Relative Intensity Noise Transfer in Fiber Raman Amplifiers with Multiple Coherent or Incoherent Pumps

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A Thesis

in

The Department

of

Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science at

Concordia University

Montreal, Quebec, Canada

November 2005

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Your file Votre référence
ISBN: 0-494-14293-6
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ISBN: 0-494-14293-6

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ABSTRACT

Relative Intensity Noise Transfer in Fiber Raman Amplifiers with Multiple Coherent or Incoherent Pumps

YongMei Zhu

Fiber Raman amplifiers (FRAs) suffer from relative intensity noise (RIN) transfer from pumps to signals. RIN transfer for FRAs with single pump to one signal was well investigated. However, RIN transfer for FRAs with multiple pumps to multiple signals has not been investigated so far.

We used an equivalent modulation index to evaluate RIN transfer for FRAs with multiple pumps. As such, a general RIN transfer function of multiple pumps to multiple signals for FRAs with multiple pumps is derived. The model is verified with approximate calculations with an analytical model. Based on the model we first investigated DC RIN transfer including signal to signal transfer. It is shown that longer wavelength signals suffer from a larger DC RIN transfer. Also FRAs using incoherent pumps suffer from a larger DC RIN transfer. The full characteristics of RIN transfer are compared for FRAs in non-pump depletion and depletion regimes.

ACKNOWLEDGMENTS

Most of all, I would like to express my great gratitude to my research advisor Professor John X Zhang for his supports and guidance over the past two years. His high expectation and enlightening advices have helped me stay improved, and made this thesis possible.

Learning together with other members in fiber optic communication system field has greatly enriched my education and life. I would like to thank all of them for their support and encouragement: Ting Zhang, Bin Han and JingHong Fan. Their suggestions made the task of research enjoyable.

Finally, but not at least, I would like to thank my husband, my parents, and my son; their love and encouragement made me overcome difficulties and complete this thesis.

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CHAPTER 1 INTRODUCTION

In this chapter, four sections will be included. In Section 1.1, development of optical fiber communications is briefly reviewed and types of optical fiber amplifiers are introduced. In Section 1.2, fiber Raman amplifiers and relative intensity noise are described. In Section 1.3, motivations and basic ideas of this thesis are presented. Thesis structure and main contents of each chapter are described to help understanding this thesis in Section 1.4.

1.1 Evolutions of optical fiber and types of optical amplifiers

The first optical fiber was invented in 1854 and practically used for medical imaging over short distance in the 1950s [1]. However it was impossible to use for communications because of its high-loss (around 1000dB/km).

The first generation of fiber link operated around wavelength of 850nm, which was a low-loss transmission window of early silica fiber. It was commercially available in 1980 [2]. The second generation optical fiber worked at 1300nm window where the fiber had lower power loss and less signal dispersion. In 1981, the bit rate limitation was overcome by using the single-mode fiber instead of multimode fiber [3]. The third generation fiber operated at 1500nm window since the dispersion-shifted fiber overcame the large signal dispersion at that window [4] [5]. In 1989, the introduction of optical amplifier gave a major boost to fiber transmission. The fourth generation has increased bit rate and transmission length due to applications of optical amplifiers. It avoids the complexity of optical-electrical-optical (O-E-O) conversion, reduces the equipment cost and extends the transmission span of the DWDM systems.

The optical amplifiers are basically divided into three types: semiconductor optical amplifiers (SOAs), erbium-doped fiber amplifiers (EDFAs) and fiber Raman amplifiers (FRAs).

SOAs have two major sub-types: Fabry-Perot amplifier (FPA) and traveling wave amplifier (TWA). SOAs are used as wavelength converters, optical clock and data regenerators [5].

EDFAs make use of Erbium as a gain medium by doping the fiber core during the manufacturing process [6-8]. EDFAs are used as in-line amplifiers that operate over multiple fiber spans without expensive O-E-O conversion. The broad bandwidth of EDFAs is ideal for supporting transmission on the low-loss spectral window of silica-based fiber.

The research of FRAs began in 1970s, but FRAs were practically used in optical transmission system in the mid 1990s due to the development of suitable high power pumps [5]. Since they have very broad bandwidth and flat on-off Raman gain using multiple pumps or incoherent pumps, FRAs are popularly used in DWDM system now.

1.2 FRAs and their relative intensity noise

For FRAs, spontaneous Raman scattering occurs in optical fibers when a pump wave is scattered by the silica molecules. It is an isotropic process so it occurs in all directions [4]. When the pump power exceeds to the threshold value, the spontaneous Raman scattering process becomes into the stimulated Raman scattering (SRS). SRS can occur in both forward and backward directions in optical fibers. In the case of SRS, the incident pump photon gives up its energy to create another photon with reduced energy at a lower frequency. Then the remaining energy is absorbed by the medium in the form of optical phonons [4]. So only optical pump can make the Raman amplifiers work.

Using different wavelength of optical pump can amplify signal at any range of wavelengths so a very broad bandwidth (~100-nm) and flat Raman gain can be obtained with multiple coherent or incoherent pumps in DWDM system. That is the main advantage of FRAs over any other types of amplifiers [9][10].

FRAs are mainly divided into two types: distributed fiber Raman amplifiers (DFRAs) and discrete fiber Raman amplifiers (DisFRAs). The gain of DFRAs is distributed through transmission fiber and the gain of DisFRAs occurs within discrete elements in transmission systems.

Since the SRS is a nonresonant process, it is inherently fast, occurring over subpicosecond time scales [14]. Therefore, pump power fluctuations can, in principle, be transferred to signals as noise. This noise is called relative intensity noise (RIN). RIN transfer from a pump to a signal can be described in frequency domain [11]. For a given amplifier working in non-depletion pump regime, RIN transfer depends on the pumping direction, the pump and signal wavelength, and the value of Raman gain. The following characteristics of the fiber are relevant to Raman gain: fiber length, pump power, pump attenuation coefficient, dispersion and dispersion slope.

1.3 Motivations and basic ideas of this thesis

It was well known that relative intensity noise from pump to signal degrades FRAs performance. According to previous investigations, when one signal is pumped by one coherent pump, the pump laser exhibits some intensity noise and transfers this noise to the signal. So for FRAs, RIN transfer from the pump impairs the system because the intensity noise is introduced while the signal is amplified. RIN transfer has been investigated for FRAs with a single pump [11] or dual-order pump [21].

Nowadays, multiple coherent pumps can make FRAs work in high capacity long haul DWDM optical transmission systems with over 100 nm flat bandwidth [9][15-18]. Very recently, it is found that incoherent pumps can replace multiple coherent pumps to have better gain-flatness for a certain number of pumps [19][20]. So investigating RIN transfer for FRAs with multiple coherent or incoherent pumps in DWDM system is practically necessary. This thesis is focused on RIN transfer for FRAs with multiple coherent or incoherent pumps in DWDM systems.

For FRAs with multiple coherent or incoherent pumps in DWDM systems, signal relative intensity noise can be caused by RIN transferring from multiple pumps to the reference signal, from pumps to pumps and from other signals to the reference signal. In order to explore RIN transfer for FRAs from all pumps and other signals to the reference signal, an equivalent modulation index is proposed and derived. Then RIN transfer model for FRAs with multiple pumps to multiple signals is built up and verified.

1.4 Thesis structure

The structure of this thesis is described and the main contents are presented for each chapter.

In Chapter 2, the analytical RIN transfer model for FRAs, which is with one pump to one signal, is introduced [11]. The complex modulation indexes for multiple signals and multiple pumps are derived. Then an equivalent modulation index is proposed and derived. Eventually, RIN transfer model with multiple pumps to multiple signals is established.

In Chapter 3, the proposed RIN transfer model for FRAs is verified with different cases. First the proposed model is verified with one forward or backward pump to one signal in both non- pump depletion and pump depletion regime. Then this model with multiple pumps is verified by using approximate calculation from an analytical method.

In Chapter 4, performance of DC RIN transfer for FRAs with multiple coherent pumps is investigated from three aspects: considering RIN transferring from indirect pumps, different pumping schemes, and considering RIN transferring from the other signals or not. In Section 4.1, the relationship between DC RIN transfer and Raman gain is studied. Then DC RIN transferring from indirect pump is analyzed. While in Section 4.2, DC RIN transfer for FRAs considering RIN transfer from other signals is compared with not considering it. DC RIN transfer for FRAs with forward pumping scheme is compared with backward scheme in Section 4.3.

In Chapter 5, an incoherent pump concept is introduced and the model of incoherent pump is presented in Section 5.1. While in Section 5.2, DC RIN transfer for FRAs with different FWHM bandwidth of incoherent pumps to C+L band signals is studied. For a certain FWHM bandwidth of incoherent pump, DC RIN transfers with different fiber lengths, different pump power and different direction pumping schemes are compared respectively. In Section 5.3, DC RIN transfer with coherent pumps is compared with incoherent pumps.

In Chapter 6, RIN transfer for FRAs is analyzed from three aspects: with forward or backward pumping scheme, with multiple coherent or incoherent pumps and with pumps to one or to one of C band signals. In Section 6.1, RIN transfer with multiple coherent pumps is investigated. In Section 6.2, RIN transfer with incoherent pump is analyzed. While in Section 6.3, performance of RIN transfer using one coherent pump is compared with using one incoherent pump.

