SSB modulation cannot completely suppress the carrier of Channel 1 (λ_2), as observed in Figure 4.8(a). In addition, the optical filter cannot entirely remove redundant carriers and signals. For example, as shown in Figure 4.8(b), the RF₂ component modulated onto λ_3 persists, while in Channel 2, the redundant RF₂ component modulated onto λ_4 also remains. These residual components interfere during heterodyne detection, introducing minor crosstalk between the two channels. Nevertheless, the level of crosstalk is sufficiently small to be considered negligible.

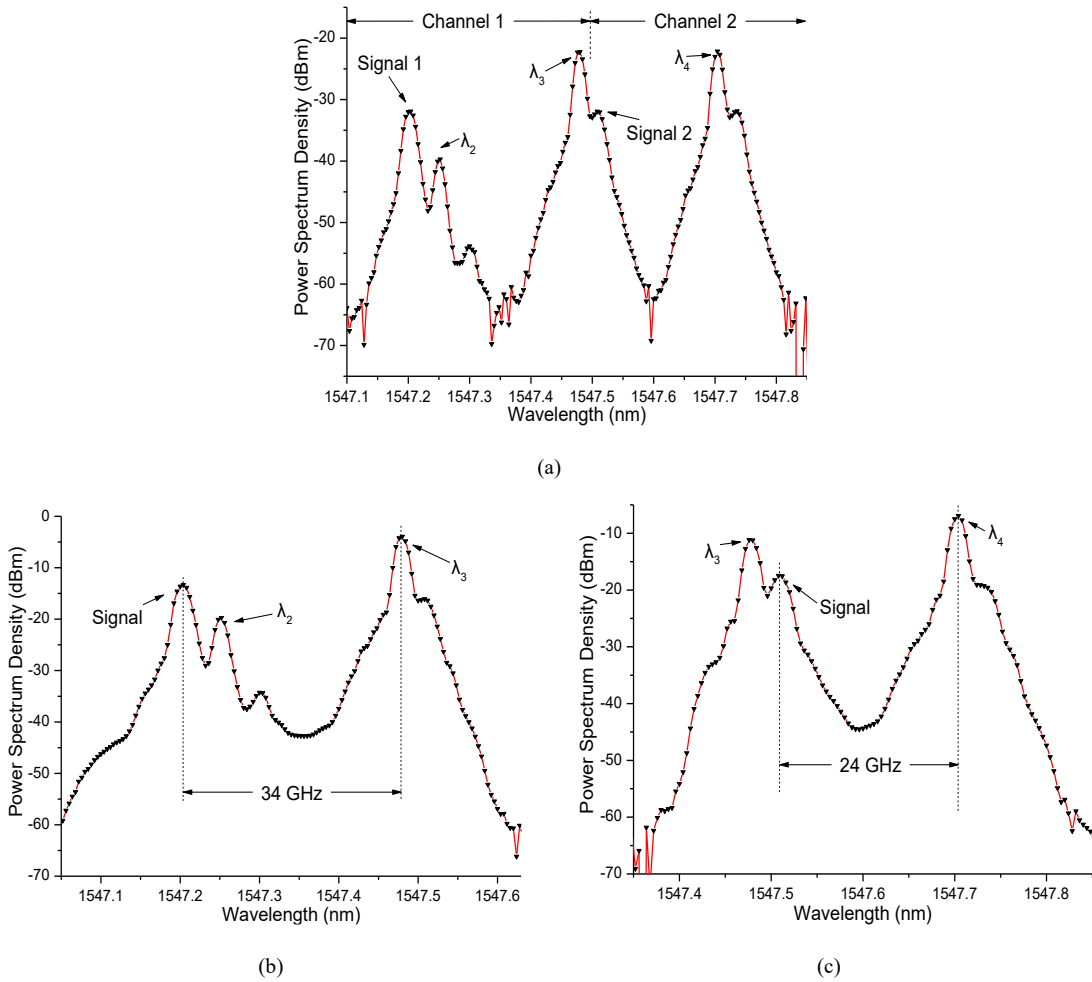


Figure 4.8. The optical spectrum in *Technique 2* at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1 (a).

To ensure a fair comparison, RF_1 and RF_2 used in *Technique 2* are identical to those in *Technique 1*. In a BtB optical setup, the received optical powers of Channel 1 and Channel 2 were measured at 0.69 mW and 0.81 mW, respectively. The eye diagrams of the two received mmWave signals are shown in Figure 4.9(a) and (c), while their corresponding EVM values are presented in Figure 4.9(b) and (d). The measured EVMs are 6.4% for Channel 1 and 7.9% for Channel 2. However, the performance of Channel 2 remains inferior to that of Channel 1. Despite component differences, Channel 2 still relies on two comb lines (λ_3 and λ_4) carrying two modulated signals, which reduces spectral efficiency and lowers the power spectral density of the desired signal, further degrading its performance.

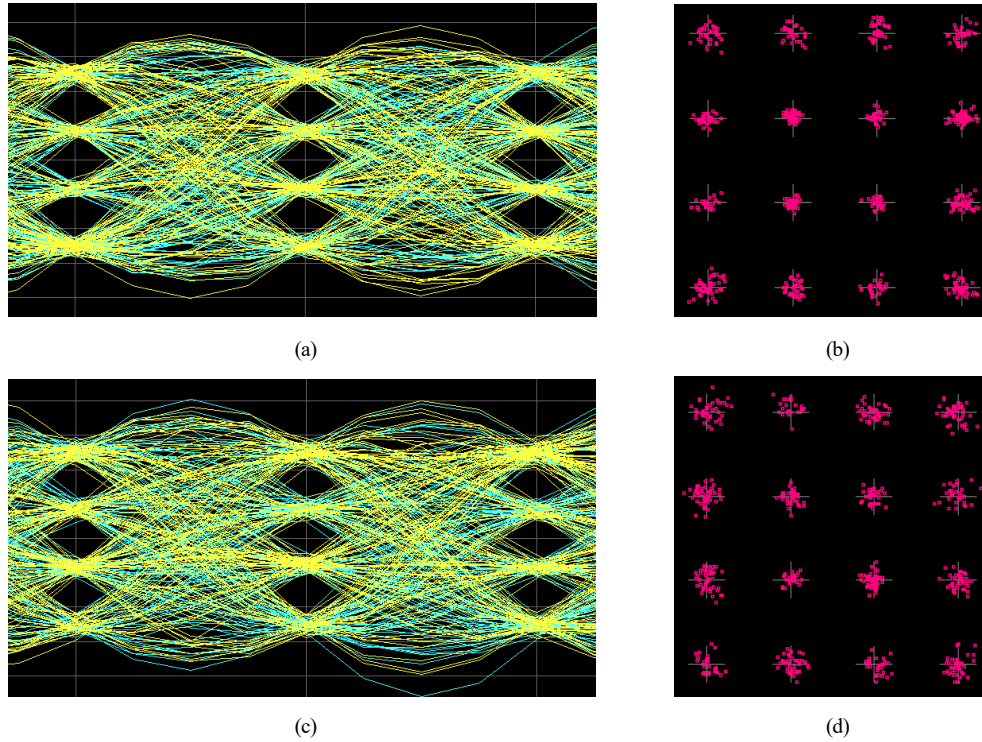


Figure 4.9. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

In summary, *Technique 2* achieves improved spectral efficiency by reusing one comb line, thereby outperforming *Technique 1*. However, this approach requires an I/Q modulator, increasing

system complexity. Moreover, the reuse of a comb line reduces robustness. Nevertheless, *Technique 2* demonstrates a favorable trade-off between efficiency and performance compared with *Technique 1*.

4.2.3 Result of *Technique 3*

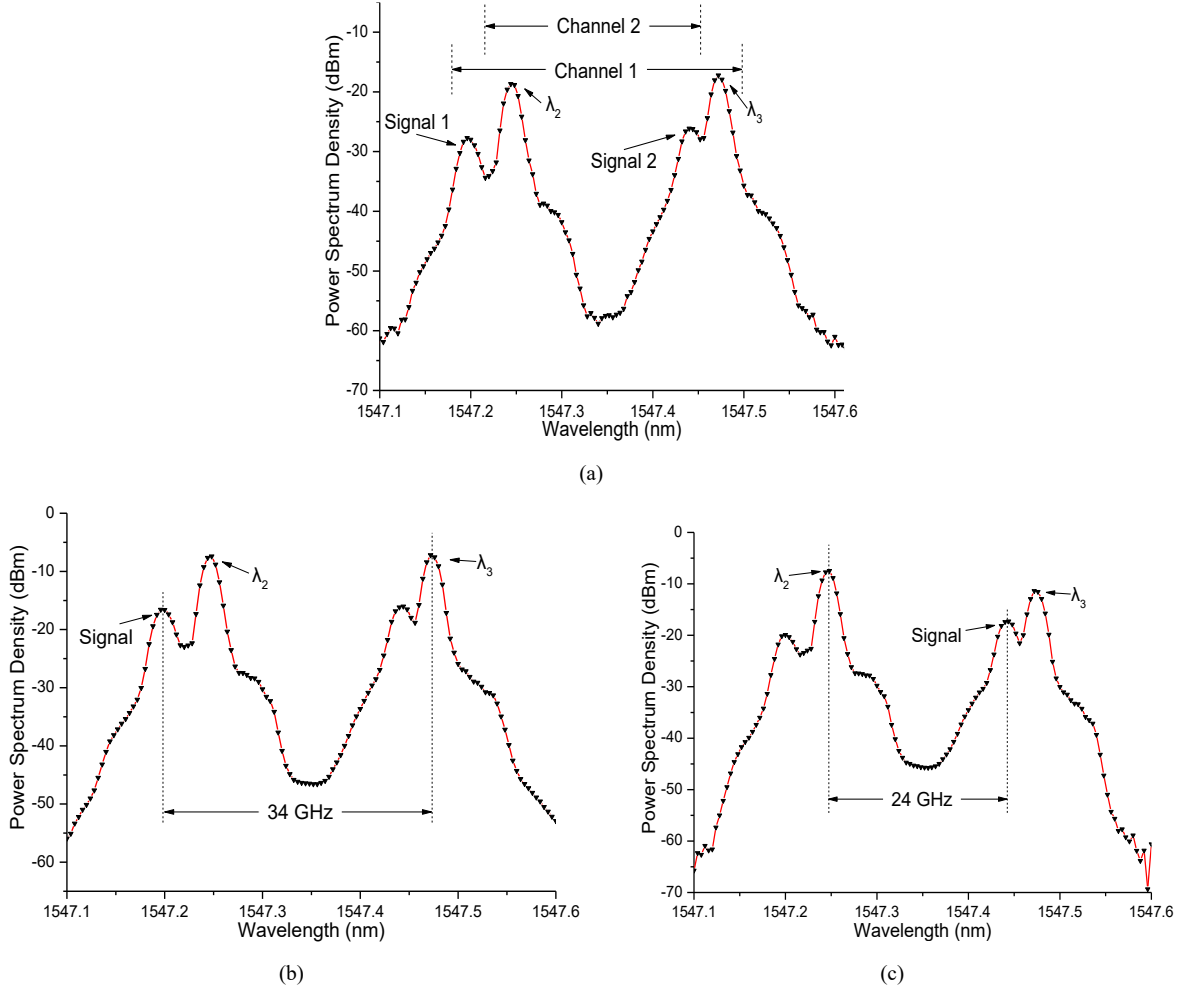


Figure 4.10. The optical spectrum in *Technique 3* at (a) Point E, (b) Point F, and (c) Point G of Figure 4.1(a).

In *Technique 3*, only two comb lines (λ_2 and λ_3) are employed, further enhancing spectral efficiency. Each carrier is SSB modulated, with λ_2 driven by RF₁ and λ_3 by RF₂. The corresponding optical spectra at Points E, F, and G of Figure 4.1(a) are shown in Figure 4.10. However, as illustrated in Figure 4.10(b) and (c), the optical filter cannot entirely suppress the undesired signals

and carriers, which reduces the available signal power after heterodyne detection. An additional advantage of *Technique 3* is that both MZMs operate as SSB modulators, thereby eliminating the need for an I/Q modulator.

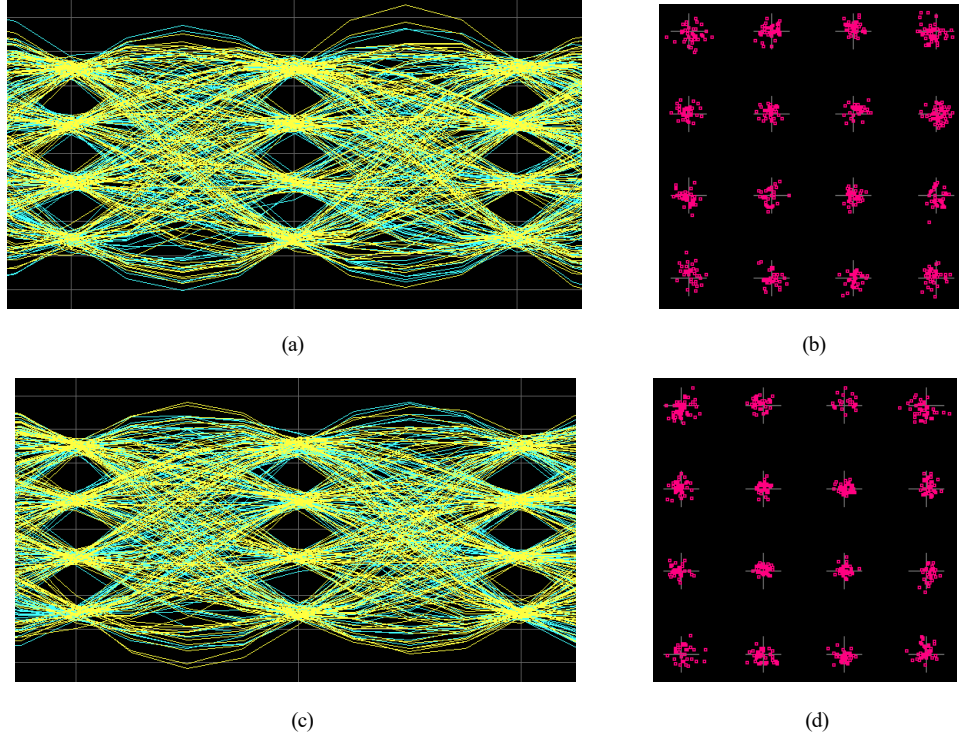


Figure 4.11. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

Similar to the previous techniques, *Technique 3* also employs the same RF_1 and RF_2 signals. In the BtB optical system, the received optical powers of Channel 1 and Channel 2 were measured at 1.34 mW and 1.03 mW, respectively. The corresponding EVM values were calculated as 7.4% for Channel 1 and 6.8% for Channel 2. The eye diagrams and constellation plots of the received signals are shown in Figure 4.11. Due to the higher optical power in *Technique 3*, noticeable nonlinear effects are observed, as evidenced in Figure 4.11. Interestingly, in this case, Channel 1 exhibits worse performance than Channel 2. As shown in Figure 4.10(b), the presence of residual carriers and undesired signals occupies a significant portion of the optical power, lowering the

power spectral density of the desired mmWave signal after heterodyne detection and thereby degrading Channel 1's performance. In contrast, most of the unwanted carriers and signals in Channel 2 can be effectively suppressed by an optical filter, resulting in better performance.

In summary, *Technique 3* reuses two comb lines across the two channels, achieving excellent spectral efficiency. Its performance is superior to that of *Techniques 1* and 2. Moreover, this structure eliminates the need for an I/Q modulator, further simplifying the system design.

4.2.4 Result of *Technique 4*

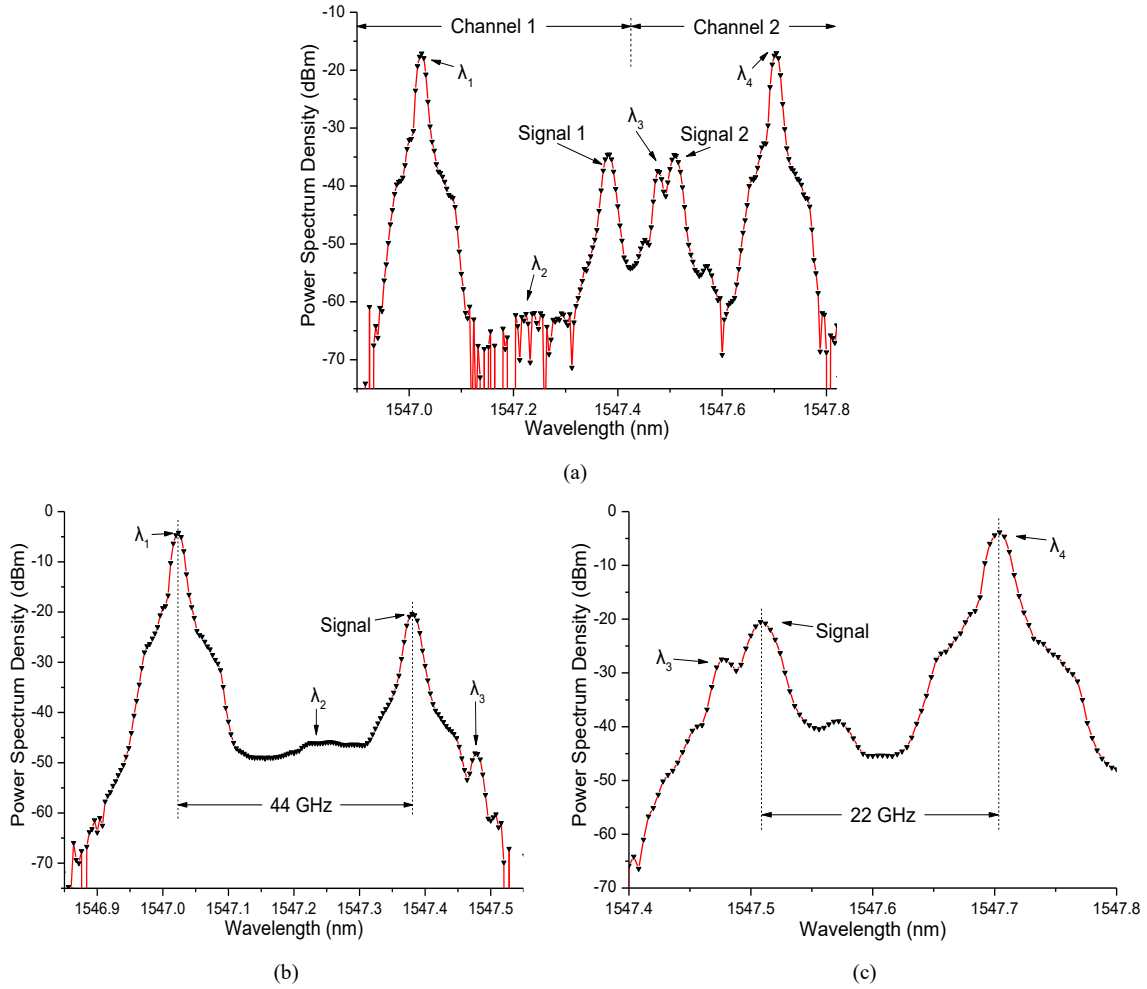


Figure 4.12. The optical spectrum in *Technique 4* at (a) Point C, (b) Point D, and (c) Point E of Figure 4.1 (b).

Finally, we consider *Technique 4*, which features a structure entirely different from the previous techniques. Figure 4.12 presents the optical spectra corresponding to Points D, E, and F of Figure 4.1(b). In this setup, a wave shaper is employed to select two non-adjacent comb lines, λ_1 and λ_4 , while simultaneously filtering out λ_3 as the carrier. The carrier is then modulated using CS-SSB with an I/Q modulator, driven by an RF signal at different center frequencies, as illustrated in Figure 4.5(a). This RF signal is an I/Q waveform comprising two 16-QAM 2 GBaud signals located at 6 GHz and 12 GHz, respectively. As shown in Figure 4.12(b) and (c), *Technique 4* introduces no cross-talk and demonstrates the best overall performance among the four techniques.

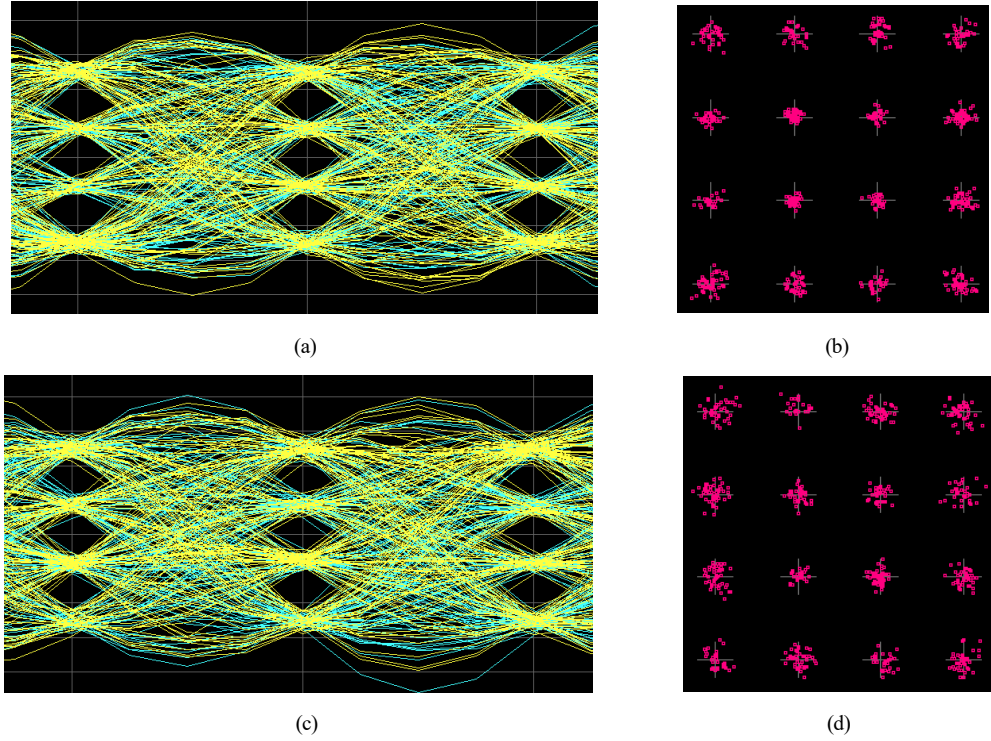


Figure 4.13. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

Upon heterodyne reception, the signals are upconverted to 44 GHz and 22 GHz. As shown in Figure 4.12(b) and (c), no cross-talk or unwanted frequency components appear around the desired mmWave signals. Consequently, *Technique 4* can achieve the best performance without

requiring elevated received optical power.

The received optical power is measured at 0.55 and 0.68 mW for channel 1 and 2 in the BtB setup. The performance is also excellent, with an EVM of 7.1% and 6.0% for channel 1 and 2, respectively. The eye diagrams and constellations of both channels are depicted in Figure 4.13.

4.3 Wireless Experimentation Results

To further evaluate the proposed techniques, a 2-m wireless link was introduced after heterodyne detection, as illustrated in Figure 4.14. In this configuration, *Techniques 1, 2, and 3* adopt the same structure shown in Figure 4.14(a), while *Technique 4* is implemented with its distinct structure shown in Figure 4.14(b). As in the previous analysis, we first examine the case without fibre transmission, i.e., the BtB mmWoF scenario.

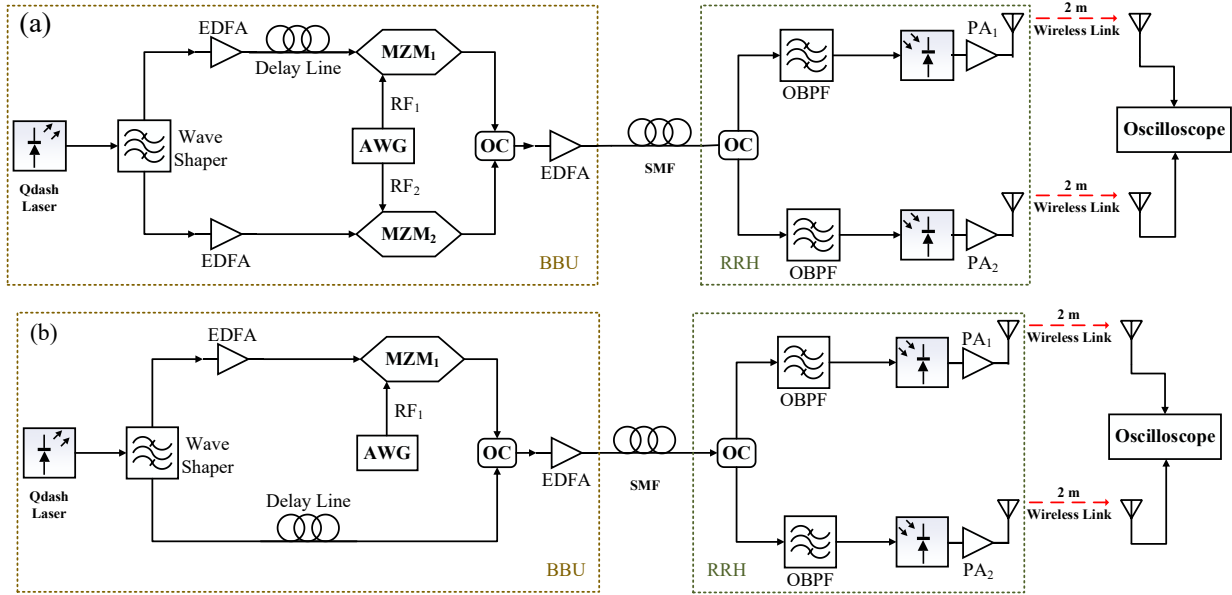


Figure 4.14. Block diagram of proposed multiplexing *Technique 1, 2, and 3* is shown on (a), *Technique 4* is shown on (b).

The EVM comparison between the techniques with and without the 2-m wireless link is

summarized in **Error! Not a valid bookmark self-reference..** Overall, the influence of the wireless link is around 0.3 dB, indicating that the main limitation of the wireless mmWoF system is the RoF link rather than the wireless link. For *Technique 4*, the influence of the wireless link is higher than that in the other techniques. This is caused by the relatively higher attenuation in the wireless link at 22 GHz and 44 GHz, compared to the 24 GHz and 34 GHz associated with *Technique 1*, *2*, and *3*. The attenuation of the wireless link at 22 GHz and 44 GHz is 4.8 dB higher than the data sheet, hence a higher influence.

Table 4.1. Comparison of with and without wireless link in EVM (%)

Technique	EVM w/ wireless link	EVM w/o wireless link
1	7.6/8.5	7.4/8.2
2	7.1/8.0	6.4/7.9
3	7.6/7.1	7.4/6.8
4	7.5/6.7	7.1/6.0

Next, fibre transmissions over 10 km and 50 km are considered. Table 4.2 summarizes the EVM results of the four proposed multiplexing structures with 16-QAM 2 GBaud signals under BtB, 10 km, and 50 km transmission. Among the four techniques, *Technique 4* consistently achieves the best performance across all transmission distances, while *Technique 1* shows the poorest performance, as expected. It is also observed that fibre transmission degrades the performance of all four techniques compared with the BtB case.

Table 4.2. Comparison of four multiplexing techniques in EVM (%)

Technique	2 Gbaud/s		
	BtB	10 km	50 km
1	7.6/8.5	9.6/9.5	9.5/9.6
2	7.1/8.0	8.3/8.7	9.2/9.4
3	7.6/7.1	8.3/8.6	9.0/9.1
4	7.7/6.7	7.1/7.4	8.8/8.4

4.4 Summary and Discussion of Frequency Multiplexing Techniques

In this study, four mmWave frequency multiplexing techniques have been experimentally compared, utilizing multiple highly coherent comb lines generated by a QD-MLL as optical carriers. Each technique demonstrates unique advantages and limitations. *Technique 1* is the most straightforward and robust in terms of architecture and implementation simplicity, yet it delivers the lowest performance and spectral efficiency. *Technique 2* improves both performance and spectral efficiency compared with *Technique 1*, but at the cost of requiring an I/Q modulator, which increases system complexity. *Technique 3* further enhances performance and spectral efficiency while maintaining simplicity comparable to *Technique 1*, as it does not require an I/Q modulator. *Technique 4* achieves the best results in terms of EVM performance and eliminates crosstalk. However, it demands more complex hardware, including both an I/Q modulator and a wave shaper or specialized filter.

Despite these differences, all four techniques demonstrate satisfactory performance, with EVM consistently remaining below 9.6% even after 50 km of SMF transmission. These results indicate that all four proposed frequency multiplexing techniques are promising and viable solutions for future fronthaul transmission systems.

Chapter 5 Basic Characterization of Quantum-Dash Semiconductor Optical Amplifier

In this chapter, a 5-layer QD-SOA is characterized in detail. The analysis focuses on performance parameters that significantly influence its applicability in communication systems. Specifically, the gain and NF across the S+C band (1460 - 1565 nm) are measured under varying temperatures and bias currents. Furthermore, the influence of QD layers is also investigated.

5.1 SOA Structure and Measurement Methods

5.1.1 Structure of QD-SOA

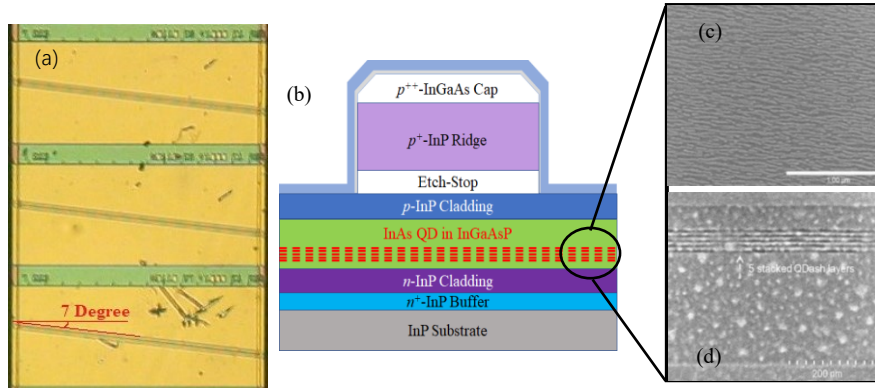


Figure 5.1. (a) Top view of QD-SOA chips. (b) Cross-sectional structure of QD-SOA. (c) SEM image of the top view of the QD layer. (d) SEM image of cross-section around QD layers.

QD-SOA used in this work is an InP-based waveguide, which is tilted 7° to the longitudinal direction of the chip to minimize the reflection [63]. The multiple anti-reflect TiO₂/SiO₂ layers are coated at both facets of QD-SOA, resulting in a $< 10^{-4}$ mode reflectivity [63]. The top view of QD-SOA is shown in Figure 5.1(a), which displays three cascaded QD-SOA chips within a larger bar that containing 15 identical chips. The diameter of a single QD-SOA chip is measured as 1.5 mm $\times$ 0.8 mm $\times$ 0.1 mm. The cross-sectional structure of the QD-SOA chip is shown in Figure 5.1(b).

The active region of the QD-SOA contains five layers of InAs QDs buried with 10 nm $\text{In}_{0.816}\text{Ga}_{0.184}\text{As}_{0.392}\text{P}_{0.608}$. The average QD density in each active layer is around $1.5 \times 10^{10} \text{ cm}^{-2}$ [93]. The composition of InGaAsP was chosen to have a photoluminescence peak of $1.15 \mu\text{m}$ at 300 K. Figure 5.1(c) and (d) show the scanning electron microscope (SEM) images of the top view and cross-section of the QD layer. This QD structure provides both carrier and optical confinement. The designing and fabrication details of QD-SOA are described in [62].

5.1.2 Measurement Method.

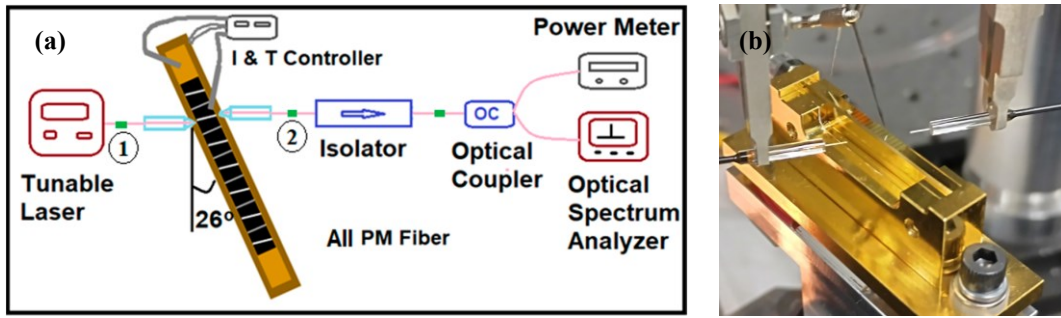


Figure 5.2. (a) The block diagram of the QD-SOA measurement system (Figure 2 of Ref [63]). (b) The picture of the QD-SOA holder and focusers.

Figure 5.2(a) shows the block diagram of the measurement system. The core component, the QD-SOA bar, is mounted on a gold-plated copper carrier attached to a central post, providing both mechanical support and thermal conduction, as shown in Figure 5.2(b). The bottom of the QD-SOA chip serves as the ground and is connected to the gold-plated mounting, while the top metal mask of the chip is used as the bias contact. Two metal probes are employed to bias the QD-SOA, and two optical focusers are used to couple the input and output laser beams with the device under test.

Because the QD-SOA waveguide is tilted by 7° , the QD-SOA and its mount are rotated counterclockwise by 26° relative to normal, ensuring that the input and output beams remain

parallel to the focusers after facet refraction. A semiconductor temperature controller is integrated into the mount to maintain the QD-SOA at the desired temperature during measurements. An ILX LDC-3722 laser controller is used to regulate both the bias current and the device temperature. Finally, two lensed fibres are employed as focusers to couple the input and output laser beams between the fibre and the QD-SOA waveguide.

For the system setup, an Agilent 81682A tunable laser is used as the seed laser during gain and NF measurements. The laser output is coupled into the QD-SOA via the input focuser and, after amplification, collected by the output focuser. To minimize back reflections from downstream measurement devices, a two-stage polarization-maintaining (PM) isolator is placed after the output focuser. A PM coupler is then used to split the amplified signal: 10% of the power is directed to a Thorlabs PM100D power meter for real-time monitoring, while the remaining 90% is measured using a Yokogawa AQ6380 optical spectrum analyzer (OSA).

A computer with a GPIB to USB convertor is used to control the tunable laser, laser controller, and OSA to provide fully automated operation. Instrument control is achieved using Python via the Virtual Instrument Software Architecture (VISA) protocol.

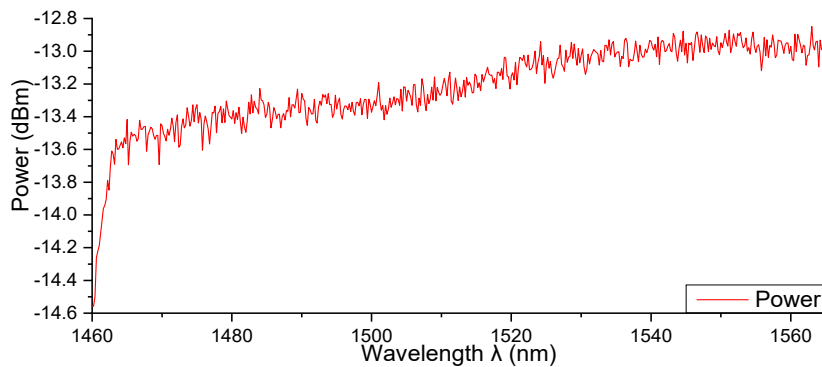


Figure 5.3. Reference power of the system without SOA.