Chapter 7 concludes and summarizes the contributions of this thesis. Then future works relative to this thesis are proposed.

CHAPTER 2 RIN TRANSFER MODEL FOR FIBER RAMAN AMPLIFIERS

In this chapter, analytical RIN transfer model for FRAs with one pump to one signal and RIN transfer model with multiple pumps to multiple signals are respectively presented. In Section 2.1, basic dynamic optical power equations, complex modulation index equations and RIN transfer for FRAs with one pump to one signal [11] are introduced. While in Section 2.2, complex modulation indexes for multiple pumps and multiple signals based on dynamic optical power equations are derived. Then an equivalent complex modulation index is proposed and derived. Finally the RIN transfer model is established for FRAs with any number of coherent or incoherent pumps to any number of multiple signals.

For RIN transfer model with multiple coherent or incoherent pumps to multiple signals, optical nonlinearity [12] other than Raman scattering is ignored. The signal beam is also assumed to be initially free from RIN.

2.1 Analytical RIN transfer model for FRAs with one pump

The accurate modeling of fiber Raman amplifiers is important for modern communication system design [25]. In this section analytical RIN transfer model for FRAs with one pump to one signal is described.

First optical fiber as FRAs is illustrated in Figure 2.1. For forward pump, the pump is injected into the beginning of the fiber. For backward pump, the pump is injected into the end of the fiber.

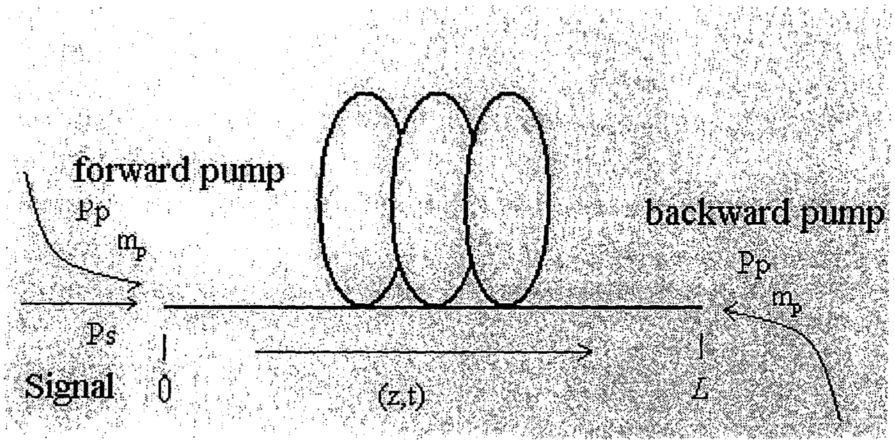

Figure 2.1 – Optical fiber as FRAs

It is very convenient to get spatial and time dependent equations governing the evolution of the continuous wave signal power and the pump power. It takes all effects considered to be of interest in practical FRAs into account: attenuation, signal gain from pump and pump depletion by signal. The spatial and time dependent power equations for one pump and one signal are given by [11].

$$\frac{\partial P_p(z,t)}{\partial z} \mp d\frac{\partial P_p(z,t)}{\partial t} = -\alpha_p P_p(z,t) - C_R P_p(z,t) P_s(z,t) \tag{2.1a}$$

$$\frac{\partial P_s(z,t)}{\partial z} = -\alpha_s P_s(z,t) + C_R P_s(z,t) P_p(z,t) \tag{2.1b}$$

The distance in the fiber length L going from the left to the right is denoted as variable z and t is time. P_p(z,t) is the spatial and time dependent pump power and P_s(z,t) is the spatial and time dependent continuous wave signal power. α_p or α_s is the optical fiber attenuation coefficients (1/m) for pump and signal respectively. The upper signs of $\mp$ correspond to the forward propagating case and the lower signs to the backward propagating case. The Raman gain coefficient is $C_R = g_R / A_{eff}$ where g_R is the Raman gain provided by the pump at the signal wavelength and A_{eff} is the effective cross-section area. The parameter of d is the "walk-off" parameter, which is given by $d = \frac{1}{V_s} \mp \frac{1}{V_p}$ [20]. To get the group velocity V_s or V_p, it needs group index n since $V = c/n$ where c is the speed of light in vacuum. The group index n is computed by the Sellmeier function [23] $n = n_0 + (S_0/8)\cdot(\lambda - \lambda_0^{\,2}/\lambda)^2 \cdot c$, where n_0 is the group index at the fiber zero-dispersion wavelength λ_0, S_0 is the dispersion slope at λ_0, and λ is the pump or signal laser wavelength.

The spatial and time dependent optical signal or pump power is given by [21]

$$P(z,t) = P(z)\cdot[1 + M(z,t)] \tag{2.2}$$

$P(z)$ is the steady-state optical power at location z and $M(z,t)$ is the spatial and temporary complex modulation index, which indicates the power fluctuations. The spatial and temporal components of the modulation index can be separated and written as:

$$M(z,t) = m(z)\cdot \exp(i\cdot\Omega\cdot t) \tag{2.3}$$

where sinusoidal time dependence at an angular frequency Ω is assumed and $m(z)$ is the complex spatial modulation index. It is assumed that the complex modulation indexes are small so that $|m_p|\cdot|m_s| << 1$. The set of differential equations with the real and imaginary components of the complex spatial modulation index $m\ (z)$ are given as [21].

$$\frac{\partial m_p(z)}{\partial z} \pm i\cdot\Omega\cdot d\cdot m_p(z) = -C_R\cdot P_s(z)\cdot m_s(z) \tag{2.4a}$$

$$\frac{\partial m_s(z)}{\partial z} = C_R \cdot P_p(z) \cdot m_p(z) \qquad (2.4b)$$

$m_p(z)$ and $m_s(z)$ are complex modulation indexes of pump and signal. From Equations (2.3) and (2.4), the spatial and time dependent complex modulation index $M(z,t)$ for pump or signal can be obtained. The complex RIN transfer $H_{sp}(L,\Omega)$ from one pump to one signal is defined by [21],

$$M_s(L,\Omega) = H_{sp}(L,\Omega) \cdot M_p(0,\Omega) \qquad \text{forward pump} \qquad (2.5a)$$

$$M_s(L,\Omega) = H_{sp}(L,\Omega) \cdot M_p(L,\Omega) \qquad \text{backward pump} \qquad (2.5b)$$

where $M_s(L,\Omega)$ is the spatial and temporary complex modulation index of signal at output location z=L; $M_p(0,\Omega)$ is the spatial and temporary complex modulation index of pump at input location z=0 for forward pump; $M_p(L,\Omega)$ is the complex modulation index of pump at input location z=L for backward pump. $H_{sp}(L,\Omega)$ is the RIN transfer with one pump to one signal.

2.2 RIN transfer model for FRAs with multiple coherent or incoherent pumps

The RIN transfer model with one pump to one signal cannot be used for FRAs with multiple coherent or incoherent pumps in DWDM systems. The broad bandwidth and flat Raman gain of Raman amplifiers can be achieved with multiple coherent or incoherent pumps for amplifying multiple signal channels simultaneously in DWDM systems. The effects that couple signals and pumps propagating are illustrated in Figure 2.2. The following effects are included along with the capability of modeling any number of signals and pumps [29]:

- Attenuation
- Raman gain pumped by signals
- Pump depletion by signals

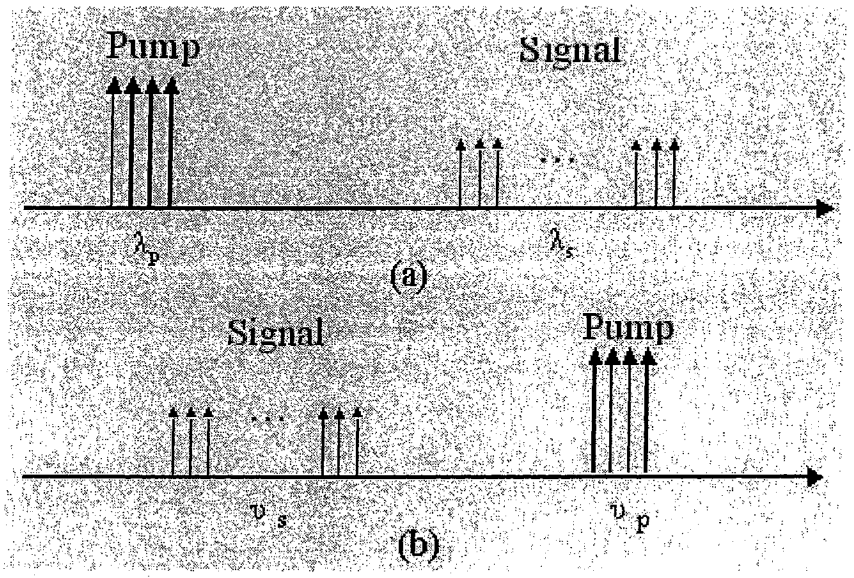

Figure 2.2 - Illustration of frequency or wavelength intervals for the numerical calculation.

The entire spectral range of interest is represented (a) in wavelength and (b) in frequency

The forward or backward multiple coherent or incoherent pumps and multiple signals interaction propagation for all frequencies v are given by,

$$
\begin{aligned}
\frac{\partial P_i(z,t)}{\partial z} \mp d_{(reference-signal)i}\frac{\partial P_i(z,t)}{\partial t} &= -\alpha_i P_i(z,t) && \square \\
&+ P_i(z,t)\sum_{j}^{v_j>v_i} C_R(v_j,v_i)P_j(z,t) && \square \qquad (2.6a) \\
&- P_i(z,t)\sum_{j}^{v_j<v_i} \frac{V_j}{V_i}\cdot\frac{v_i}{v_j}\cdot C_R(v_j,v_i)P_j(z,t) && \square
\end{aligned}
$$

for the pumps, where term $d_{(reference-signal)i}$ is the walk-off parameter between the reference signal and the i-th channel pump, term □ presents fiber attenuation, □ is the gains from higher frequency (shorter wavelength) pumps, □ is the depletions from lower frequency (longer wavelength) pumps and signals. This channel j can be signal or pump, v_i or v_j is the frequency of the i-th or j-th channel. V_i or V_j is group velocity denoted by subscript for different frequencies. The propagation equation is given by

$$\begin{aligned} \frac{\partial P_i(z,t)}{\partial z} &= -\alpha_i P_i(z,t) && \square \\ &+ P_i(z,t)\sum_j^{v_j>v_i} C_R(v_j,v_i)P_j(z,t) && \square \qquad (2.6b) \\ &- P_i(z,t)\sum_j^{v_j<v_i} \frac{V_j}{V_i}\cdot\frac{v_i}{v_j}\cdot C_R(v_j,v_i)P_j(z,t) && \square \end{aligned}$$

for the considered signal, term □ presents fiber attenuation, □ is the gain from higher frequency (shorter wavelength) pumps and signals, □ is the depletions from lower frequency (longer wavelength) signals.

The spatial and time dependent optical powers are given by [21]

$$P_i(z,t) = P_i(z)\cdot[1+M_i(z,t)] \qquad (2.7)$$

$P_i(z)$ i-th channel steady-state optical power at location z and $M_i(z,t)$ the i-th channel temporal complex modulation index, which indicates the power fluctuations, can be separated and written as:

$$M_i(z,t) = m_i(z)\cdot\exp(I\cdot\Omega\cdot t) \qquad (2.8)$$

where sinusoidal time dependence at an angular frequency Ω is assumed. $m_i(z)$ is the i-th channel complex spatial modulation index. Here **I** is the imaginary part of complex number. It is assumed that the complex modulation indexes are small so that $|m_i|\cdot|m_j|<<1$. Substitution of (2.7) and (2.8) into (2.6) yields a set of differential equations for the i-th channel steady state optical powers $P_i(z)$ and for the i-th channel real and the imaginary components of the complex spatial modulation index $m_i(z)$.

The steady state optical powers equations $P_i(z)$ are given as:

$$\frac{dP_i^+(z)}{dz}=-\alpha_i P_i^+(z)$$

$$+P_i^+(z)\sum_{j}^{v_j>v_i}(C_R(v_j,v_i)\cdot\left[P_i^+(z)+P_j^-(z)\right] \tag{2.9a}$$

$$-P_i^+(z)\sum_{j}^{v_j<v_i}\frac{v_j}{v_i}\frac{V_j}{V_i}C_R(v_j,v_i)\cdot[(P_j^+(z)+P_j^-(z)]$$

$$\frac{dP_i^-(z)}{dz}=-\alpha_i P_i^-(z)$$

$$+P_i^-(z)\sum_{j}^{v_j>v_i}(C_R(v_j,v_i)\cdot\left[P_i^+(z)+P_j^-(z)\right] \tag{2.9b}$$

$$-P_i^-(z)\sum_{j}^{v_j<v_i}\frac{v_j}{v_i}\frac{V_j}{V_i}C_R(v_j,v_i)\cdot[(P_j^+(z)+P_j^-(z)]$$

$P_j^+(z)$ and $P_j^-(z)$ are forward and backward steady state optical powers at the j-th frequency channel and at the location of z;

The complex modulation index equations for backward multiple coherent or incoherent pumps are given as the following:

$$\frac{\partial m_i^+(z)}{\partial z}=\sum_{j}^{v_j>v_i}C_R(v_j,v_i)\cdot[P_j^-(z)\cdot m_j^-(z)] \qquad \square$$

$$+\sum_{j}^{\nu_j>\nu_i} C_R(\nu_j,\nu_i)\cdot[P_j^{+}(z)\cdot m_j^{+}(z)] \qquad \square \qquad (2.10a)$$

$$-\sum_{j}^{\nu_j<\nu_i}\frac{V_j}{V_i}\cdot\frac{\nu_i}{\nu_j}\cdot C_R(\nu_j,\nu_i)\cdot[P_j^{+}(z)\cdot m_j^{+}(z)] \qquad \square$$

for the considered signal. $m_j^{+}(z)$ and $m_j^{-}(z)$ are forward and backward complex spatial modulation indexes at the j-th frequency and at the location of z. □ indicates the pumps at the j-th frequency transferring its RIN into the i-th frequency signal at the location of z; □ indicates the other signals at j-th frequency, which is higher than i-th frequency, transferring its RIN to i-th frequency signal at the location of z; □ indicates the other signals at j-th frequency, which is lower than i-th frequency, depleting the i-th frequency signal RIN at the location of z .

$$\frac{\partial m_i^{-}(z)}{\partial z}+\mathrm{I}\cdot\Omega\cdot d_{i(reference\text{-}signal)}\cdot m_i(z)$$

$$=\sum_{j}^{\nu_i>\nu_j} C_R(\nu_j,\nu_i)\cdot[P_j^{-}(z)\cdot m_j^{-}(z)] \qquad \square$$

$$-\sum_{j}^{\nu_j<\nu_i}\frac{V_j}{V_i}\cdot\frac{\nu_i}{\nu_j}\cdot C_R(\nu_j,\nu_i)\cdot[P_j^{-}(z)\cdot m_j^{-}(z)] \qquad \square \qquad (2.10b)$$

$$-\sum_{j}^{\nu_j<\nu_i}\frac{V_j}{V_i}\cdot\frac{\nu_i}{\nu_j}\cdot C_R(\nu_j,\nu_i)\cdot[P_j^{+}(z)\cdot m_j^{+}(z)] \qquad \square$$

for the pumps. Term $\mathrm{I}\cdot\Omega\cdot d_{i(reference\text{-}signal)}\cdot m_i(z)$ is the i-th frequency pump walk-off or velocity difference from the reference signal. □ is the pump at j-th frequency, which is higher than the i-th frequency, transferring its RIN to i-th frequency at the location of z; □ is the pump at j-th frequency, which is lower than i-th frequency, depleting the i-th frequency pump RIN at the location of z; □ is the j-th frequency signal depleting the i-th frequency pump RIN at the location of z;

Considering forward pumping scheme, Equation (2.10a) and (2.10b) are changed to

$$\begin{aligned}\frac{\partial m_i^+(z)}{\partial z} &= \sum_j^{v_j>v_i} C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square \\ &+\sum_j^{v_j>v_i} C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square \qquad (2.10c) \\ &-\sum_j^{v_j<v_i} \frac{V_j}{V_i}\cdot\frac{v_i}{v_j}\cdot C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square\end{aligned}$$

for the considered signal and

$$\begin{aligned}&\frac{\partial m_i^+(z)}{\partial z} - \mathrm{I}\cdot\Omega\cdot d_{ij(reference-signal)}\cdot m_i(z) \\ &= \sum_j^{v_i>v_j} C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square \\ &-\sum_j^{v_j<v_i} \frac{V_j}{V_i}\cdot\frac{v_i}{v_j}\cdot C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square \qquad (2.10d) \\ &-\sum_j^{v_j<v_i} \frac{V_j}{V_i}\cdot\frac{v_i}{v_j}\cdot C_R(v_j,v_i)\cdot[P_j^+(z)\cdot m_j^+(z)] && \square\end{aligned}$$

for the pumps. Each term has the same meaning as the backward pumping and only the pump direction is different.

The effects, which couple signals and pumps propagating in the same and opposite directions, have been analyzed. Solving their propagation equations becomes a two-point boundary problem [24]. To apply those differential equations for FRAs with length L, the fiber can be separated into n sections. Each section is an elemental amplification section and has a length of $\Delta z = \frac{L}{n}$, where Δz is the step size. With the increase of section number n, the step size is smaller and calculation accuracy is improved. However, the section number n cannot be increased unlimitedly, since the computation time is also increased. Figure 2.3 and Figure 2.4 give the evolution of a transmission fiber for the forward and backward directions.