In this chapter, only the communication performance of our QD-SOA is considered.

Therefore, the coupling loss between the SOA and the focusers is not calibrated. All gain and NF values reported in this chapter are based on FtF measurements.

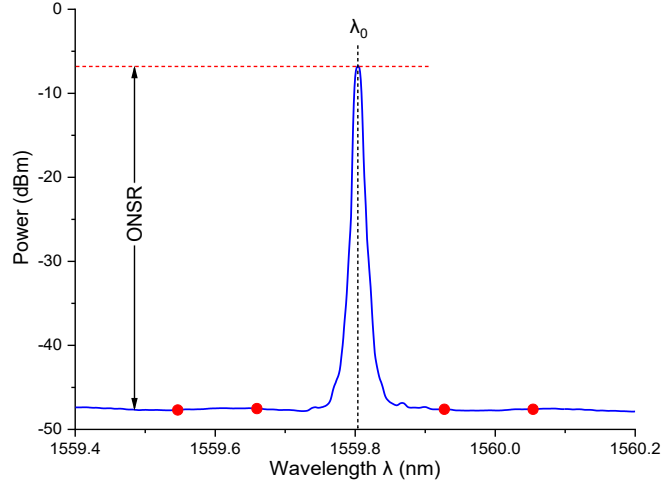


Figure 5.4. An example of recorded power spectrum density during gain and NF measurement.

Prior to measuring the gain and noise figure (NF), the reference optical power was recorded by directly connecting Point 1 and Point 2 in Figure 5.2(a), bypassing the QD-SOA. The seed laser was configured to generate the input light at the desired power level, with the wavelength swept from 1460 nm to 1565 nm in steps of 0.2 nm. At each step, the OSA recorded the output of the OC and identified the peak power. The peak power spectral density and its corresponding wavelength were stored as the reference data, denoted as $P_{ref}(\lambda)$, which includes both the power and attenuation characteristics of the system as a function of wavelength. Figure 5.3 shows the reference spectrum when the seed laser power was set to -10 dBm. It can be observed that there is approximately a 1.5 dB variation across the S+C band.

After obtaining the reference power, the QD-SOA is added back to the system. The temperature and bias current of QD-SOA is set by the laser controller to desired value. The tunable laser will generate a seed laser at the desired power and sweep from 1460 nm to 1565 nm with a step of 0.2 nm, once the QD-SOA is stable. The QD-SOA will amplify the seed laser, and the output

of QD-SOA is then analyzed at OSA. During the sweep, the spectrum will be recorded in the OSA at each wavelength. An example of recorded power spectrum density is shown in Figure 5.4. The peak power and its wavelength are recorded as $P_{out}(\lambda)$. The amplified spontaneous emission (ASE) around the peak is also recorded as $P_{ASE}(\lambda)$, which is the average of four point around peak power separated by 0.2 nm. With the $P_{out}(\lambda)$ and $P_{ASE}(\lambda)$, we can calculate the optical signal to noise ratio (OSNR) at each wavelength, denoted as $OSNR(\lambda)$:

$$OSNR(\lambda) = P_{out}(\lambda) - P_{ref}(\lambda) \quad (5-1)$$

With $P_{ref}(\lambda)$ and $P_{out}(\lambda)$, the gain of the QD-SOA at certain bias current and temperature can be calculated by:

$$G(\lambda) = P_{out}(\lambda) - P_{ref}(\lambda) \quad (5-2)$$

where $G(\lambda)$ is the gain of QD-SOA at wavelength λ .

The NF is calculated based on the $P_{ASE}(\lambda)$ and $G(\lambda)$ with following formular:

$$NF(\lambda) = \frac{1}{hc^2} \times \frac{\lambda}{\Delta\lambda} \times \frac{P_{ASE}(\lambda)}{G(\lambda)} \quad (5-3)$$

where h is Planck's constant (6.626×10^{-34} J·s), $\Delta\lambda$ is the resolution of OSA. In this measurement, the resolution is set to $\Delta\lambda = 0.01$ nm.

5.2 Results and Discussion of Device Characterization

5.2.1 Baseline Scenario: 20 °C, 300 mA Biased

During the measurement, the output data of QD-SOA with different temperature, input power, bias current, and input wavelength is captured. It is challenging to cover all the details of each scenario in this thesis. Therefore, the performance of QD-SOA at temperature at 20 °C and 300 mA biased is considered as baseline scenario, and discussed in detail. For the remaining

scenarios, the results are summarized and compared with the baseline measurements to highlight the influence of temperature and bias current on device performance.

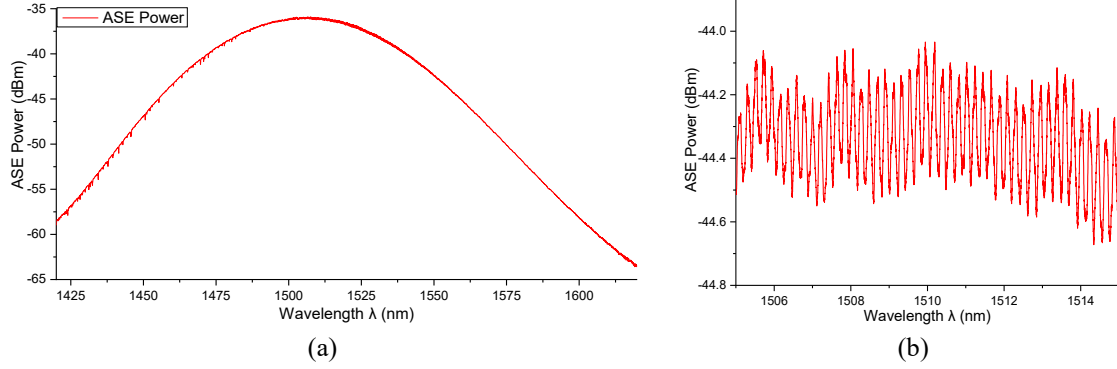


Figure 5.5. (a) The overall ASE output of QD-SOA. (b) Closed ASE spectrum around ASE peak.

The ASE output spectrum of the QD-SOA without an input signal is shown in Figure 5.5(a). The ASE peak occurs at 1506.56 nm with a power of -35.91 dB. The corresponding 3-dB bandwidth of the ASE is 58.16 nm, with a range from 1477.18 nm to 1534.53 nm. A magnified view of the spectrum around the peak wavelength is shown in Figure 5.5(b). The ripple amplitude of this device is approximately 0.2 dB, and the spacing between two adjacent ripple peaks is 0.21 nm. The cavity length of QD-SOA can be calculated by:

$$L_{cavity} = \frac{\lambda_1 \lambda_2}{2n|\lambda_2 - \lambda_1|} \quad (5-4)$$

where, λ_1 and λ_2 represent the wavelengths of two adjacent ripple peaks, and n denotes the refractive index of the QD-SOA waveguide. For the measured device, the refractive index is $n = 3.22$. Using the ripple spacing of 0.21 nm, the cavity length L_{cavity} is calculated to be approximately 1.46 mm, which corresponds well with the physical length of the QD-SOA chip.

Figure 5.6(a) presents the gain spectrum across the S+C band (1460-1565 nm) measured at different input powers. Under the small-signal (-20 dBm input), the peak gain is 17.68 dB at 1507.80 nm. The gain peak exhibits a red shift of 1.2 nm, compared with the ASE peak. The

corresponding 3-dB gain bandwidth is 56.6 nm, spanning from 1481.60 nm to 1538.20 nm, which is 1.6 nm narrower than the 3-dB ASE bandwidth.

Figure 5.6(b) illustrates the OSNR as a function of wavelength for different input powers. the OSNR reaches up to -45.8 dB, under the small-signal condition. Figure 5.6(c) presents the NF versus wavelength under varying input powers. Under small-signal conditions, the NF is as low as 6.3 dB. As shown in Figure 5.6(b) and (c), The increasing of input power leads to an almost linear decrease of OSNR (in dB), while the NF remains nearly constant as long as the input power is below -5 dBm.

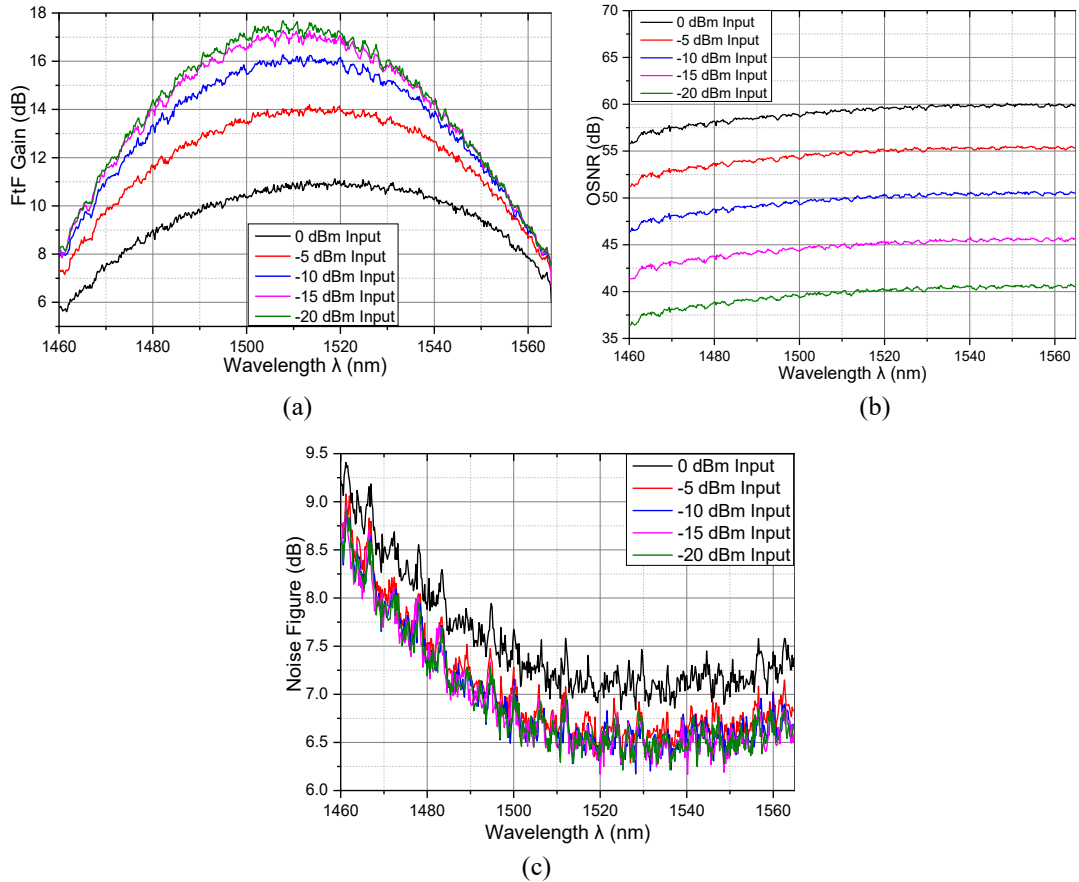


Figure 5.6. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with different input power.

Figure 5.7(a) shows the relationship between input power and gain at two wavelengths:

1507.8 nm, corresponding to the gain peak, and 1550.0 nm, which is commonly used in communication systems. Figure 5.7(b) shows the relationship between input power and NF. The results indicate that as input power increases, the gain decreases due to saturation. The 1-dB compression point (P_{1dB}) is approximately -4.5 dBm at 1550 nm and -12.5 dBm at 1507.8 nm. Regarding NF, the results show that when the input power is lower than -5 dBm, the NF remains nearly constant.

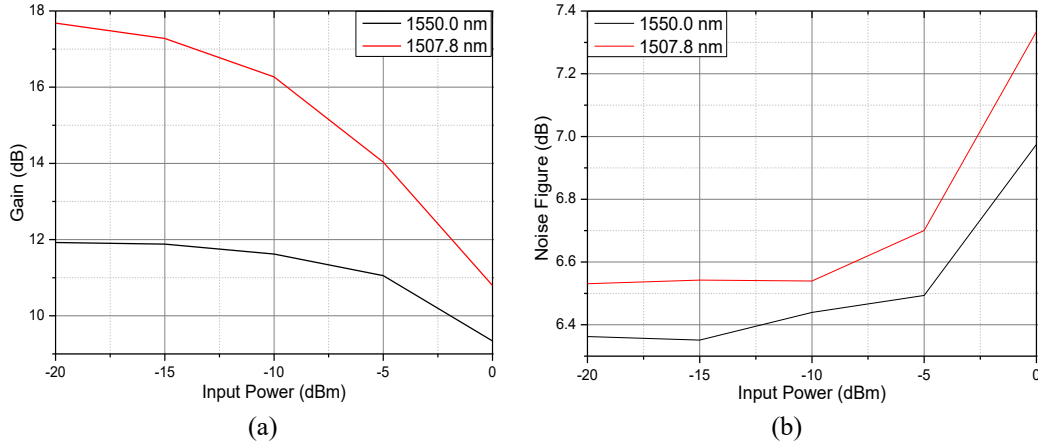


Figure 5.7. The (a) FtF gain and (b) NF of QD-SOA versus input laser power at peak gain wavelength (1507.8 nm) and 1550.0 nm.

5.2.2 The Influence of Bias Current

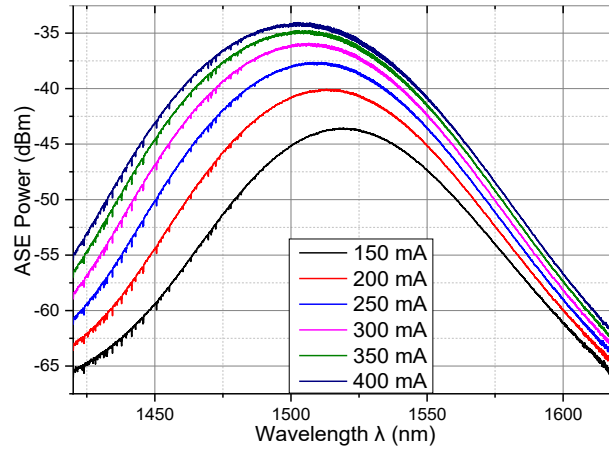


Figure 5.8. The ASE output of QD-SOA at different bias current.

In this series of measurements, the QD-SOA temperature was maintained at 20 °C, while the bias current was varied from 150 mA to 400 mA. Figure 5.8 shows the ASE output spectra of the QD-SOA under different bias currents. As the current increases, the ASE center wavelength exhibits a blue shift from 1518.70 nm to 1479.14 nm. At the same time, the 3-dB bandwidth broadens from 53.7 nm to 77.6 nm. In addition, the spectral ripple increases with bias current, rising from 0.2 dB at 150 mA to 0.8 dB at 400 mA.

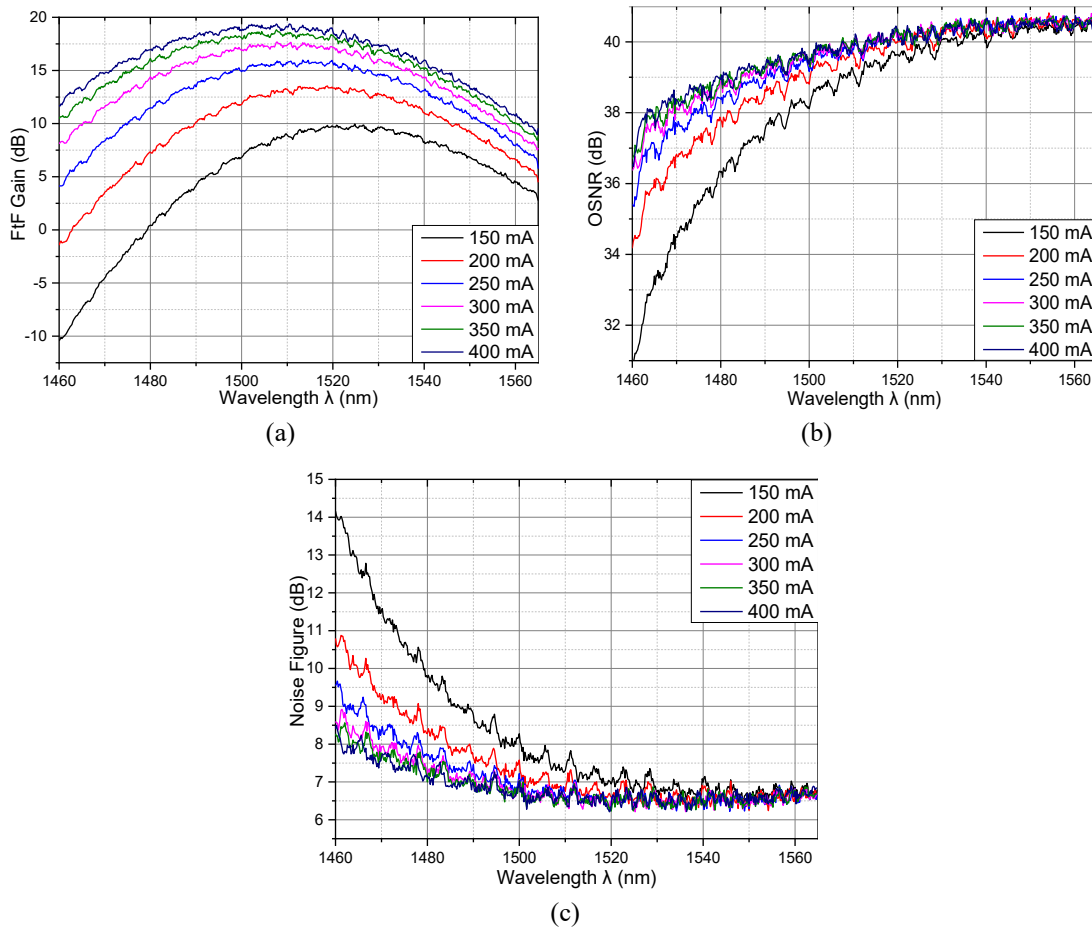


Figure 5.9. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with difference bias current.