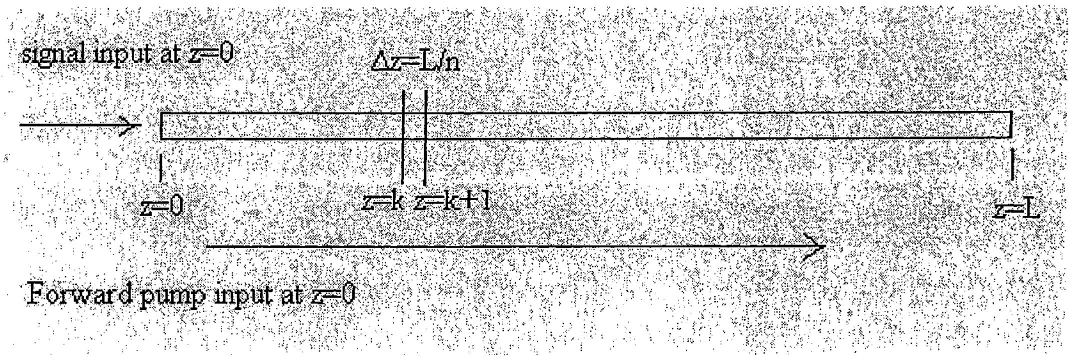

Figure 2.3 The transmission fiber of n sections for the forward propagation direction

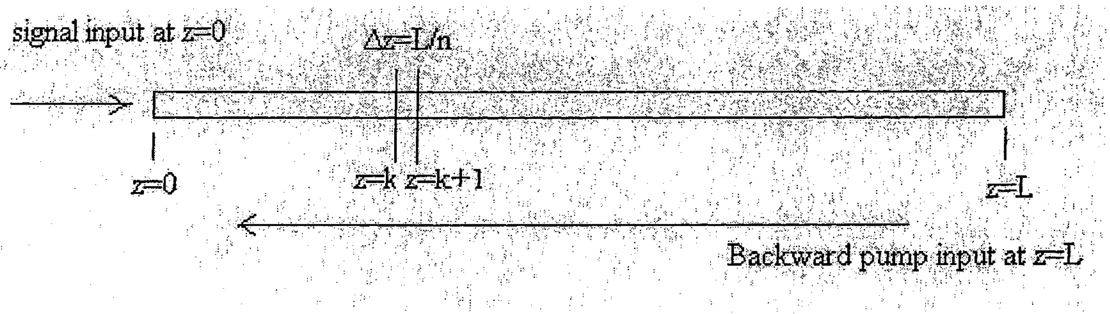

Figure 2.4 The transmission fiber of n sections for the backward propagation direction

The equations of complex modulation indexes for multiple pumps or signals have been presented but the RIN transfer can only be calculated from one pump to one signal as in Section 2.1. Since RIN transfer for FRAs with multiple coherent or incoherent pumps to multiple signals can precisely describe real relative intensity noise transferring in DWDM system, it is important to investigate RIN transfer with multiple coherent or incoherent pumps. An equivalent modulation index provides measurements of RIN transfer with multiple coherent or incoherent pumps in DWDM system. Then an equivalent pump is assumed to have the same performance as multiple coherent or incoherent pumps. The assumption is:

$$P_{eq}(z,t) = \sum_i P_i(z,t) \tag{2.11}$$

$P_{eq}(z,t)$ is the equivalent spatial and time dependent optical power of multiple coherent or incoherent pumps at location z.

$$P_{eq}(z) = \sum_i P_i(z) \tag{2.12}$$

$P_{eq}(z)$ is the equivalent steady state optical power of multiple coherent or incoherent pumps at the location z.

$$P_{eq}(z,t) = P_{eq}(z) \cdot [1 + M_{eq}(z,t)] \tag{2.13}$$

M_{eq} is the equivalent complex modulation index of the multiple coherent or incoherent pumps, and the equivalent spatial and temporal components of the modulation indexes are given as:

$$M_{eq}(z,t) = m_{eq}(z) \cdot \exp(I \cdot \Omega \cdot t) \tag{2.14}$$

Substitute Equation (2.14) into Equation (2.13)

$$P_{eq}(z,t) = P_{eq}(z) \cdot [1 + m_{eq}(z) \cdot \exp(I \cdot \Omega \cdot t)] \tag{2.15}$$

$m_{eq}(z)$ is the equivalent complex spatial modulation index of multiple coherent or incoherent pumps. Using (2.7), (2.8) and (2.11), we obtain

$$P_{eq}(z,t) = \sum_i P_i(z) \cdot [1 + m_i(z) \cdot \exp(I \cdot \Omega \cdot t)] \tag{2.16}$$

Combining Equation (2.15) and Equation (2.16), we have

$$P_{eq}(z)\cdot[1+m_{eq}(z)\cdot\exp(I\cdot\Omega\cdot t)]=\sum_i P_i(z)\cdot[1+m_i(z)\cdot\exp(I\cdot\Omega\cdot t)] \tag{2.17}$$

$$P_{eq}(z)\cdot m_{eq}(z)=\sum_i P_i(z)\cdot m_i(z) \tag{2.18}$$

So the equivalent modulation index of multiple coherent or incoherent pumps is:

$$m_{eq}(z)=\sum_i P_i(z)\cdot m_i(z)/P_{eq}(z) \tag{2.19}$$

The equivalent RIN transfer $H^{eq}(L,\Omega)$, which corresponds to a transmission span of fiber length L, is defined by

$$H_j^{eq}(L,\Omega)=\frac{M_j(L,\Omega)}{M_{eq}(0,\Omega)} \qquad \text{forward pump} \tag{2.20a}$$

$$H_j^{eq}(L,\Omega)=\frac{M_j(L,\Omega)}{M_{eq}(L,\Omega)} \qquad \text{backward pump} \tag{2.20b}$$

M_j is the complex modulation index of the signal. Since M(z,t) can get from $M\ (z,t)=m\ (z)\cdot\exp(I\cdot\Omega\cdot t)$, the equivalent RIN transfer can be easily get with forward or backward multiple coherent or incoherent pumps.

CHAPTER 3 VERIFICATIONS OF RIN TRANSFER MODEL FOR FIBER RAMAN AMPLIFIERS

The RIN transfer model for FRAs with multiple pumps to multiple signals has been proposed in Chapter 2. In this chapter, the model will be verified by comparing with the results of calculations and measurements that analytical model provided [11] [22]. In Section 3.1, RIN transfer model is verified for FRAs in non-pump depletion regime using one forward or backward pump to one signal [11]. The simulations are done to compare with the example given in [11]. In Section 3.2, the model working in depletion pump regime is verified with in [22]. In Section 3.3, the model is verified by approximate analytical calculations with the examples of FRAs with multiple pumps.

3.1 Verifications of RIN transfer model in non-pump depletion regime

In order to verify the correctness of the proposed RIN transfer model for FRAs with one pump to one signal, the simulations are done to compare with the results of calculations or examples from analytical model. The analytical model considers the effect of RIN in a strong pump beam traveling in a single–mode optical fiber, either with or against the direction of a coexisting weak signal beam of a different optical wavelength [11].

The fiber is assumed to exhibit wavelength-dependent attenuation and dispersion, but those optical nonlinearities other than Raman scattering is ignored. The signal beam is also assumed to be initially free from RIN, pump depletion effects are neglect and a small amount of modulation at frequency f is applied to the pump.

Verification 1:

The RIN transfer for FRAs with one forward pump to one signal is verified by the calculation results using analytical model. From analytical model, the RIN transfer with one forward pump to one signal can be calculated by [11]:

$$|H\ (f)|^2 = (\ln(10^{(G_R/10)}))^2 \left(\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (2\pi D \Delta\lambda V_s f)^2}\right)$$

$$\cdot (1 - 2\exp(-\alpha_p L)\cos(2\pi D \Delta\lambda L f) + \exp(-2\alpha_p L)) \qquad (3.1)$$

for long length fiber, this simplifies to

$$|H\ (f)|^2 = (\ln(10^{(G_R/10)}))^2 \left(\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (2\pi D \Delta\lambda V_s f)^2}\right) \qquad (3.2)$$

$$|H\ (f)|^2\ (dB) = 20\log(\ln(10^{(G_R/10)})) + 10\log\left(\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (2\pi D \Delta\lambda V_s f)^2}\right) \qquad (3.3)$$

in decibels. G_R is the on-off gain of distributed FRAs in dB units; α_p is the attenuation coefficient of the pump; L_{eff} is the effective fiber length and $L_{eff} = (1-\exp(-\alpha_p L))/\alpha_p$; The dispersion D at wavelength λ, $D = S_0(\lambda - \lambda_0)$ where λ_0 is the fiber zero dispersion wavelength, S_0 is the fiber zero dispersion slop, wavelength $\lambda=(\lambda s+\lambda p)/2$ and λs or λp is signal or pump wavelength; L is the fiber length; $\Delta\lambda$ is the difference wavelength between the pump and the signal; The group velocity at signal wavelength, $V_s = c/(n_0 + S_0(\lambda_s - \lambda_0)^2 c/8)$, where c is optical velocity in vacuum and n_0 is the group index at fiber zero dispersion wavelength λ_0.

In order to calculate the RIN transfer for FRAs using the analytical model, the parameters are chosen as the typical example: The signal wavelength λs is1551nm and its power is 0.5mW; The pump wavelength λp is 1455nm and its power is 368mW; The attenuation at pump wavelength α_p is $5.5\times10^{-5}\mathrm{m}^{-1}$; The fiber is TW reach fiber and its length L is 80km; The fiber zero dispersion wavelength λ_0 is 1400nm; The fiber zero dispersion slop S_0 is 0.04 ps/nm^2-km; fiber zero dispersion group index n_0 is 1.47; The on-off Raman gain G_R is around 12.6dB, and $L_{eff} = 17.866km$; chromatic dispersion D is 4.12ps/km-nm; Δλ is 96nm; $V_s = 2.039\times10^8$ m/s and $c = 3\times10^8$ m/s.

The theoretical calculation results from the analytical model and the simulation results from proposed model are shown in Figure 3.1:

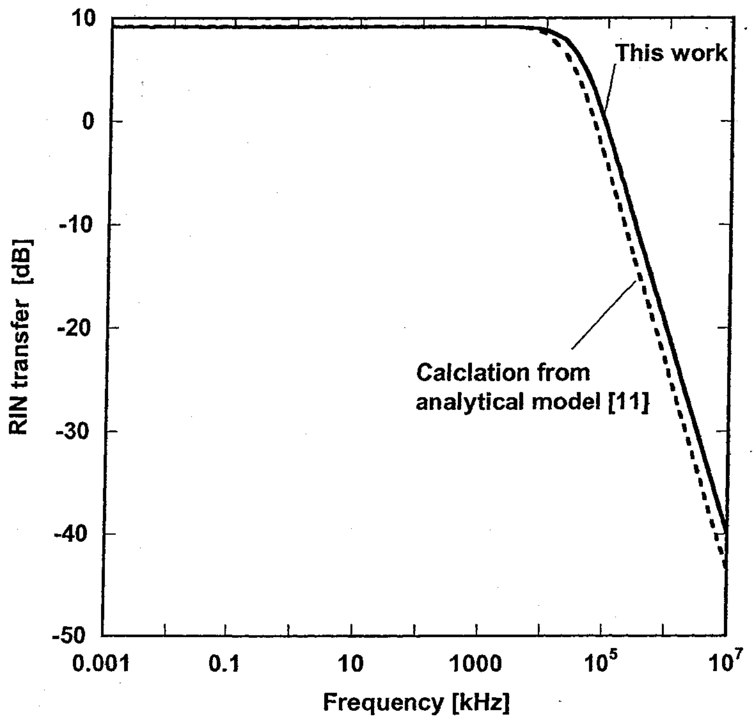

Figure 3.1 RIN transfer with one forward pump to one signal, by theoretical calculation from analytical model and simulation from proposed model.

Verification 2:

Having done the verification with forward pump, here it will be verified with one backward pump. The RIN transfer for FRAs with one backward pump to one signal from analytical model [11] is given by

$$|H(f)|^2 = (\ln(10^{(G_R/10)}))^2 (\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (4\pi f)^2}) \\ \cdot (1 - 2\exp(-\alpha_p L)\cos(4\pi f T) + \exp(-2\alpha_p L)) \qquad (3.4)$$

For long length fiber, this simplifies to:

$$|H(f)|^2 = (\ln(10^{(G_R/10)}))^2 (\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (4\pi f)^2}) \qquad (3.5)$$

$$|H(f)|^2 \,(dB) = 20\log(\ln(10^{(G_R/10)})) + 10\log(\frac{(V_s / L_{eff})^2}{(\alpha_p V_s)^2 + (4\pi f)^2}) \qquad (3.6)$$

in decibels.The parameters are as same as Verification 1 and only the pump direction is changed from forward to backward.

The theoretical calculation results from analytical model and the simulation results from the proposed model are shown in Figure 3.2:

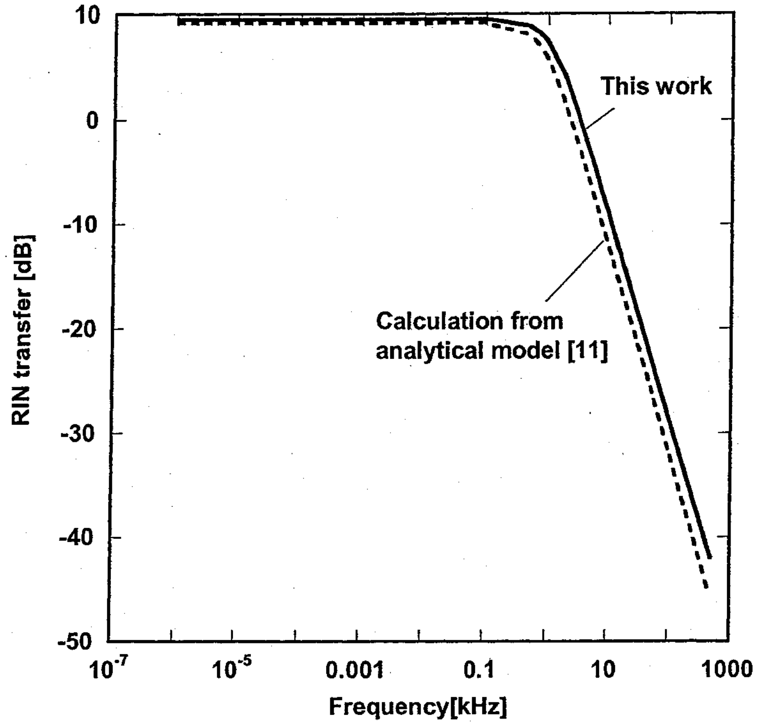

Figure 3.2 RIN transfer with one backward pump to one signal, by theoretical calculation from analytical model and simulation from proposed model.

Verification 1 and Verification 2 show that the RIN transfer with one forward or backward pump to one signal from the proposed model fits the one from the analytical model well. The slight difference of the RIN transfers from these two models is due to the use of simplified formulas in the analytical model.

Verification 3:

In order to further verify the proposed model, the example of the measurements and theoretical calculations given in [11] are compared with the results of simulation with the proposed model. The parameters used in this verification are in the following:

The Truewave RS fiber is considered. The signal wavelength is 1550nm. The pump wavelength is 1455nm and the on-off Raman gain is 12.6dB. The dispersion at 1550nm is

2.3ps/km-nm and the attenuation at 1455nm is 0.25dB/km. The fiber length is 81.1km, and attenuation at 1455nm is 0.25dB/km.

The RIN transfer with one forward or backward pump to signal, which is obtained from simulation results using the proposed model, is shown in Figure 3.3.

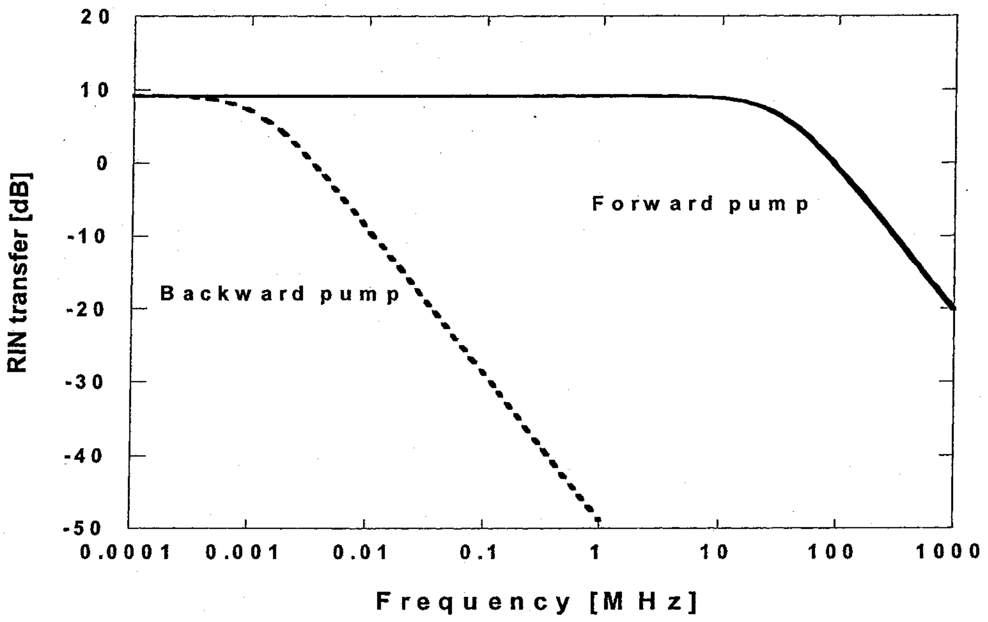

Figure 3.3 RIN transfer with one forward or backward pump to one signal from the proposed model.

The RIN transfer with one forward or backward pump to one signal, which is obtained from the calculations or measurements using analytical model, is shown in Figure 3.4.