To further examine the influence of bias current, the gain, OSNR, and NF were measured under a small input signal (−20 dBm). Figure 5.9(a) shows that the gain increases with bias current; however, the increase becomes marginal when the current rises from 350 mA to 400 mA. This

suggests that the bias current limitation of the QD-SOA is around 400 mA. The reduced gain improvement at high bias levels is attributed to thermal effects, where the heat generated cannot be efficiently dissipated to the temperature controller, thus limiting performance.

Figure 5.9(b) presents the OSNR of the QD-SOA at different bias currents. At 150 mA and 200 mA, the gain is relatively low, resulting in poor OSNR, especially at shorter wavelengths. When the bias current exceeds 250 mA, the OSNR slightly improves at shorter wavelengths, while remaining nearly unchanged at longer wavelengths. Figure 5.9(c) shows the NF versus wavelength for different bias currents, exhibiting a trend similar to that of the OSNR.

Table 5.1 summarizes the 3-dB gain bandwidth and peak gain wavelength for different bias currents. With increasing bias current, the peak gain wavelength shifts toward shorter wavelengths, while the 3-dB gain bandwidth broadens.

Table 5.1. The peak gain wavelength and 3-dB bandwidth are shown at different bias current.

Bias Current (mA)	Peak Gain Wavelength (nm)	3-dB Bandwidth (nm)
150	1530.4	51.8
200	1518.8	52.2
250	1513.4	54.8
300	1513.4	56.8
350	1510.0	59.0
400	1507.6	62.8

The gain and NF across the S+C band were also measured at different input powers for each bias current. However, much of the data reflects the direct principle that higher input power results in lower gain, and consequently worse OSNR and NF. To avoid redundancy, we present the gain and NF only at the peak gain wavelength and at 1550.0 nm for each bias current. Figure 5.10(a) and (b) show the gain and NF of the QD-SOA versus input power at the peak gain wavelength (as

listed in Table 5.1). Figure 5.11(a) and (b) show the corresponding results at 1550.0 nm.

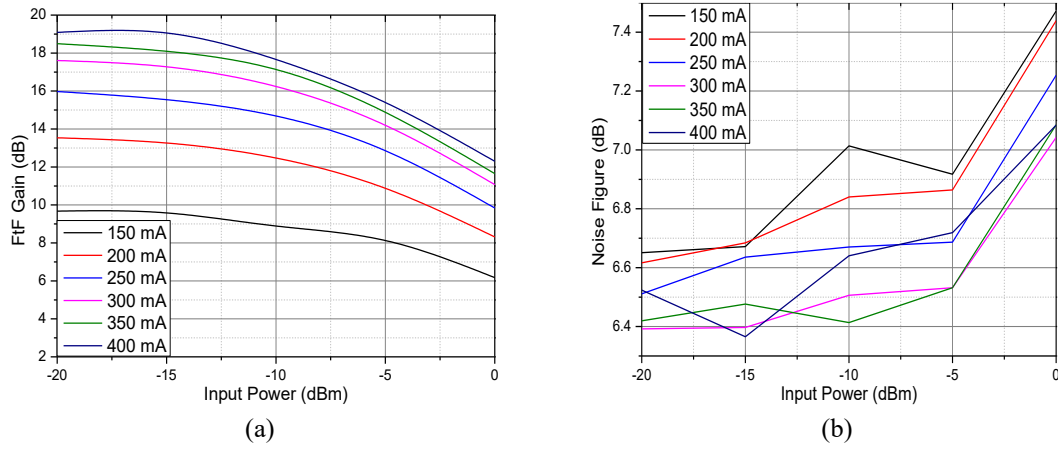


Figure 5.10. The (a) FtF gain and (b) NF of QD-SOA versus input power at peak gain wavelength.

It is evident that the gain increases with bias current at both the peak gain wavelength and at 1550.0 nm. Regarding NF, the lowest values at the peak gain wavelength are achieved at bias currents of 300 mA and 350 mA. At 1550.0 nm, which lies outside the 3-dB gain bandwidth, the NF does not exhibit a clear trend with respect to bias current.

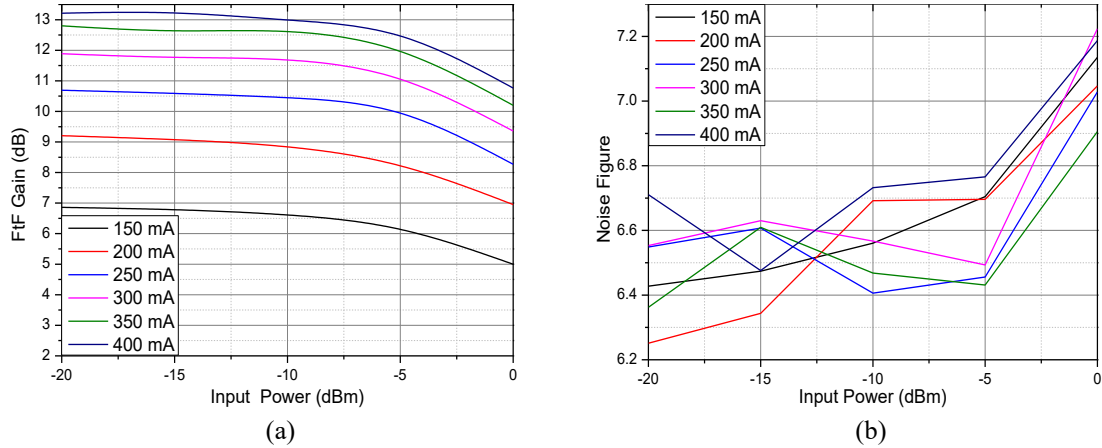


Figure 5.11. The (a) FtF gain and (b) NF of QD-SOA versus input power at 1550.0 nm.

5.2.3 The Influence of Temperature

In this series of measurements, the bias current was fixed at 300 mA while the temperature

of the QD-SOA was varied from 15 °C to 40 °C. Figure 12 shows the ASE output spectra of the QD-SOA at different temperatures. As the temperature increases, the ASE power decreases. At the same time, the ASE center wavelength exhibits a red shift from 1503.94 nm to 1523.64 nm, and the 3-dB bandwidth broadens from 56.3 nm to 63.66 nm. In addition, the spectral ripple decreases with temperature, reducing from 0.9 dB at 15 °C to 0.2 dB at 40 °C.

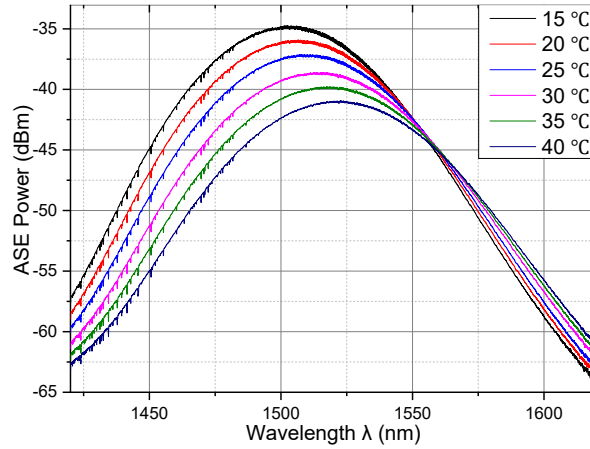


Figure 5.12. The ASE output of QD-SOA at different temperature.

Table 5.2. The peak gain wavelength and 3-dB bandwidth at different temperature.

Temperature (°C)	Peak Gain Wavelength (nm)	3-dB Bandwidth (nm)
15	1501.4	54.8
20	1507.8	55.6
25	1515.6	57.8
30	1514.6	58.4
35	1519.2	59.2
40	1526.2	59.4

To further examine the influence of temperature, the gain, OSNR, and NF were measured under a small input signal (−20 dBm). Figure 5.13(a) shows that as the temperature increases, the gain decreases. Figure 5.13(b) presents the OSNR of the QD-SOA at different temperatures, clearly indicating that higher temperatures result in reduced OSNR. Figure 5.13(c) illustrates the NF as a function of wavelength under varying temperatures, showing a similar trend to the OSNR, i.e.,

higher temperatures lead to higher NF.

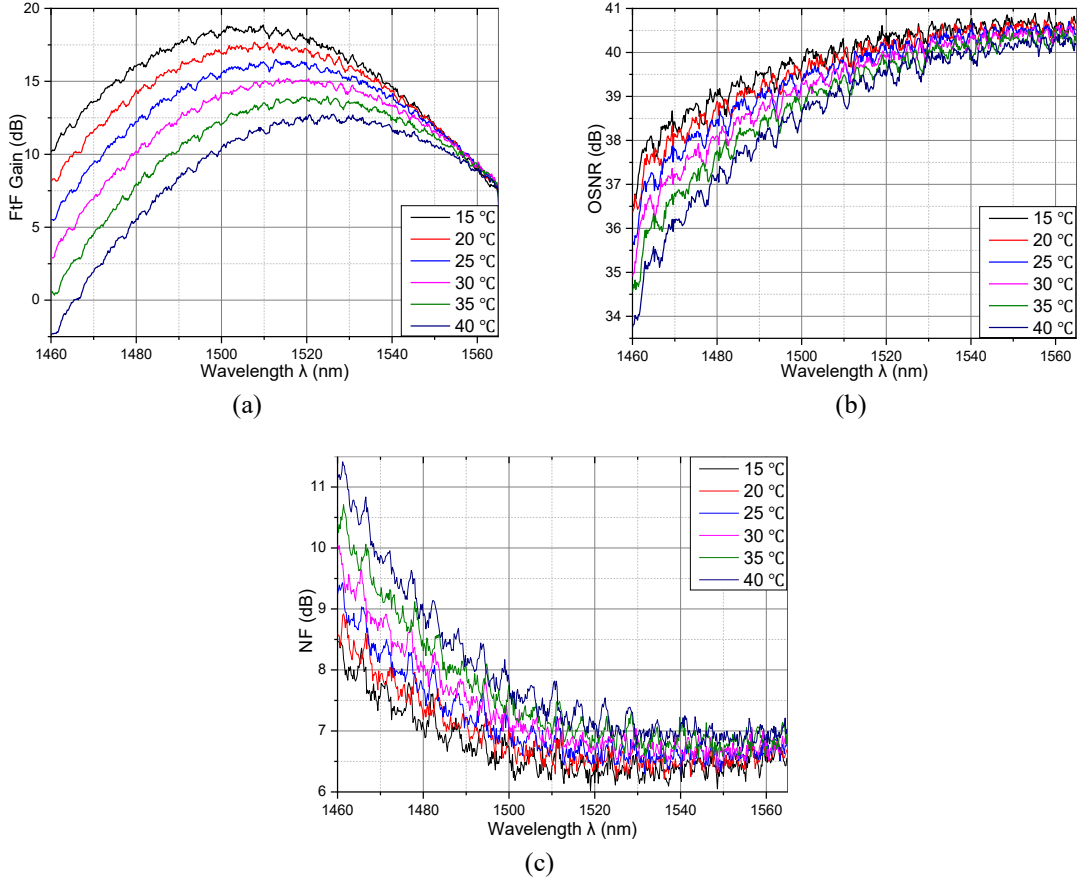


Figure 5.13. The (a) FtF gain, (b) OSNR, and (c) NF of QD-SOA versus wavelength with different temperature.

Table 5.2 summarizes the 3-dB gain bandwidth and peak gain wavelength at different temperatures. With increasing temperature, the peak gain wavelength shifts toward longer wavelengths, while the 3-dB gain bandwidth broadens.

Measurements of gain and noise figure (NF) across the S+C band were carried out for a range of input powers at different QD-SOA operating temperatures. To maintain consistency with earlier analyzes, the discussion focuses on two representative wavelengths: the peak gain wavelength and 1550.0 nm. The specific peak gain values obtained at each temperature are summarized in Table 5.2. Figure 5.14(a) and (b) show the dependence of gain and NF on input

power at the peak gain wavelength, while Figure 5.15 (a) and (b) show the corresponding results at 1550.0 nm.

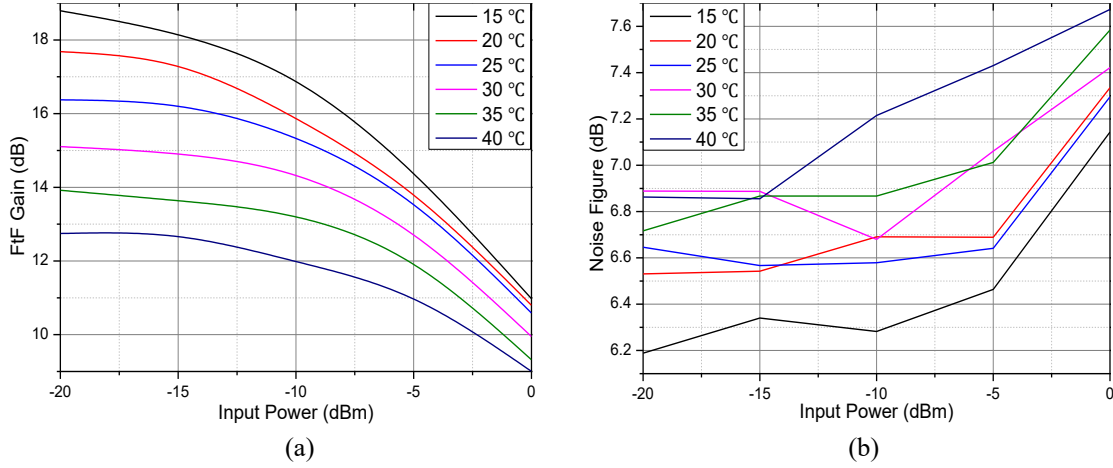


Figure 5.14. The (a) FtF gain and (b) NF of QD-SOA versus input power at peak gain wavelength.

The results clearly show that gain decreases as temperature increases, both at 1550 and at the peak gain wavelength. Regarding NF, the device exhibits the lowest values at 15 °C for both cases. For higher temperatures, the general trend indicates that NF increases as temperature rises.

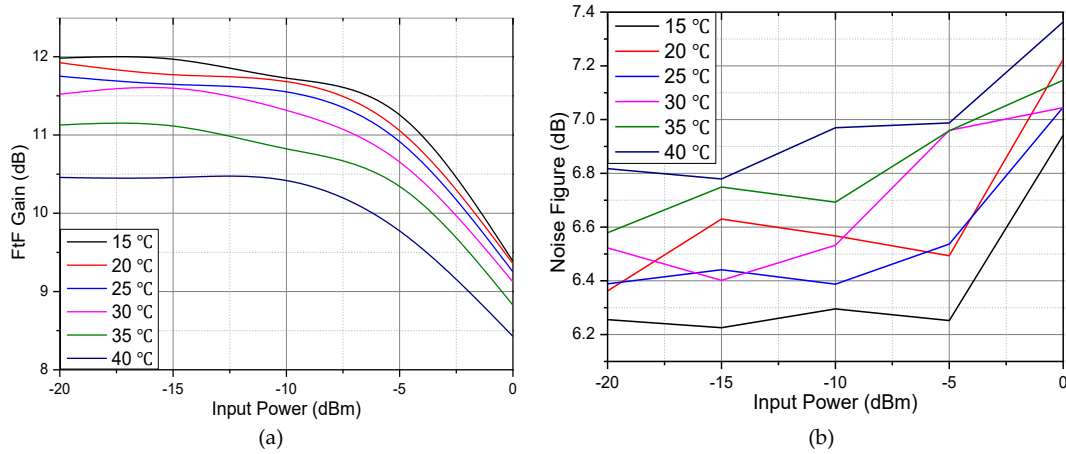


Figure 5.15. The (a) FtF gain and (b) NF of QD-SOA versus input power at 1550.0 nm.

5.2.4 Temperature Stability

The previous section considered only general communication conditions. However,

specific applications require operation over a wider temperature range [63]. Therefore, in this section, measurements were extended to temperatures from 17 °C to 80 °C. Since higher operating temperatures were required, the SOA holder shown in Figure 5.2(b) could not be used for temperature control. Instead, a larger heating pad was employed. This alternative SOA holder, however, does not support gain and NF measurements of the QD-SOA; only ASE spectra were recorded under these conditions. Therefore, in this section, temperature from 17 °C to 80 °C is further considered and measured.

Figure 5.16 shows the ASE spectrum of the 5-layer QD-SOA measured under a bias current of 450 mA at temperatures ranging from 17 °C to 80 °C. As the operating temperature increased, the ASE output intensity gradually decreased, and the spectral peak shifted toward longer wavelengths.

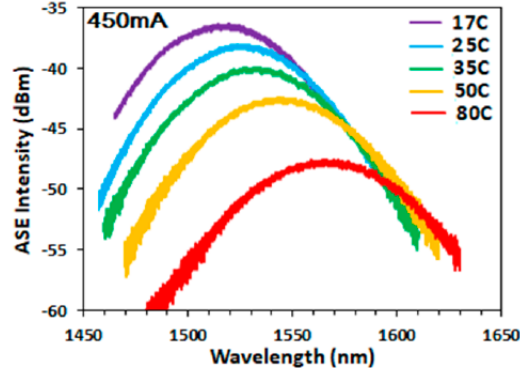


Figure 5.16. ASE spectrum of the 5-layer QD-SOA versus temperature from 17 - 80 °C.

Figure 5.17(a) and (b) present the dependence of ASE peak intensity, peak wavelength, and 3-dB bandwidth on bias current and temperature. As shown in Figure 5.17(a), the ASE peak intensity reaches saturation at around 400 mA across all tested temperatures. The corresponding ASE peak wavelength spans from 1515.7 to 1581.3 nm, thus covering both the C-band and L-band. Meanwhile, the 3-dB ASE bandwidth broadens with increasing bias current and temperature, reaching a maximum of 80 nm at 450 mA and 80 °C.