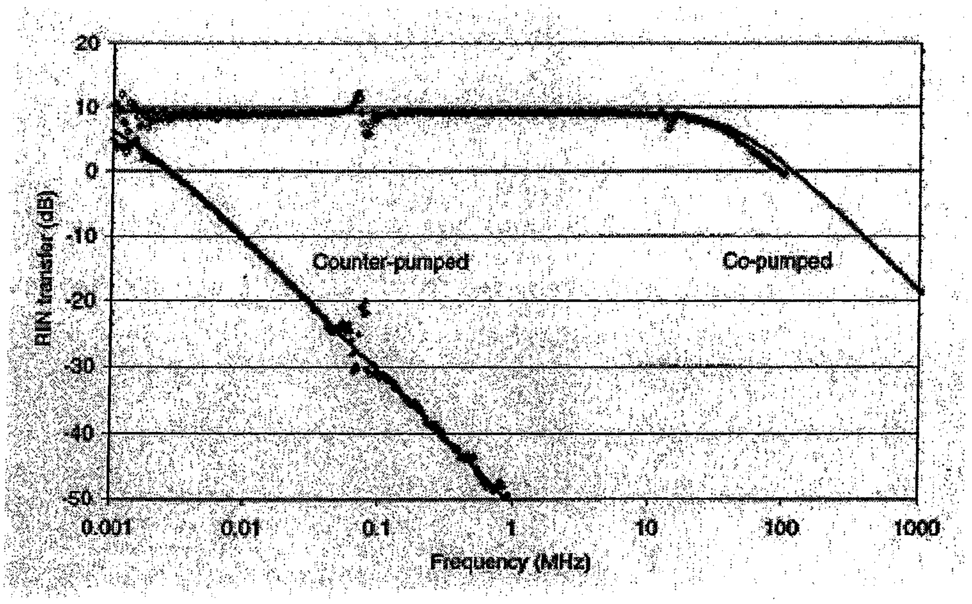

Figure 3.4 RIN transfer with one forward pump or backward pump to one signal from the example of [11], solid line indicates calculation results and dotted line indicates measurements with analytical model.

Co-pump is also called forward pump and counter-pump is also called backward pump. So Verification 3 shows the proposed model perfectly fits with the example in [11].

Through Verification 1, Verification 2 and Verification 3, the verifications of the proposed RIN transfer model has been done in non- pump depletion regime with one forward or backward pump to one signal.

3.2 Verifications of RIN transfer model for FRAs in pump depletion regime

The previous verifications are limited to non- pump depletion regime. In DWDM systems, the multiple signals powers are big enough to make FRAs work in pump depletion regime. Therefore it is important to analyze the effects of pump depletion on the

RIN transfer.

In order to verify the correctness of the proposed RIN transfer model in pump depletion regime, the input signal power is increased. The RIN transfer will be verified by the conclusions that the lower frequency of RIN transfer is low and the bandwidth is broadened in pump depletion regime [22].

For forward pumping scheme, the signal power is increased from 0.01mW to 0.5mW and further to 50mW at wavelength 1551nm. The fiber is TW-Reach fiber and the length is 60km. The pump power is changed from 365mW to 368mW and further to 850mW in order to get the same on-off Raman gain. The signal power from 0.01mW to 0.5mW is in the small signal range, which the on-off Raman gain is almost the same at the same pump power, and the RIN transfer is proportional to the on-off Raman gain [11].

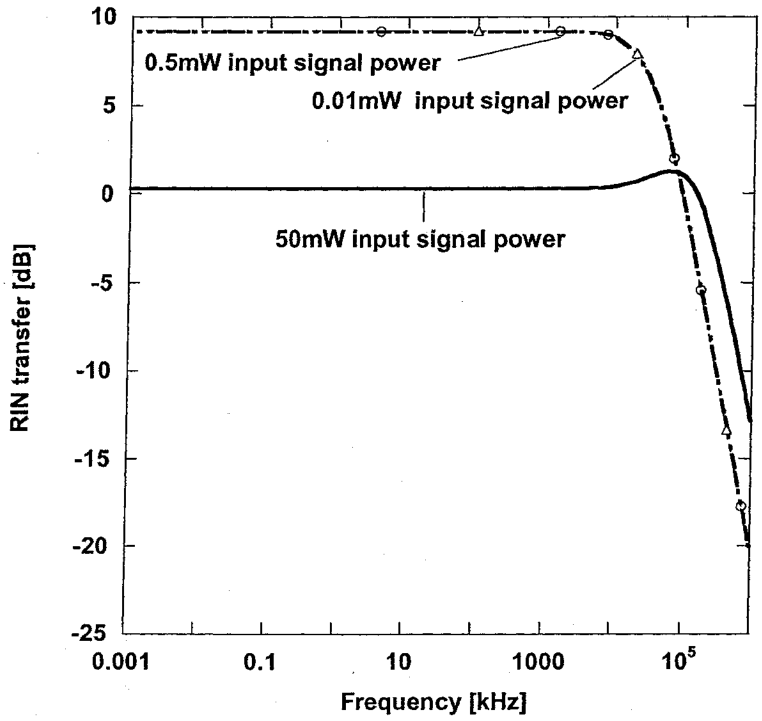

Figure 3.5 RIN transfer with one forward pump in non-pump depletion and pump

depletion regime.

According to Figure 3.5, the RIN transfer is almost the same when signal power increases from 0.01mW to 0.5mW. When the signal power is increased from 0.5mW to 50mW, FRAs work in pump depletion regime. The low frequency RIN transfer is decreased from 9dB to 0.1 dB. For 0.5mW signal power case, –3dB corner frequency is around 50MHz and for 50mW signal power case, -3dB corner frequency is around 300MHz. The DC RIN transfer is lower and the electronic bandwidth is broadened in depletion pump regime. These properties agree to [22] very well.

For backward pumping scheme, the signal power is increased from 0.5mW to 50mW (similar with the total power of C band signals) to 100mW (similar with the total power of C+L band signals) at wavelength 1551nm.

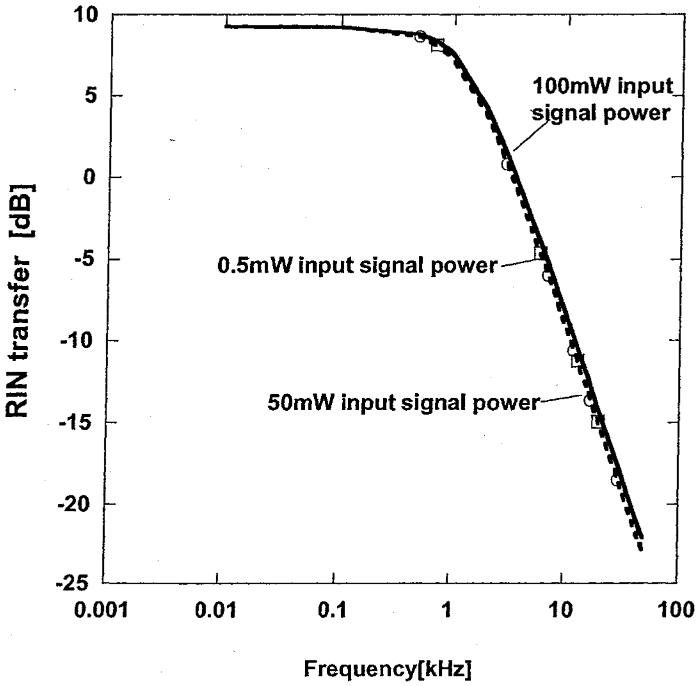

Figure 3.6 RIN transfer in non- pump depletion regime with one backward pump.

The same on-off Raman gain can be achieved at the same pump power in this case. Changing the signal power from 0.1mW to 50mW does not affect the on-off gain and the RIN transfer since the FRAs work in non- pump depletion regime with backward pumping scheme. The RIN transfer for FRAs is proportional to the on-off Raman gain as [11] in non- pump depletion regime.

3.3 Verification of RIN transfer model for FRAs with multiple pumps

Since the RIN transfer for FRAs with multiple coherent or incoherent pumps has not been investigated before, it is necessary to verify the proposed model with multiple pumps by using approximate calculations from the analytical model.

The RIN transfer with six backward coherent pumps to one signal is considered here as an example. The wavelength of the six pumps is 1425nm, 1436nm, 1447nm, 1461nm, 1485nm, and 1500nm respectively. The power of the six pumps is 150mW, 110mW, 97mW, 97mW, 79mW and 44mW respectively. These parameters of pumps can make the 89 signals in C band get more flat on-off Raman gain. Now only consider one signal. The signal wavelength is 1539.43nm and the signal power is 0.5mW.

For backward pumping scheme, the RIN transfer from the analytical model for long length fiber is given by Equation 3.6. Using approximate method, G_R is the on-off Raman gain from the six backward pumps, α_p is chosen to be the mean value of the six pumps' attenuation and L_{eff} is the mean of the effective fiber lengths of the six pumps.