Figure 5.17(c) shows the temperature dependence of ASE peak intensity (left axis) together with the peak wavelength and 3-dB bandwidth (right axis). The ASE peak intensity shows stronger sensitivity to temperature variations at lower bias currents, while the temperature-induced changes in peak wavelength and 3-dB bandwidth remain relatively consistent across different bias conditions. On average, the ASE peak wavelength shifts at a rate of $0.77 \text{ nm}/^{\circ}\text{C}$, which closely matches the previously reported value of $0.78 \text{ nm}/^{\circ}\text{C}$ in [94].

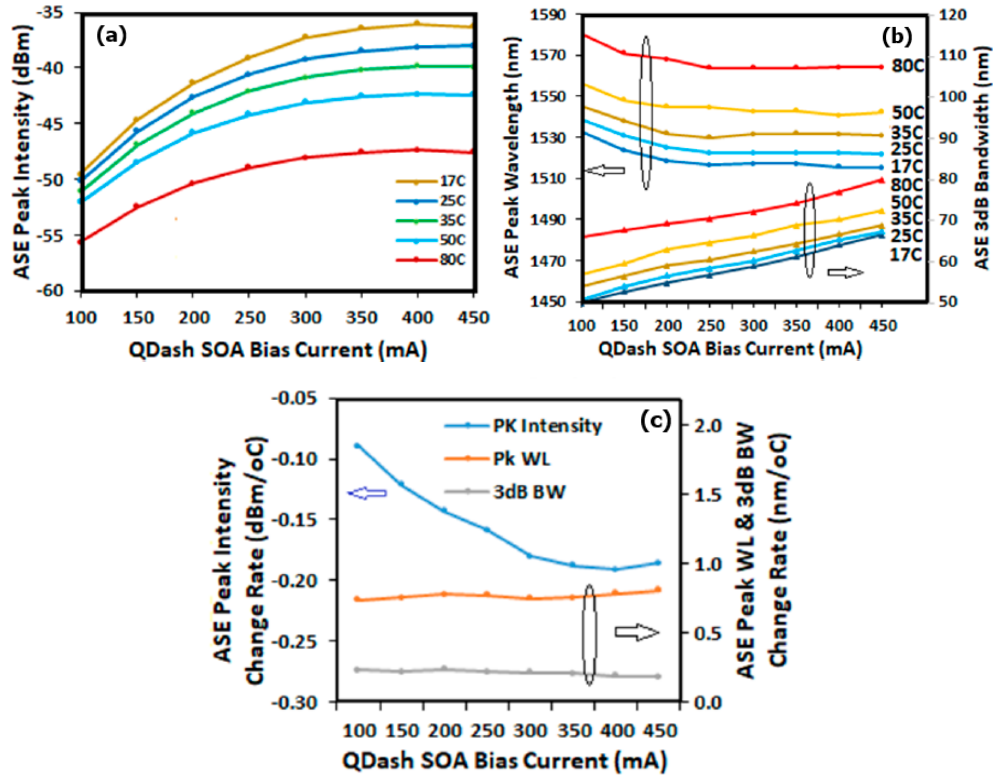


Figure 5.17. The (a) ASE peak power spectrum density, (b) ASE peak wavelength, 3-dB bandwidth versus bias current and temperature, and (c) rate of change with temperature of ASE peak power spectrum density, peak wavelength, and 3-dB bandwidth.

5.2.5 Discussion of Characterization Results

In this section, the performance of the QD-SOA has been systematically investigated. The ASE, gain, OSNR, and NF were measured under different temperatures, bias currents, and input

laser powers. Based on these results, the characteristics of the QD-SOA can be extrapolated to similar conditions relevant to communication systems.

Overall, the results indicate that device performance improves under lower temperatures, higher bias currents, and lower input powers, leading to higher gain and reduced OSNR. Nevertheless, a key limitation of the 5-layer QD-SOA is that its peak gain wavelength lies outside the C-band, which restricts its suitability for practical optical communication systems where C-band operation is essential. This limitation can be addressed by employing an eight-layer QD-SOA, whose peak gain wavelength lies in the C-band under most conditions. Therefore, future work will focus on investigating the 8-layer QD-SOA, which is expected to achieve improved performance across the C-band.

5.3 Influence QD Layers

In this section, the QD-SOAs contain 3-, 5-, 8-, or 12-layers of QD, which are measured and compared. The ASE, gain, and NF are measured with different QD-SOAs.

5.3.1 Measurement Setup

The experimental configuration used in this section closely follows the setup described in Section 5.2, as shown in Figure 5.2 (a). To ensure thermal stability, a thermoelectric cooler was integrated beneath the copper block, maintaining the device temperature within the range of 17 to 80 °C. A low-noise, battery-powered laser diode driver (ILX LDC-3722) provided the DC bias current for the SOA. Optical coupling was achieved using lensed fibres at both input and output facets. On the output side, a two-stage PM fibre isolator was employed to suppress back-reflections from the subsequent measurement apparatus.

To determine the fibre coupling loss, the total optical power emitted directly from the SOA waveguide was first measured using a large-area photodetector (Thorlabs S132C). A lensed PM fibre was then carefully aligned to the SOA output facet, and the coupled power was recorded. Based on the difference between these two measurements (expressed in dBm), the coupling loss was calculated to be 3.2 dB per facet in this setup.

A PM 90/10 OC was subsequently inserted into the setup. The 10% port was connected to a power meter, Thorlabs S144C and PM100D, for monitoring of the coupled power in real-time, while the 90% port was directed to an OSA, Ando AQ6317B, for spectral measurements.

To characterize the device prior to spectrum measurements, a tunable laser source, Agilent 8164A, was routed through the same isolator and 90/10 coupler used in the setup. At each wavelength under test, the input peak power was recorded before fibre alignment (Point 1 in Figure 5.2(a)), while the corresponding output peak power was measured after alignment (Point 2 in Figure 5.2(a)). The FtF gain was calculated from the difference between these two measurements. The intrinsic chip gain of the QD-SOA was then obtained by adding twice the coupling loss to the FtF gain value. This procedure isolates the amplifier's intrinsic performance by compensating for external coupling losses and setup variations.

In this section, the gain is calculated following Section 5.2, but NF is calculated with a simpler function, as:

$$NF(\lambda) = \frac{2P_{ASE}(\lambda)}{h\nu G(\lambda)B_0} \quad (5-5)$$

where $P_{ASE}(\lambda)$ is the power spectral density of ASE noise measured after fibre coupling, $G(\lambda)$ is the SOA's FtF gain, h is the Planck's constant, ν is the frequency of input wavelength, and B_0 is the OSA's resolution bandwidth used in the measurements. The factor of 2 represents the

polarization effect of the SOA.

5.3.2 Measurement Results

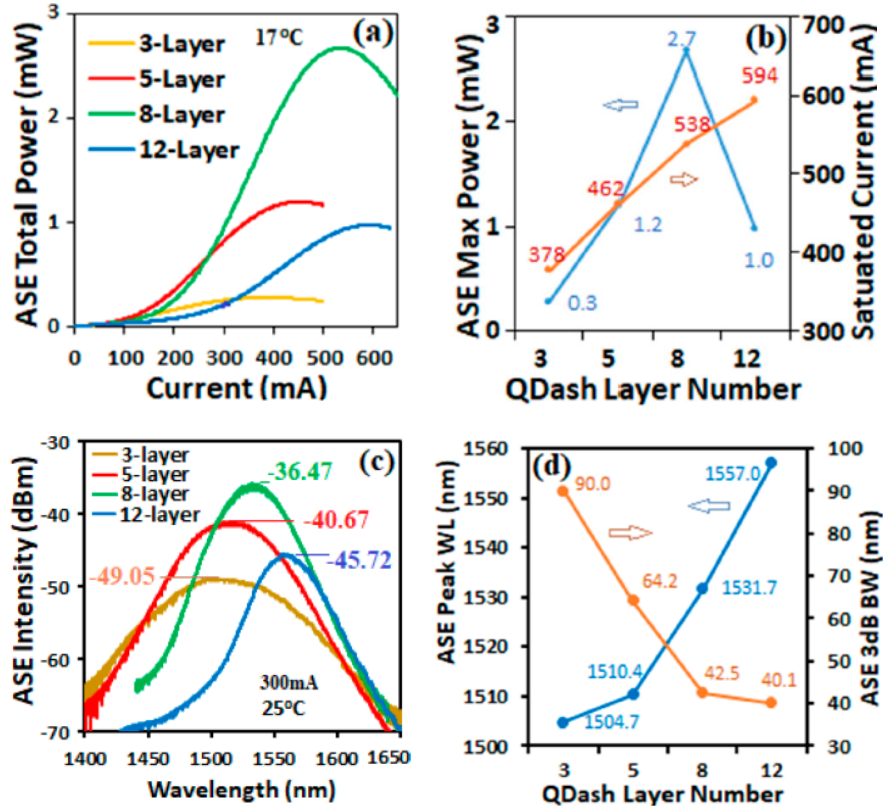


Figure 5.18. (a) ASE total output power of the SOAs versus bias current for the different numbers of QD layers in the active region. (b) The maximum ASE power (left axis) and saturated current (right axis) versus QD layer number. (c) ASE spectra at a bias current of 300 mA and 25 °C with peak powers indicated in dBm. (d) ASE peak wavelength (left axis) and 3 dB bandwidth (right axis) versus number of QD layers.

Figure 5.18(a) shows the dependence of total ASE output power on bias current for SOAs incorporating 3-, 5-, 8-, and 12-layers of QD in the active region, measured at 17 °C. The measurements were performed using a large-area photodetector to capture all emitted light. As shown on the left axis of Figure 5.18(b), the maximum ASE output increased steadily as the number of QD layers rose from three to eight, but declined once the layer count reached twelve. In contrast, the saturated bias current corresponding to the peak output power, plotted on the right axis of Figure

5.18 (b), exhibited an almost linear increase with the number of QD layers.

Figure 5.18(c) presents the ASE spectra of the SOA devices measured at a bias current of 300 mA and a temperature of 25 °C. The peak output powers, highlighted in the figure, increase progressively as the number of QD layers is raised from three to eight, before declining when the layer count reaches twelve. This variation follows the same trend observed in the maximum total ASE power, confirming a strong correlation between spectral peak behavior and overall ASE output.

Figure 5.18(d) shows the evolution of the ASE peak wavelengths as the number of QD layers increases. The peaks progressively red-shift from 1504.7 nm (3 layers) to 1510.4 nm (5 layers), 1531.7 nm (8 layers), and 1557.0 nm (12 layers). This shift can be attributed to the reduction in carrier density per layer when more QD layers are incorporated, since the total bias current was kept constant during measurement. At higher carrier densities, the higher energy states of the QDs are occupied, which enhances gain at shorter wavelengths and produces a blueshift accompanied by spectral broadening. Conversely, as the carrier density per layer decreases, the ASE peak moves toward longer wavelengths and the spectrum narrows. This trend is clearly observed in the 3-dB ASE bandwidth, which contracts from 90.0 nm to 64.2 nm, 42.5 nm, and 40.1 nm as the number of layers rises from 3 to 12.

Figure 5.19(a) shows the chip gain as a function of input optical power for the SOAs containing 3-, 5-, 8-, and 12-layers of QD, each measured at its respective peak gain wavelength. From these measurements, the small-signal chip gain and the 3-dB saturated output power were extracted, with the results plotted against the number of QD layers in Figure 5.19(b) and (c), respectively.

The QD-SOA with 3-layers produced a small-signal chip gain of 18.9 dB, which was modest, but it delivered the highest 3-dB saturated output power at 18.2 dBm. Adding more layers substantially changed the balance between these two parameters. With 5-layers, the gain increased sharply to 25.4 dB, though the output power dropped to 15.2 dBm. The 8-layer device provided the highest gain, reaching 26.4 dB, while its saturated output power continued to fall, reaching 12.6 dBm. In contrast, the twelve-layer SOA showed a reduced gain of 21.9 dB, coupled with the lowest 3-dB saturated output power of 11.7 dBm.

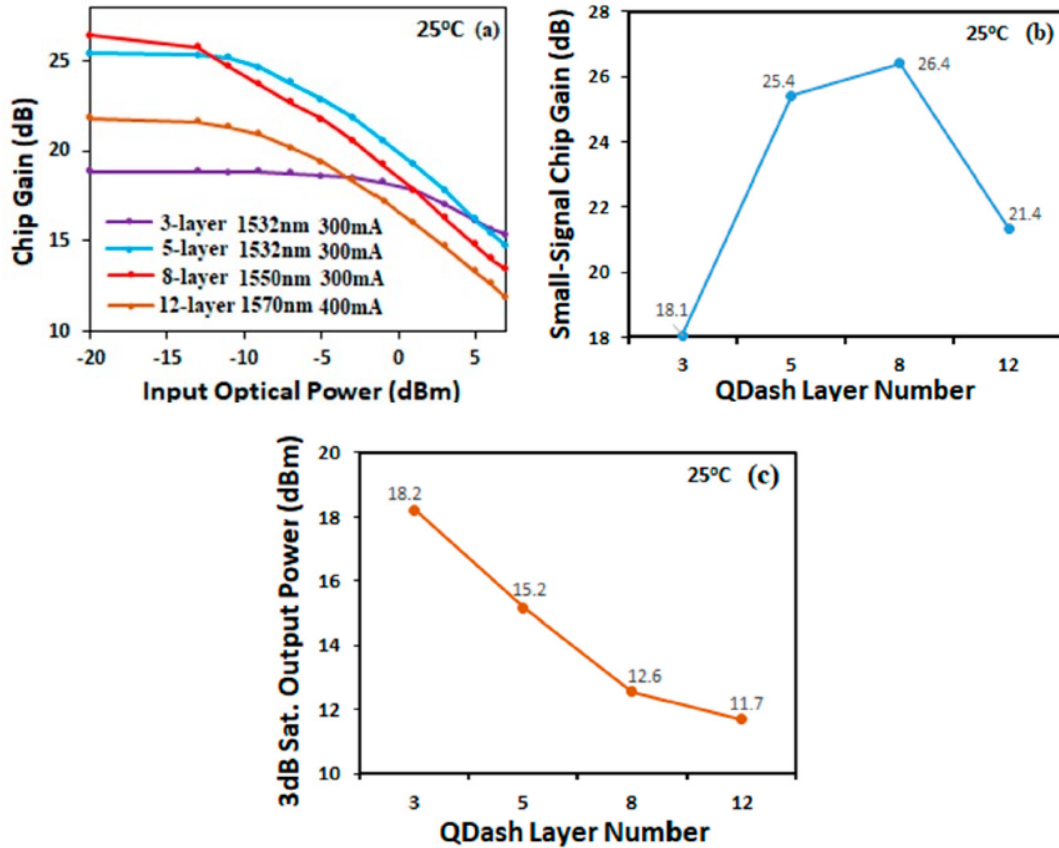


Figure 5.19. (a) SOA chip gain as a function of input optical power for the four different QD devices at 25 °C at the indicated wavelength and current, (b) small-signal chip gain and (c) 3 dB saturated output power vs. number of QD layers.

Because of the high gain achieved, the NF of the QD-SOAs is dominated by signal-spontaneous beat noise. Figure 5.20(a) presents the measured NF as a function of input optical

power for devices with different numbers of QD layers, each operated at its respective peak wavelength and bias current. The data reveal that the NF generally increases as the number of QD layers rises, both under small-signal and large-signal conditions, with the increase being more pronounced at higher input powers. For instance, in the 3-layer SOA, the NF increased modestly by only 0.6 dB, from 5.5 dB to 6.1 dB, as the input power was raised from -13 dBm to 7 dBm. In contrast, the 12-layer SOA exhibited a larger rise of 1.1 dB, from 7.3 dB to 8.4 dB, over the same input power range, as shown in Figure 5.20(b).

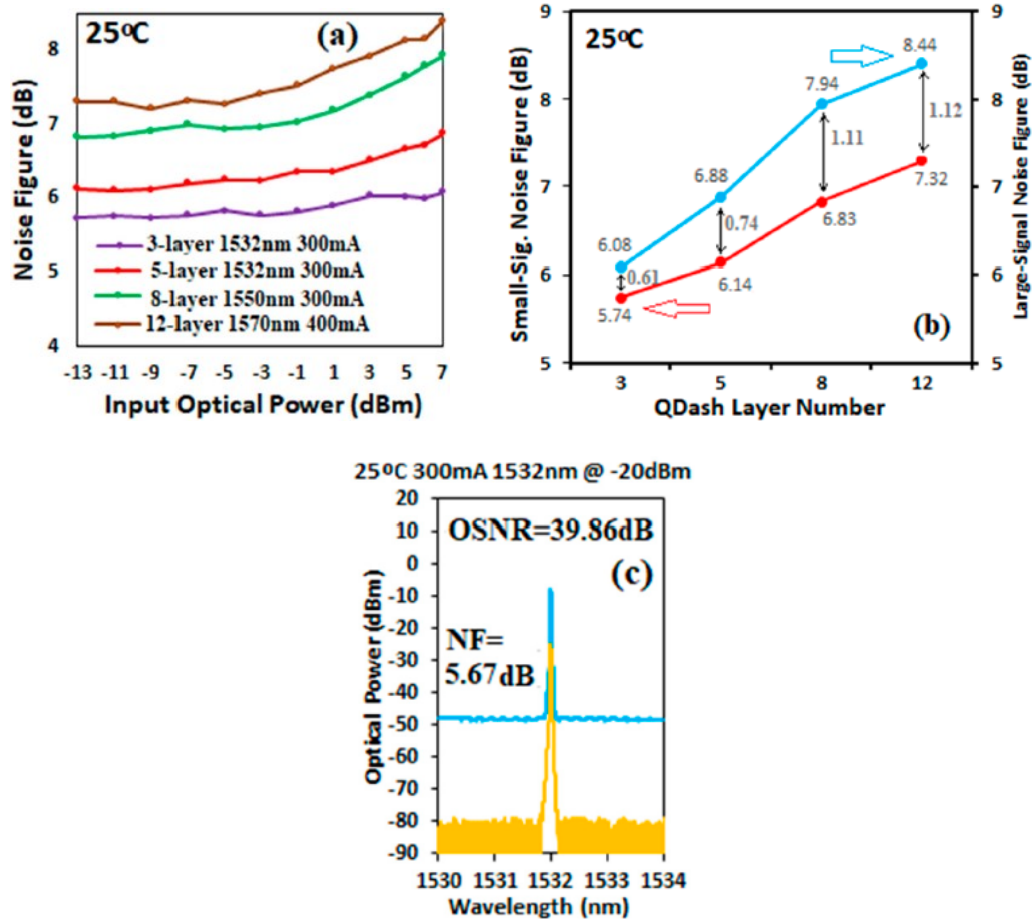


Figure 5.20. (a) NF as a function of input power for SOAs with different numbers of QD layers at 25 ° C and specific measurement wavelengths and bias currents. (b) Small-signal NF at -13 dBm (left axis) and large-signal NF at 7 dBm (right axis) for SOAs versus QD layer number. (c) Spectra of input laser source (yellow) and output SOA (blue) measured at 1532 nm, 300 mA, and 25 ° C for a 5-layer SOA.