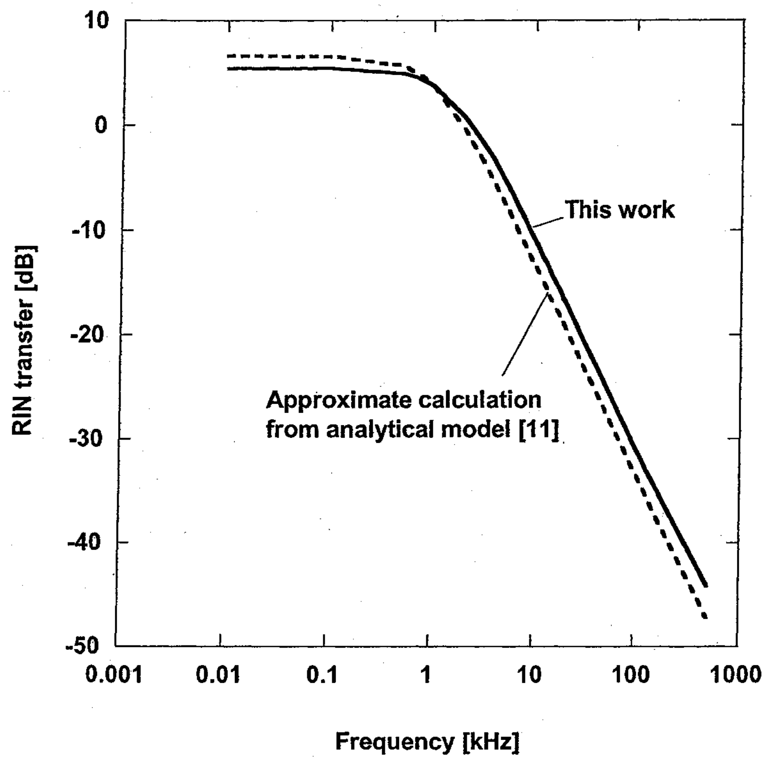

Figure 3.7 Comparison of the RIN transfer from the proposed model with the approximate calculations from analytical model using six backward coherent pumps.

According to Figure 3.7, the RIN transfer from the proposed model closely fits the RIN transfer with approximate calculation results from the analytical model using six backward coherent pumps. It cannot be verified precisely due to not having the precise model for multiple pumps yet.

In this chapter, RIN transfer from the proposed model for FRAs has been verified with different cases. With one pump to one signal, the proposed RIN transfer model for FRAs has been verified with the different direction pumping schemes in pump depletion regime or in non- pump depletion regime. The proposed RIN transfer model with multiple pumps also is verified by using approximate calculation results from analytical model.

CHAPTER 4 PERFORMANCE OF DC RIN TRANSFER FOR FIBER RAMAN AMPLIFIERS WITH MULTIPLE COHERENT PUMPS

Since the proposed RIN transfer model has been verified in previous chapter, the RIN transfer for FRAs can be investigated in DWDM system, which needs multiple coherent or incoherent pumps to get flatness of on-off Raman gain.

All comparisons in this chapter are based on the same parameters: the fiber type of TW-Reach Fiber which is a popular single mode fiber used in transmission, C+L band 184 signal channels with channel spacing of 50 GHz over the spectrum from 1530nm to 1605 nm, 0.5mW per channel input power except extra illustration.

In Section 4.1, performances of DC RIN transfer with multiple coherent pumps are investigated with different numbers of coherent pumps or different direction pumping schemes or different fiber lengths. The relationship between DC RIN transfer and on-off gain is studied, and DC RIN transfer from indirect pumps is analyzed. In Section 4.2, DC RIN transfer considering RIN transferring from the other signals is compared with not considering it. In Section 4.3, with multiple coherent pumps, DC RIN transfer for forward pumping scheme is compared with backward pumping scheme.

4.1 Performance of DC RIN transfer for FRAs with multiple backward pumps

Since backward multiple pumps are more suitable for FRAs in DWDM systems [26], performance of DC RIN transfer with backward pumping to each of C+L-band signals is important to be investigated.

Case 1: DC RIN transfer with two coherent backward pumps

The power of two backward pumps is 330mW and 218mW respectively. The wavelength of the two pumps is 1441nm and 1484nm respectively. The fiber length is 60km. The modulation index of these pump lasers is assumed 1.0% of the pump power.

In this case, although the total C+L band signal power is around 92 mW, the backward scheme makes FRAs work in non-pump depletion regime. The DC RIN transfer is somewhat proportional to the on-off gain in DWDM system as shown in Figure 4.1. Slight difference with the values of precise proportional to the on-off gain is due to RIN transferring from shorter wavelength signal to longer wavelength and RIN transferring from indirect pump. The pump wavelength difference is 43nm and the Raman gain coefficient from pump to pump at this wavelength difference is small, so the DC RIN transfer from indirect pump is small. The DC RIN transfer from other signals is small because the signal power is small.

The DC RIN transfer with two coherent backward pumps is not only relative to its on-off gain, but also relative to the RIN transferring from the other pumps and from the other signals.

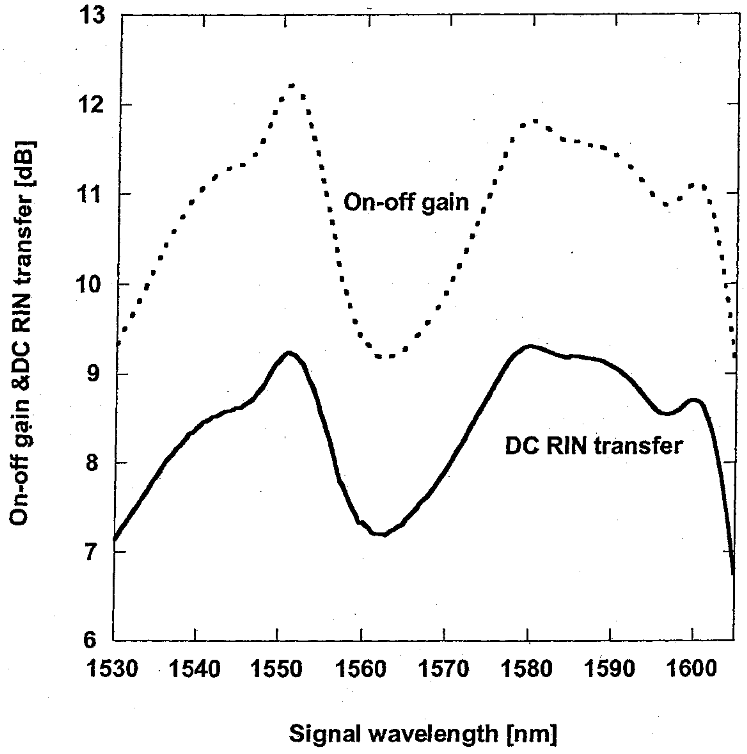

Figure 4.1 The on-off gain and the DC RIN transfer with two backward pumps.

Case 2: The DC RIN transfer with the different fiber lengths.

The fiber length is 40km, 60km and 100km respectively. The other parameters are as Case 1.

As shown in Figure 4.2, the average DC RIN transfer increases along with the fiber length. The reason is that the average on-off gain for FRAs increases along with the fiber length in non-depletion pump regime. The DC RIN transfer is approximate proportional to the on-off gain with two backward pumps. There are two reasons that the DC RIN transfer is not precise proportional to the on-off gain as the RIN transfer from one pump to one signal in the non-depletion pump regime. First, the DC RIN transfer with two pumps has somewhat DC RIN transferring from indirect pump. Since the difference wavelength of the two pumps is 43nm and the Raman gain from pump to pump is small, the DC RIN transferring from indirect pump is small. Second, the DC RIN transfer in DWDM system has small RIN transferring from other signals to the reference signal because the input signal power is small.

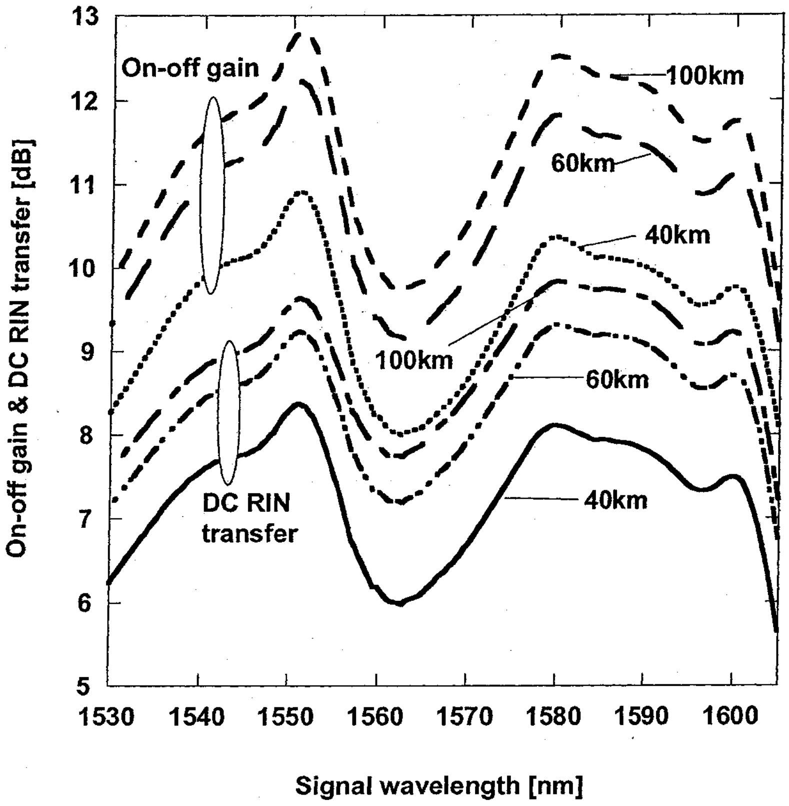

Figure 4.2 The on-off gain and the DC RIN transfer with different fiber length.