The QD-SOAs demonstrated here exhibit lower NF values compared with QW-SOAs previously reported in [95]. To further assess performance, the InAs/InP QD-SOA investigated in this study was benchmarked against the device reported in [96]. Figure 5.20(c) presents the spectra of the input tunable laser and the output from the QD-SOA under -20 dBm input power, a wavelength of 1532 nm, a bias current of 300 mA, and a device temperature of 25 °C. Under these conditions, the measured OSNR and NF were 39.9 dB and 5.7 dB, respectively. In comparison, the device in [96] achieved an OSNR of 34.3 dB and an NF of 4.8 dB under nearly identical test conditions. It is worth noting, however, that the NF values in [96] were calculated without accounting for polarization effects, while the present measurements employed polarization-maintaining fibres. When a correction factor of 2 is applied to their NF result, the QD-SOA investigated here provides an OSNR advantage of 5.5 dB relative to the device in [96].

5.3.3 Discussion of the Influence of QD Layers

A set of 1500-nm InAs/InP QD-SOAs targeting both the C- and L-bands was investigated, with devices fabricated using 3, 5, 8, and 12 stacked QD layers. Their overall characteristics, including ASE spectra, gain, bandwidth, and noise figure, were systematically compared. The 8-layer QD-SOA delivered the highest performance in terms of chip gain, reaching 26.4 dB at 1550 nm under a 300 mA bias at 25 °C. The 3-layer device, by contrast, exhibited the broadest 3-dB bandwidth of 90 nm, together with a saturated output power of 18.2 dBm and a low NF of 5.7 dB in the shorter-wavelength range. The 12-layer QD-SOA offered a small-signal gain of 21.8 dB and extended the operational spectrum into the L-band, highlighting the trade-offs between gain, bandwidth, and wavelength coverage as the number of QD layers increased.

Chapter 6 QD Gain Medium Based mmWave Front Haul Transmission System

In this chapter, QD-MLLs and QD-SOAs are jointly employed in a heterodyne-detected mmWoF fronthaul transmission system. The ultimate objective is to replace all EDFAs used in Figure 3.1, Figure 3.3, and Figure 4.1 with QD-SOAs. Due to limitations in the experimental setup, this goal is pursued step by step. In Section 6.1, a five-layer QD-SOA is used to replace a single EDFA in a single-channel system. In Section 6.2, both EDFAs are replaced with an eight-layer QD-SOA. Finally, in Section 6.3, the QD-SOA is evaluated in a multiplexed system.

6.1 Step One: One EDFA is Replaced

6.1.1 System Setup

To assess the communication performance of the QD-SOA, it was integrated into the mmWoF link shown in Figure 6.1. A 29-GHz spaced multi-wavelength QD-MLL, identical to the source described in [37], served as the laser. The comb lines were separated using a wave shaper (II-VI 16000A), which extracted λ_1 at 1543.476 nm and λ_2 at 1543.248 nm into two distinct branches. λ_1 was boosted by OA₁ and modulated with an SHF-46215B I/Q MZM driven by QAM or OFDM signals generated by a Keysight M8195A arbitrary waveform generator. A delay line was inserted into the λ_2 branch to ensure equal optical path lengths for both carriers. The two branches were then recombined by a 50/50 OC and amplified by OA₂. The amplified output was fed into the QD-SOA, followed by heterodyne detection using a New Focus 1014 photodetector. The resulting mmWave RF signal was further amplified and transmitted across a 2-m wireless link before being captured and analyzed on a Tektronix DPO73304SX oscilloscope.

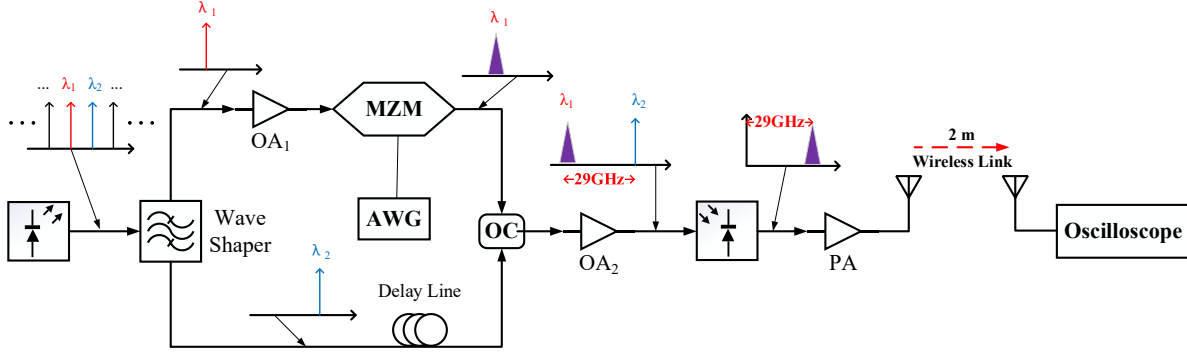


Figure 6.1. The block diagram of the mmWave over fibre system with one QD-SOA.

In principle, both OA_1 and OA_2 in this system could be replaced with QD-SOAs. However, due to constraints in the available test bed, only one QD-SOA could be integrated at a time. Accordingly, two experimental configurations were examined: in the first, OA_1 was replaced with a QD-SOA while OA_2 remained an EDFA (Amonics AEDFA-PA-35-B-FA); in the second, OA_2 was replaced with a QD-SOA while OA_1 was retained as an EDFA.

When OA_1 is replaced by the QD-SOA, its fundamental functionality and compatibility within the system are confirmed. This configuration further demonstrates that the QD-SOA does not introduce additional phase noise or degrade the coherence between the two comb lines, ensuring stable system operation.

When OA_2 is replaced with the QD-SOA, its low cross-gain and cross-phase modulation characteristics can be directly evaluated. In this scenario, the optical input signal at the time domain of OA_2 is more complex, as it already contains modulated channels. The QD-SOA must therefore amplify these signals without introducing significant distortion or inter-channel interference, thereby partially confirming its suitability for multi-channel operation. To prove this, here is the mathematical explanation: from Equation (2-15), it is simplified as:

$$E(t) = I(t) \sin(\omega_{o1}t + \varphi_1(t)) + Q(t) \cos(\omega_{o1}t + \varphi_1(t)) + \cos(\omega_{o2}t + \varphi_2(t)) \quad (6-1)$$

where $I(t)$ and $Q(t)$ are the base band I/Q signals, ω_{01} corresponds to the wavelength of λ_1 , and $\varphi_1(t)$ and $\varphi_2(t)$ are the phase noises of carriers λ_1 and λ_2 . Here, it is assumed that there is no amplitude noise to simplify the calculation. The intensity $P_2(t)$ of the signal at λ_1 is:

$$P_2(t) = \sqrt{I^2(t) + Q^2(t)} \quad (6-2)$$

In the SOA, cross-gain modulation inevitably occurs. Since λ_2 is a CW laser without amplitude noise, it does not itself generate cross-gain or cross-phase modulation. However, it will be affected by the power fluctuation of $P_2(t)$. The affected CW laser at λ_2 will be:

$$G^{\frac{1}{2}} \times \sum_{n=0}^{\infty} a_n P_2^n(t) \cos \left(2\pi\omega_2 t + \varphi_2(t) + \sum_{m=0}^{\infty} b_m P_2^m(t) \right) \quad (6-3)$$

where G is the constant gain of QD-SOA, a_n is the coefficient of n -th order cross-gain modulation, b_m is the coefficient of the m -th order cross-phase modulation. At the ORx, the combined signal is power-detected. The component located around the mmWave band will be:

$$\begin{aligned} & \frac{G \times \sum_{n=1}^{\infty} a_n P_2^n(t)}{2} \left(Q(t) \cos \left(2\pi(\omega_2 - \omega_1)t + \varphi_2(t) - \varphi_1(t) + \sum_{m=0}^{\infty} b_m P_2^m(t) \right) \right. \\ & \quad \left. - I(t) \sin \left(2\pi(\omega_2 - \omega_1)t + \varphi_2(t) - \varphi_1(t) + \sum_{m=0}^{\infty} b_m P_2^m(t) \right) \right) \end{aligned} \quad (6-4)$$

Since the laser source is a QD-MLL, the phase noises $\varphi_1(t)$ and $\varphi_2(t)$ effectively cancel each other. However, the amplitude noise and the phase noise introduced through cross-gain and cross-phase modulation persist in the system, which degrades overall performance. The reported QD-SOA exhibits only weak nonlinear effects and, therefore, provides adequate performance for this application.

6.1.2 System Results

Firstly, OA_1 is replaced by QD-SOA, i.e., before the MZM. The device was maintained at 20 °C and biased at 380 mA. At λ_1 (1543.476 nm), the input power into the QD-SOA was -9.50 dBm, resulting in a total output power of 5.85 dBm, corresponding to a gain of 14.35 dB. However, the MZM used in this system introduced a high insertion loss of approximately 10 dB and exhibited a low modulation index. As a result, the power of the modulated signal after the MZM was reduced to -15.70 dBm, leading to relatively poor system performance. OA_2 , implemented with an EDFA, provided a gain of 21.41 dB. Using this setup, baseband signals with 16-QAM and 64-QAM modulation formats were transmitted at symbol rates of up to 6 GBaud, achieving a maximum bitrate of 32 Gb/s with a 4-GBaud 64-QAM signal.

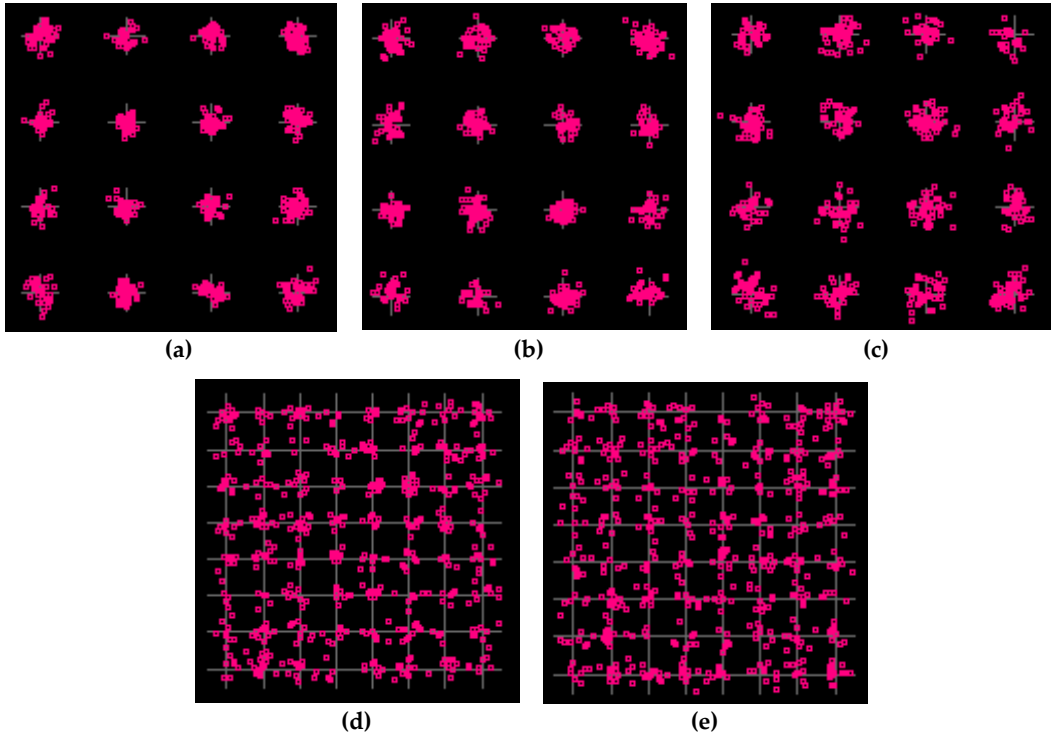


Figure 6.2. The constellation of received signal of (a) 16-QAM 2 Gbaud, (b) 16-QAM 4 Gbaud, (c) 16-QAM 6 Gbaud, (d) 64-QAM 2 Gbaud, and (e) 64-QAM 4 Gbaud.

The received signal constellations are presented in Figure 6.2. For 16-QAM transmission,

the EVM values were measured as 7.19%, 8.09%, and 10.20% at symbol rates of 2 GBauds, 4 GBauds, and 6 GBauds, respectively. In the case of 64-QAM, the corresponding EVM values were 7.77% and 8.75% for 2 GBauds and 4 GBauds.

To further assess the capability of the QD-SOA-based mmWoF system, OFDM signals were also transmitted. The overall bandwidth was 250 MHz, with each subcarrier occupying 4 MHz. The resulting constellations are shown in Figure 6.3. The measured EVMs were 7.27% for 16-QAM OFDM and 7.35% for 64-QAM OFDM. Both values satisfy the 3GPP 5G EVM requirements reported in [1].

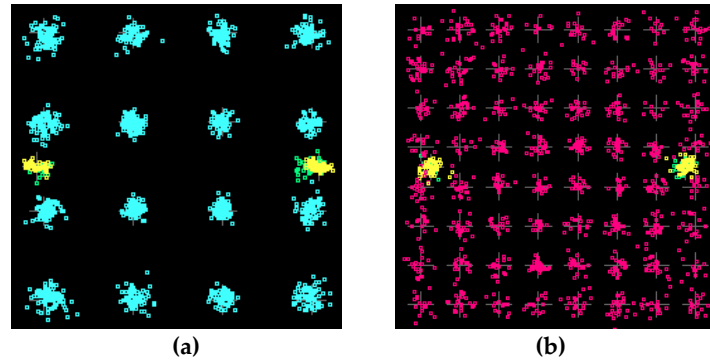


Figure 6.3. The constellation of the received signal of (a) 16-QAM OFDM and (b) 64-QAM OFDM.

Secondly, the OA_2 is replaced by QD-SOA, which is located after the OC. In this case, the QD-SOA was maintained at 20 °C and biased at 380 mA. The input optical power at λ_1 was -13.41 dBm, and the total output power reached 1.36 dBm, corresponding to a gain of approximately 14.77 dB. An EDFA was employed as OA_2 , providing a gain of 24.41 dB. As a result, the input power to the MZM was 14.91 dBm, which was sufficiently high to ensure better system performance. As in the earlier configuration, 16-QAM and 64-QAM baseband signals were transmitted at symbol rates up to 6 GBaud, achieving a maximum bitrate of 32 Gb/s with a 4 GBauds 64-QAM signal.

The constellations of the received signals are shown in Figure 6.4. For 16-QAM, the

measured EVM values were 6.48%, 7.93%, and 8.12% at 2 GBauds, 4 GBauds, and 6 GBauds, respectively. For 64-QAM, the EVM values were 6.62% and 8.29% at 2 GBauds and 4 GBauds.

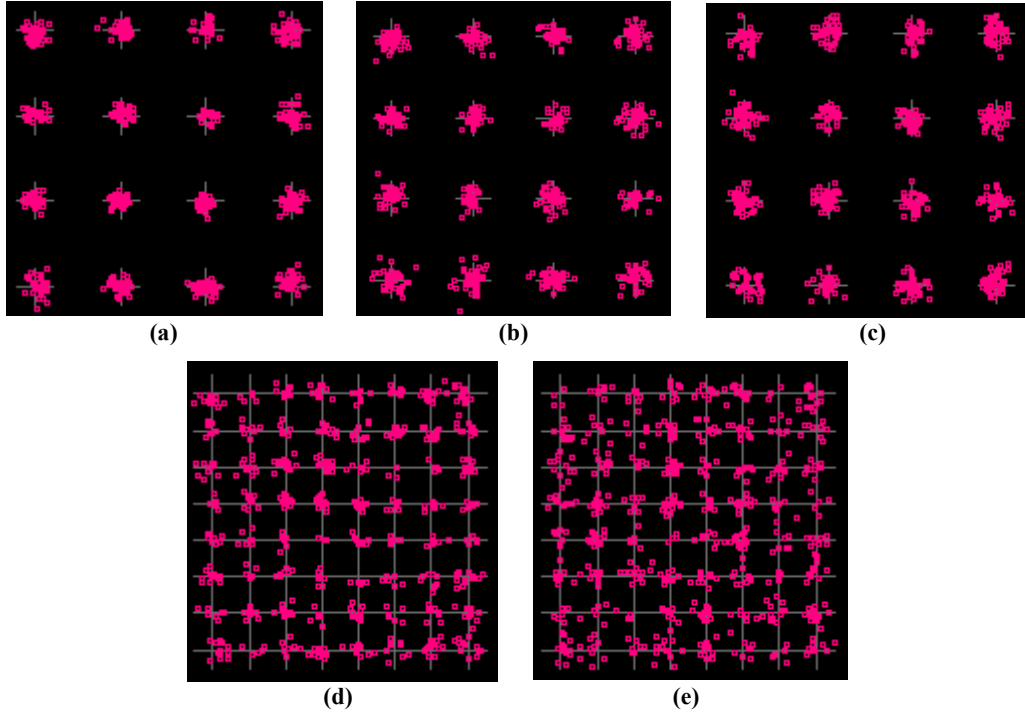


Figure 6.4. The constellation of received signal of (a) 16-QAM 2 GBauds, (b) 16-QAM 4 GBauds, (c) 16-QAM 6 GBauds, (d) 64-QAM 2 GBauds, and (e) 64-QAM 4 GBauds.

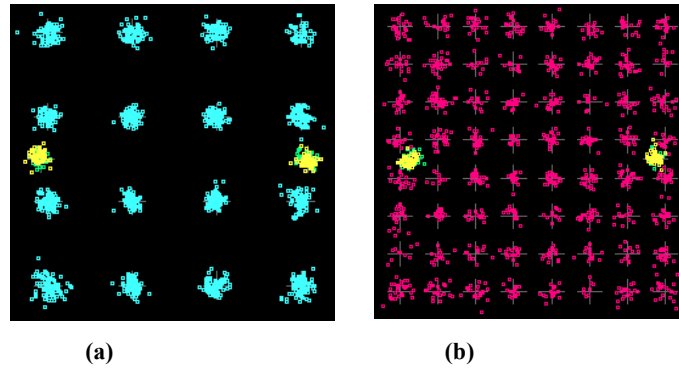


Figure 6.5. The constellation of the received signal of (a) 16-QAM OFDM and (b) 64-QAM OFDM.

To further evaluate the performance of the QD-SOA-based mmWoF system, OFDM transmission was also carried out. The total signal bandwidth was 250 MHz, with each subcarrier occupying 4 MHz. The constellations of the received signals are shown in Figure 6.5. The measured

EVMs were 7.27% for 16-QAM OFDM and 7.35% for 64-QAM OFDM, both of which satisfy the 3GPP 5G EVM requirements specified in [1].

To further assess long-distance performance, a 10-km SMF link was incorporated into the system. After transmission over 10 km of SMF followed by a 2-m wireless link, the measured EVMs for 16-QAM signals were 7.52% at 2 GBauds and 9.36% at 4 GBauds. For OFDM transmission, the EVM values after 10 km of SMF were 7.91% for 16-QAM and 8.33% for 64-QAM. These results demonstrate that the QD-SOA is capable of maintaining satisfactory performance in long-reach mmWoF fronthaul transmission systems.

6.1.3 Discussion of Step One

In this section, the QD-SOA was applied to an mmWoF system. Due to limitations of the measurement setup, only one QD-SOA could be inserted into the system at a time, either in the OA₁ or OA₂ position. Compared with the EDFA-only system, the QD-SOA delivered comparable performance. For instance, in the case of a 4-GBaud 16-QAM signal, the EVM of the EDFA-only system was reported as 8.03% [37], while the QD-SOA configuration achieved an EVM as low as 8.29%. Similarly, for a 16-QAM OFDM signal, the EVM was 6.69% with the EDFA-only system, whereas it was 6.78% when employing the QD-SOA.

These results demonstrate that the QD-SOA can effectively replace an EDFA at any position within the link. The device maintained satisfactory performance across different modulation formats, with EVM values consistently below the 3GPP requirements for 5G fronthaul transmission. Overall, the measurements highlight the strong potential of QD-SOAs for deployment in mmWoF systems, particularly if integrated into a photonic chip-based fronthaul architecture.

6.2 Step Two: Both EDFAs are Replaced

In this section, all the optical amplifiers in Figure 3.1 and Figure 3.3 are replaced with 8-layer QD-SOAs. As discussed in Section 5.3, the peak gain of the 8-layer QD-SOA lies closer to 1550 nm. Although its NF is approximately 0.5 dB higher than that of the five-layer QD-SOA, the overall performance of the eight-layer device is superior when used in conjunction with the QD-MLL. Since two QD-SOAs are required in this system, it is not feasible to mount both on the test bed shown in Figure 5.2(b). Therefore, one of the 8-layer QD-SOAs was packaged in a 14-pin butterfly module, as illustrated in Figure 6.6, while the other remained on the test bed shown in Figure 5.2(b). The packaged QD-SOA offers higher stability; however, its facet insertion losses are greater compared to the device mounted directly on the test bed.

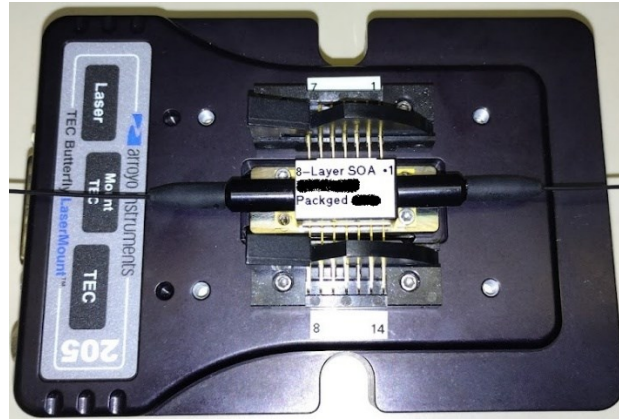


Figure 6.6. Packaged 8-layer QD-SOA in 14-pin butterfly form.

6.2.1 QD-SOAs Integrated I/Q MZM Based mmWoF Fronthaul Transmission System

The setup of the QD-SOAs with I/Q MZM based mmWoF fronthaul transmission system is the same as Figure 6.1. The OA₁ of Figure 6.1 is replaced by an 8-layer QD-SOA located on top of the test bed, and the OA₂ is replaced by a packaged 8-layer QD-SOA. The OA₁ will require a

higher gain due to the high insertion loss of the I/Q MZM modulator.

The packaged QD-SOA was maintained at 15 °C and biased at 450 mA. At λ_1 (1543.476 nm), the input power into the QD-SOA was -9.72 dBm, resulting in a total output power of 7.85 dBm, corresponding to a gain of 17.57 dB. However, the MZM used in this system introduced a high insertion loss of approximately 10 dB and exhibited a low modulation index. As a result, the power of the modulated signal after the MZM was reduced to -7.31 dBm, leading to relatively poor system performance. OA₂, implemented with the QD-SOA on the test bed, provided a gain of 12.67 dB. Using this setup, baseband signals with 16-QAM modulation formats were transmitted at symbol rates of up to 2 GBaud, achieving a maximum bitrate of 8 Gb/s.

The constellation of the received signal is shown in Figure 6.7. For 16-QAM signal, the EVM of the received signal is 8.41% and 11.03% for 1 Gbauds and 2 Gbauds, respectively.

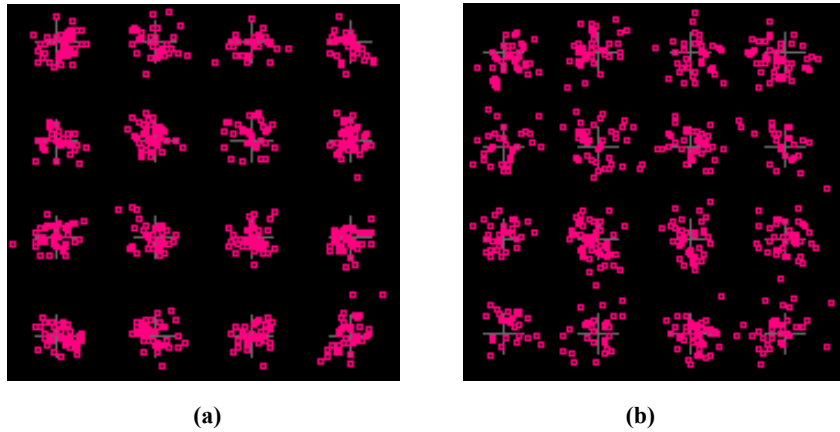


Figure 6.7. The constellation of received signal of (a) 16-QAM 1 Gbauds, (b) 16-QAM 2 Gbauds.

The performance of the I/Q-MZM-based mmWoF fronthaul transmission system was limited. This is primarily due to the relatively low gain of the QD-SOAs compared with EDFAs. In such systems, the amplifier gain must be sufficiently high to compensate for the considerable insertion loss of the I/Q MZM. Consequently, only BtB experiments were carried out in this

configuration. Nevertheless, these results still validate the concept that QD-SOAs can be effectively employed in mmWoF fronthaul transmission systems.

6.2.2 QD-SOAs Integrated SSB-MZM Based mmWoF Fronthaul Transmission System

The block diagram of QD-SOAs with SSB-MZM based mmWoF fronthaul transmission system is similar to Figure 3.3. The only difference is that the EDFAs are replaced by QD-SOAs, as shown in Figure 6.8.

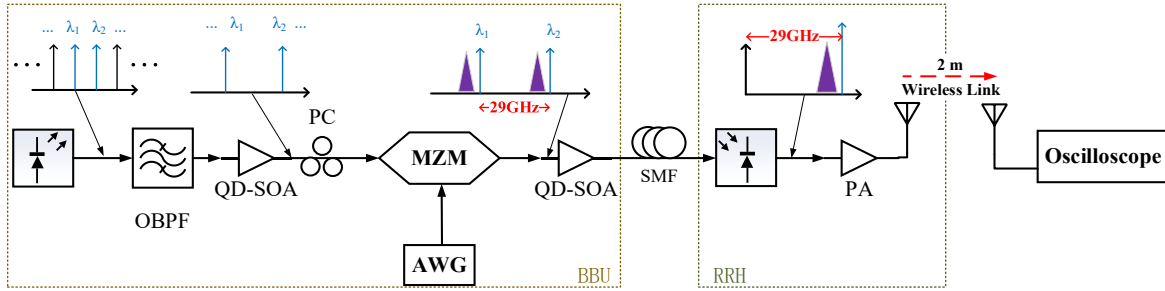


Figure 6.8. Block diagram of QD-SOAs integrated SSB-MZM based mmWoF system.

The first QD-SOA in Figure 6.8, positioned in front of the polarization controller, is an 8-layer QD-SOA situated on top of the test bed. The second QD-SOA in Figure 6.8, located after the SSB-MZM, is replaced by a packaged 8-layer QD-SOA. The first optical amplifier will require higher gain due to the relatively high insertion loss of the SSB-MZM modulator.

The same as Section 6.1, the packaged QD-SOA was maintained at 15 °C and biased at 450 mA. At λ_1 (1543.476 nm), the input power into the QD-SOA was -7.11 dBm, resulting in a total output power of 9.64 dBm, corresponding to a gain of 16.75 dB. The power of the modulated signal after the SSB-MZM was reduced to 2.17 dBm, leading to relatively poor system performance. The second QD-SOA, implemented with the QD-SOA on the test bed, provided a gain of 13.15 dB. Using this setup, baseband signals with 16-QAM modulation formats were transmitted at symbol rates of up to 2 GBauds, achieving a maximum bitrate of 8 Gb/s.

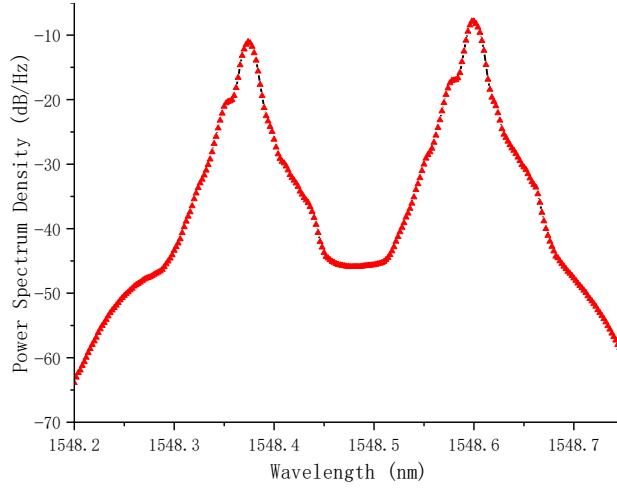


Figure 6.9. Optical spectrum at the ORx.

The optical spectrum at the ORx is shown in Figure 6.9, and the constellation of the received RF signal is shown in Figure 6.10. For 16-QAM signal, the EVM of received signal is 6.73% and 8.97% for 1 Gbauds and 2 Gbauds, respectively.

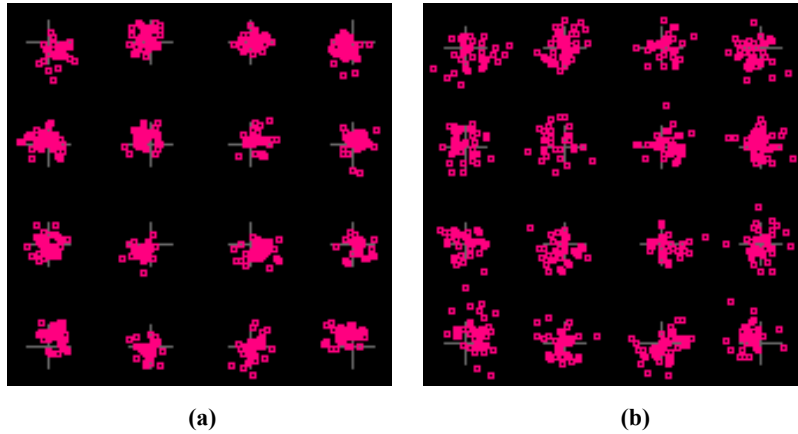


Figure 6.10. The constellation of received signal of (a) 16-QAM 1 Gbauds, (b) 16-QAM 2 Gbauds.

Since the received optical signal is better than the performance of I/Q MZM based system, 10 km of SMF transmission is added to the mmWoF link. The constellation of the received RF signal is shown in Figure 19. For 16-QAM signal, the EVM of received signal is 8.92% and 10.66% for 1 Gbauds and 2 Gbauds, respectively.

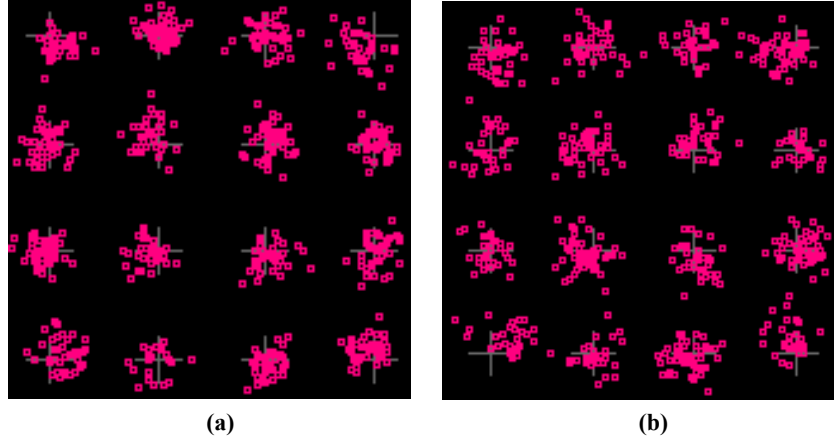


Figure 6.11. The constellation of received signal of (a) 16-QAM 1 Gbaud, (b) 16-QAM 2 Gbaud.

The performance of the mmWoF fronthaul transmission system based on QD-SOAs and an SSB-MZM is superior, primarily due to the lower insertion loss of the SSB-MZM compared with the I/Q MZM. However, noticeable nonlinearities are present in the received signal. This is mainly because the SSB-MZM was not biased at the quadrature point, which was done to increase modulation efficiency, but in turn introduced nonlinear distortion. The current results, therefore, represent a compromise between achieving higher signal power spectral density and limiting nonlinear effects.

6.2.3 Discussion of Step Two

These results demonstrate that QD-SOAs can be employed in fronthaul transmission systems as replacements for EDFAs. Owing to their compact size, QD-SOAs also offer the potential for integration into wire-bonded photonic chips. However, at the current stage, the gain of the 8-layer QD-SOAs remains lower than required. As a result, when applied in I/Q MZM based mmWoF fronthaul transmission systems, the performance is poor and not suitable for commercial deployment. In contrast, when QD-SOAs are used in SSB-MZM based mmWoF fronthaul transmission systems, better performance is achieved, as confirmed after transmission over 10 km of SMF. A summary of the results is provided in Table 6.1.

Table 6.1 The EVM (%) of the received signal in different QD-SOA based mmWoF system

	I/Q MZM	SSB-MZM	
	BtB	BtB	10 km SMF
16-QAM 1 GBauds	8.41%	6.73%	8.92%
16-QAM 2 GBauds	11.03%	8.97%	10.66%

6.3 Step Three: Using QD-SOA in Frequency Multiplexed mmWoF System

To further demonstrate the possibility of the QD-SOA, it was deployed in the frequency-multiplexed mmWoF system described in Chapter 4. However, due to laboratory limitations, only a single QD-SOA was integrated into the setup, as shown in Figure 6.12.

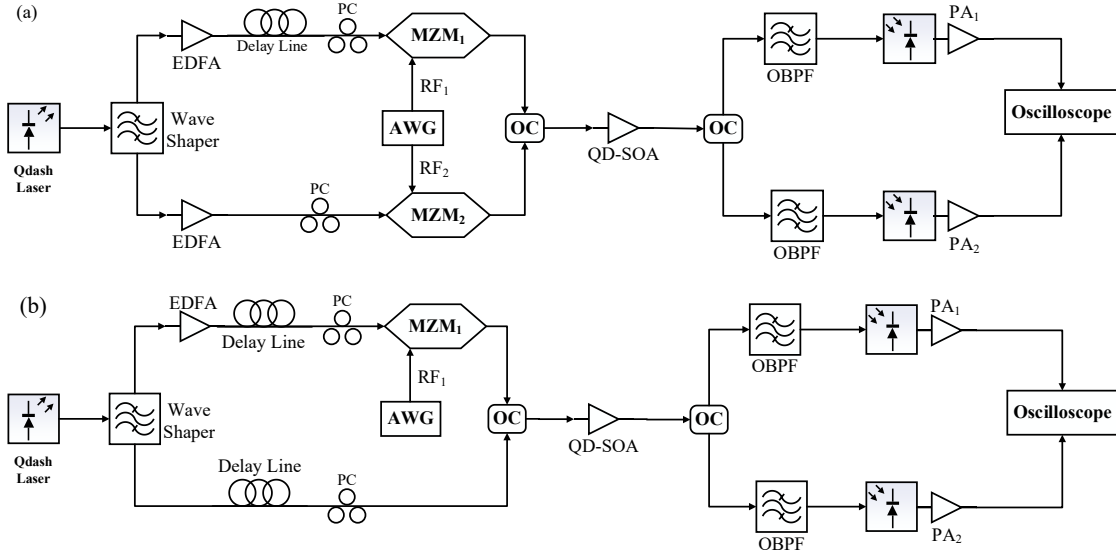


Figure 6.12. Block diagram of QD-SOA integrated frequency multiplexing *Technique 3* is shown on (a), *Technique 4* is shown on (b).

Another limitation arises from the relatively low gain of the QD-SOA, which restricts its use to *Techniques 3* and *4*, as these offer the highest power efficiency. Although only two multiplexing techniques could be experimentally verified with the QD-SOA, the results

nevertheless demonstrate its feasibility for use in frequency multiplexed mmWoF fronthaul transmission systems, particularly in dense wavelength-division multiplexing (DWDM) scenarios.

6.3.1 *Technique 3* with QD-SOA

The detailed setup of *Technique 3* is described in Section 4.1.3. In this approach, only two carriers, λ_1 and λ_2 , are employed. Each carrier is modulated using SSB with RF_1 and RF_2 , respectively, as illustrated in Figure 4.4(b) and (c). The RF signals (RF_1 and RF_2) are the same as those used in *Techniques 1* and *2*, shown in Figure 4.4(a) and (b). The combined optical signal is then transmitted through a SMF, as depicted in Figure 4.4(e), and subsequently demultiplexed using two optical filters, shown in Figure 4.4(f) and (g).

Similar to the previous techniques, the optical filters can partially remove unnecessary carriers and signals, although some cross-talk may persist. This cross-talk represents a significant drawback of this technique. Following heterodyne detection, two mmWave signals are generated, as illustrated in Figure 4.4(h) and (i). Finally, the two signals are analyzed using an oscilloscope. However, due to some of the unnecessary frequency components being too close to the passband of the PAs, cross-talk may persist.

Similar to Section 4.2.3, *Technique 3* also employs RF_1 and RF_2 signals. In the BtB optical system, the received optical powers of Channel 1 and Channel 2 were measured at 0.85 mW and 0.71 mW, respectively. The corresponding EVM values were calculated as 9.4% for Channel 1 and 8.8% for Channel 2. The eye diagrams and constellation plots of the received signals are shown in Figure 6.13. Similar to Section 4.2.3, Channel 1 exhibits worse performance than Channel 2. As shown in Figure 4.10(b), the presence of residual carriers and undesired signals occupies a significant portion of the optical power, lowering the power spectral density of the desired

mmWave signal after heterodyne detection and thereby degrading Channel 1's performance. In contrast, most of the unwanted carriers and signals in Channel 2 can be effectively suppressed by an optical filter, resulting in better performance.

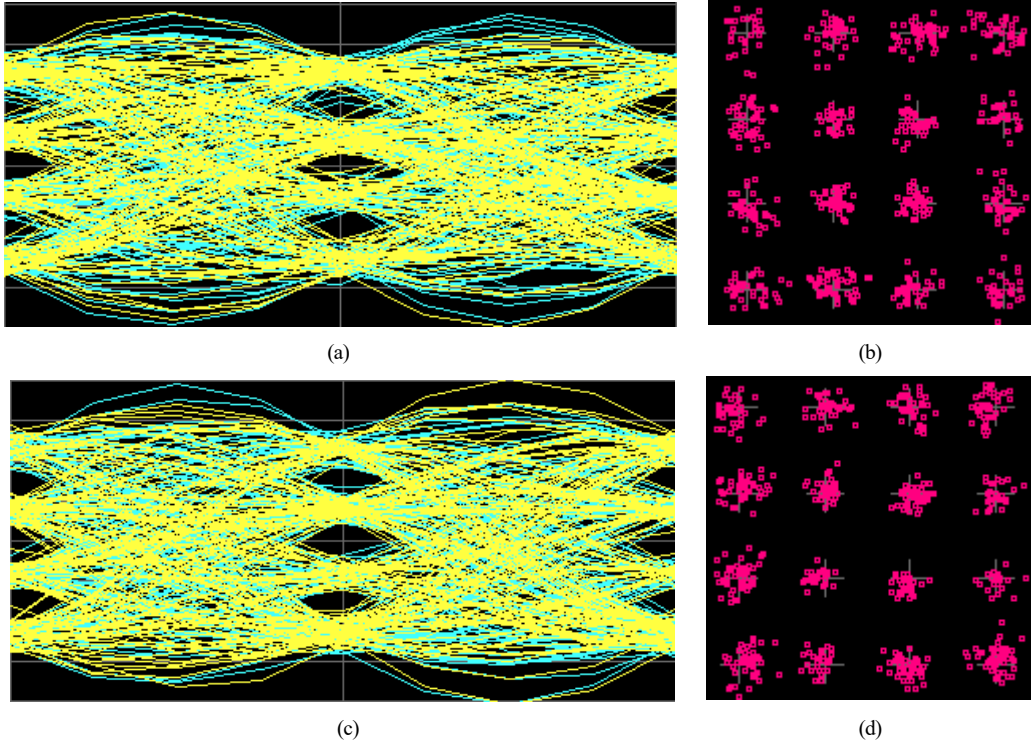


Figure 6.13. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

6.3.2 *Technique 4* with QD-SOA

The setup is the same as Section 4.1.4, except the QD-SOA is used instead of EDFA. As shown in Figure 4.5(c), the two solid blue lines represent the selected non-adjacent comb lines, while the dashed line indicates the intermediate comb lines that are suppressed. This comb line selection process is identical to that in Section 4.1.4 and cannot be realized with a standard optical filter; instead, it requires a customized fibre Bragg grating or a wave shaper. In *Technique 4*, MZM must be configured as an I/Q modulator. The RF_1 signal consists of two QAM signals at 6 GHz

and 12 GHz, as shown in Figure 4.5(a). These two RF signals are combined into an I/Q format and then modulated by MZM as illustrated in Figure 4.5(b). The resulting modulated signal is subsequently combined with the optical carrier and transmitted through the SMF.

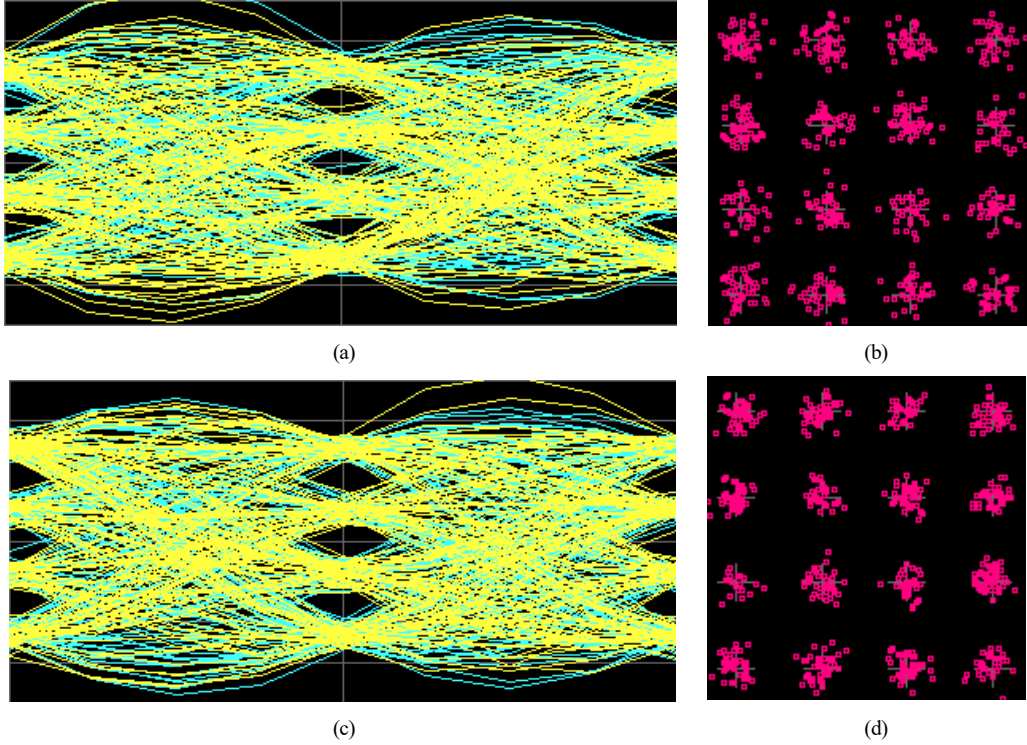


Figure 6.14. The eye diagram (a) and constellation (b) of the received mmWave signal at 34 GHz. And the eye diagram (c) and constellation (d) of the received mmWave signal at 24 GHz.

At the receiver, the two demultiplexed optical signals are separated using an OC and an optical filter, as shown in Figure 4.5(e) and (f). With a frequency spacing of 18 GHz, the two signals are well isolated, and crosstalk is effectively suppressed. Following heterodyne detection, the corresponding electrical spectra are obtained, as illustrated in Figure 4.5(g) and (h). The recovered signals are then evaluated using an oscilloscope.

The received optical power is measured at 0.46 and 0.52 mW for channel 1 and 2 in the BtB setup. The performance is also excellent, with an EVM of 9.7% and 7.8% for channel 1 and 2, respectively. The eye diagrams and constellations of both channels are depicted in Figure 6.14.

6.3.3 Discussion of Step Three

In this section, a QD-SOA was incorporated into the frequency-multiplexed mmWoF fronthaul transmission system. The results indicate that all measured values satisfy the 5G requirements specified by 3GPP. Unlike the results in Chapter 4, however, *Technique 4* does not provide the best performance when a QD-SOA is employed. This limitation arises from the combined effects of the high insertion loss of the I/Q MZM and the relatively low gain of the QD-SOA. If an SOA or EDFA with both high gain and low crosstalk were used instead, the performance would be comparable to that reported in Chapter 4.

6.4 Summary and Discussion of QD Gain Medium Based mmWave Front Haul Transmission System

The experimental evaluation demonstrates the feasibility of employing QD-SOAs in mmWoF fronthaul transmission systems as replacements for EDFAs. When integrated into both single-channel and frequency-multiplexed configurations, the QD-SOA maintained adequate performance, with EVMs consistently within the 5G requirements specified by 3GPP. These results validate their potential for use in DWDM fronthaul systems.

However, the relatively low gain of the current 5- or 8-layer QD-SOAs presents limitations. In I/Q-MZM based systems, the high insertion loss of the modulator combined with the insufficient amplifier gain led to poor performance, restricting tests to back-to-back configurations. In contrast, better results were obtained in SSB-MZM based systems, owing to the lower insertion loss, with successful transmission verified over 10 km of SMF. Furthermore, in frequency-multiplexed setups, *Techniques 3* and *4* could be realized, though *Technique 4* no longer exhibited the best performance due to the amplifier's gain limitation.

Overall, these experiments demonstrate that QD-SOAs are promising candidates for replacing EDFAs in mmWoF fronthaul transmission systems, offering advantages in compactness, energy efficiency, and potential for photonic integration. Future improvements in QD-SOA design, particularly higher gain and reduced noise, are expected to unlock their full potential, enabling robust deployment in commercial fronthaul systems and integration into chip-scale optical–photonic platforms.

Chapter 7 Conclusions and Future Work

7.1 Conclusions

In summary, this work has provided a concise review of QD-MLLs, QD-SOAs, and fronthaul transmission. A representative mmWoF fronthaul transmission system was presented and analyzed, with particular emphasis on the theory of heterodyne detection. The QD-MLL was investigated and applied as a multi-wavelength optical carrier source for mmWoF fronthaul transmission. The QD-MLL generates tens of highly coherent comb lines with narrow linewidth and low phase noise, enabling efficient heterodyne detection of mmWave carriers. Its inherent phase coherence allows for cancellation of common-mode phase noise between adjacent carriers, which is particularly advantageous for mmWoF links.

Guided by the theoretical insights obtained in earlier sections, the QD-MLL based mmWoF fronthaul transmission system was further enhanced by incorporating additional components and modifying the system structure. The performance of these improved systems was experimentally verified. Compared with the previously reported mmWoF link in [37], the EVM was reduced, owing to the improvement in overall power efficiency.

In addition, a bidirectional mmWoF fronthaul transmission system was proposed and experimentally demonstrated, confirming the flexibility and scalability of QD-MLL based architectures. These results collectively highlight that QD-MLLs provide a promising solution for next-generation fronthaul transmission, supporting the stringent requirements of 5G and beyond.

Furthermore, four frequency multiplexing techniques were proposed and experimentally

demonstrated using comb lines from the QD-MLL. These techniques exploited two to four carriers in various configurations, achieving different trade-offs between robustness, spectral efficiency, and implementation complexity. *Technique 1* offered the most straightforward and stable architecture but exhibited the lowest spectral efficiency and highest nonlinearity. *Technique 2* improved spectral efficiency by reusing one carrier, but required an I/Q modulator. *Technique 3* achieved further efficiency gains by using only two carriers without an I/Q modulator, showing improved performance compared with *Techniques 1* and *2*. Finally, *Technique 4*, which relied on a wave shaper to select non-adjacent carriers, delivered the best performance with minimal crosstalk, at the cost of higher implementation complexity and component requirements.

Overall, the QD-MLL demonstrated excellent suitability as a multi-wavelength source for mmWoF fronthaul systems. The experimental results confirmed that all proposed techniques achieved EVM values below 9.6% after 50 km of SMF transmission, satisfying the 5G fronthaul requirements. These findings highlight the strong potential of QD-MLLs as compact, efficient, and scalable optical carriers for future high-capacity fronthaul architectures.

This study has also demonstrated the feasibility of employing QD-SOAs in mmWoF fronthaul transmission systems as potential replacements for EDFA. Through a range of experiments, including single-channel transmission, OFDM and QAM modulation, fibre-wireless integration, and frequency-multiplexed architectures, QD-SOAs consistently achieved EVM values within the 5G requirements specified by 3GPP. The results highlight their ability to provide sufficient gain for advanced modulation formats and deliver stable performance after 10 km of SMF transmission followed by a 2-m wireless link. Among the devices tested, the 5- and 8-layer QD-SOAs offered the best balance between gain and noise figure, with the 8-layer variant showing better compatibility with QD-MLLs. However, performance in I/Q-MZM based systems was

constrained by high insertion loss and limited amplifier gain, whereas SSB-MZM based systems showed improved results but with some nonlinearities due to non-optimal biasing.

The main limitation of the present devices lies in their relatively low gain compared with EDFAs, which reduces effectiveness in high-loss configurations and restricts the number of multiplexing techniques that can be realized experimentally. Additional losses from packaged modules also limit performance relative to test-bed implementations. Despite these challenges, QD-SOAs offer strong potential as compact, energy-efficient, and integrable alternatives to EDFAs. Their small footprint makes them well-suited for photonic chip integration, reducing system size, cost, and power consumption for future fronthaul networks. With further improvements in gain and noise performance, QD-SOAs are expected to become key enablers of scalable mmWoF transmission, supporting both single-channel and multiplexed architectures for 5G and beyond.

7.2 Future Work

Future work will primarily focus on the development of a single photonic-chip BBU. By integrating all optical and electrical components onto a single chip, the overall size and power consumption of the BBU can be further reduced, leveraging the compactness and adequate performance of QD-MLLs and QD-SOAs. To achieve this goal, photonic wire bonding will be investigated. Some initial samples have already demonstrated successful connection of QD-MLLs to optical fibres, as shown in Figure 7.1. Further efforts will focus on connecting QD-MLLs, QD-SOAs, and modulators through photonic wire bonding to realize a fully integrated platform.

For QD-MLL-based mmWoF fronthaul transmission systems, further multiplexing schemes represent a promising approach to increase overall system capacity. Another potential direction is to extend mmWoF transmission into the terahertz domain, opening opportunities for

even higher-capacity fronthaul links.

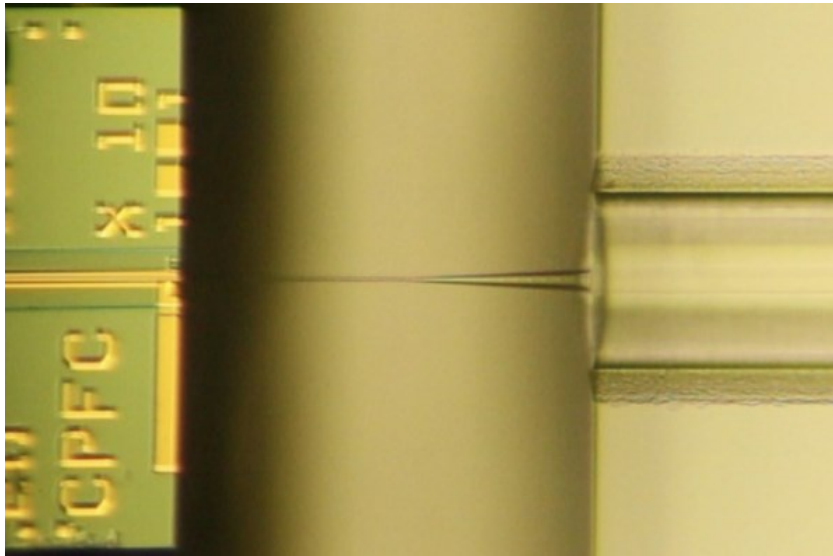


Figure 7.1 Photonic wire bonding between QD-MLL and optical fibre.

In the case of QD-SOAs, the most critical improvement will be the achievable gain. Enhancing the gain of QD-SOAs would significantly improve system performance and expand their applicability in practical fronthaul scenarios.

Finally, beyond fronthaul applications, QD gain media hold strong potential for quantum technologies. Their unique properties may be exploited in quantum communication and quantum computing, further broadening the scope of future research.

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