Case 3: The DC RIN transfer with six coherent backward pumps

The fiber length is 60km. The modulation index of these pump lasers is assumed 1.0% of the pump power. The wavelength of the six backward coherent pumps is 1425nm, 1436nm, 1447nm, 1461nm, 1485nm and 1500nm respectively. The power of the six backward coherent pumps is 150mW, 110mW, 79mW, 79mW, 97mW and 44mW respectively.

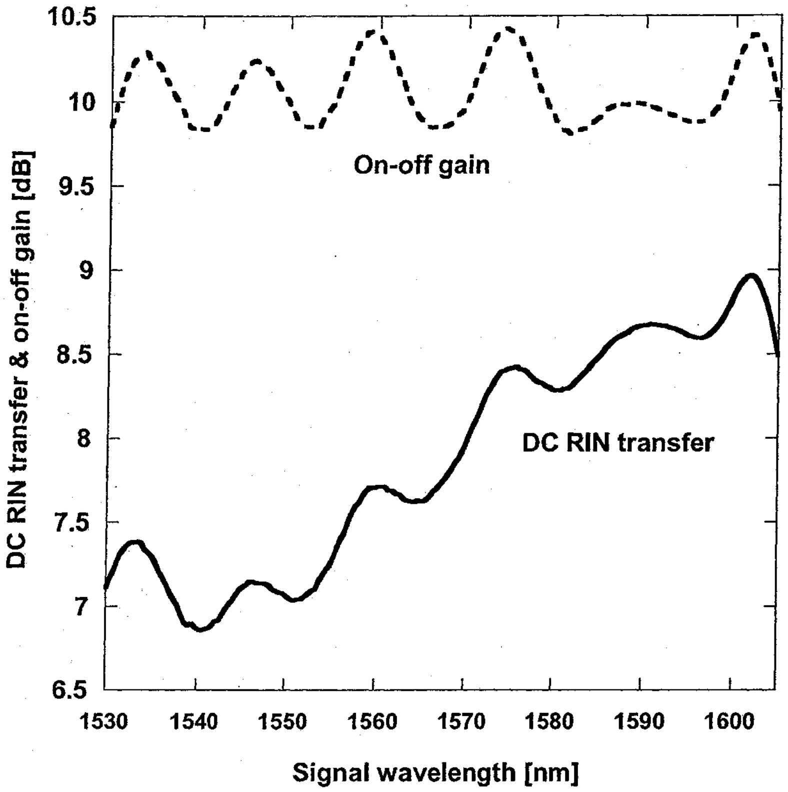

Figure 4.3 The on-off gain and the DC RIN transfer with the six backward coherent pumps.

According to Figure 4.3, the DC RIN transfer is not proportional to the on-off gain as with one pump to one signal case [11]. The DC RIN transfer with multiple pumps to multiple signals is not only relative to its on-off gain but also relative to the RIN transferring from indirect pumps and the other signals. The RIN transferring from the other signals is small since the signal power is small, but the RIN transferring from indirect pumps is big. The difference between first and last pump wavelength is about 75nm, which has big Raman gain from pump to pump, and the pump with shorter wavelength has enough power to pump the longer wavelength pumps, the RIN transfer can occur from the shorter wavelength of pumps to longer wavelength pumps. This is also called dual order pump RIN transfer. The DC RIN transfer for FRAs from dual order pump is higher than from only one pump as explained in Case4.

Case 4: The RIN transfer with one or dual order backward pump to one signal.

The signal wavelength/power is 1560nm/0.5mW. For one backward pump, the wavelength is 1465nm and power is 287mW. For dual order pumps the first order pump wavelength/power is 1465nm/13.5mW and the second order pump wavelength/power is 1375nm/640mW. The parameters are optimized in order to get the same on-off gain in these two situations. The modulation index is 1.0% pump power.

Figure 4.4 illustrates that the DC RIN transfer is 12.15dB with the dual order pump and 6.66dB with one backward pump. Although the on-off gain is the same, the DC RIN transfer has 5.50dB difference. This difference is due to the RIN transferring from indirect pump. When the wavelength difference of pumps has big Raman gain coefficient and the first pump power is big, the DC RIN transferring from indirect pump cannot be negligible.

This is main reason that the longer wavelength signal has higher DC RIN transfer than the shorter wavelength with the six backward coherent pumps.

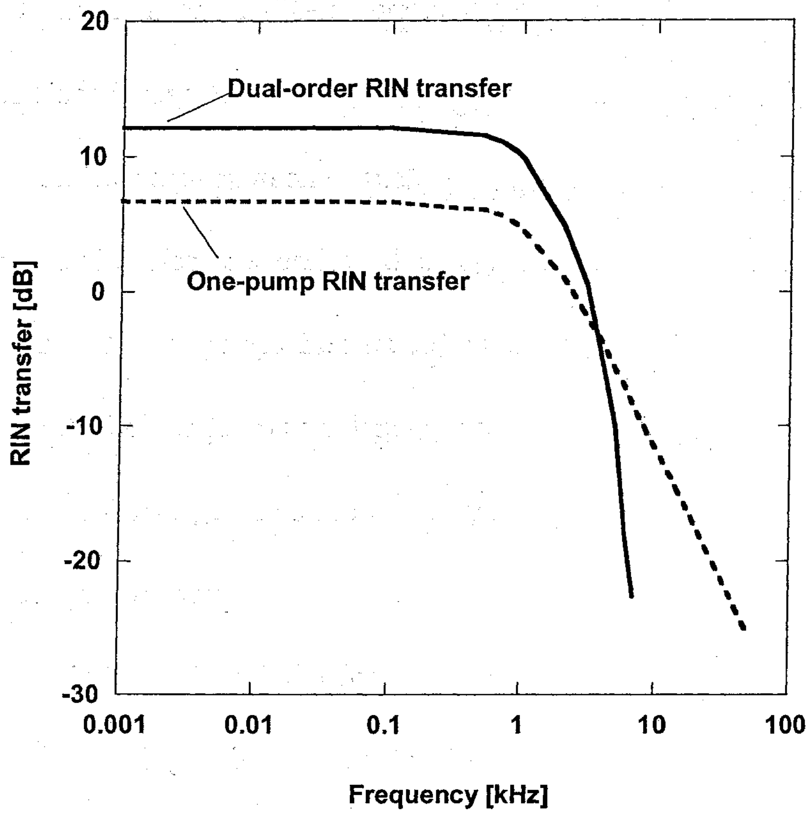

Figure 4.4 The RIN transfer with one pump or dual order pump to one signal.

Case 5: DC RIN transfer with two or six backward coherent pumps

The powers of two backward pumps are 330mW and 218mW. The wavelengths of the two pumps are 1441nm and 1484nm. The power of the six backward pumps is 150mW, 110mW, 79mW, 79mW, 97mW and 44mW respectively. The wavelength of the six backward pumps is 1425nm, 1436nm, 1447nm, 1461nm, 1485nm and 1500nm respectively. The fiber length is 60km. The modulation index of these pump lasers is assumed 1.0% of the pump power.

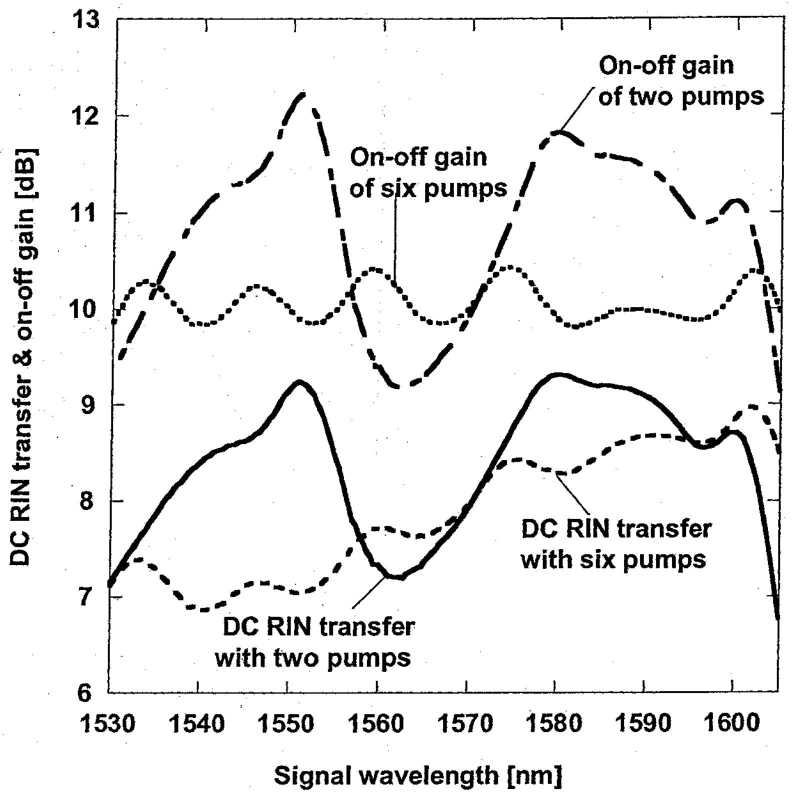

Figure 4.5 Comparison of the on-off gain and the DC RIN transfer using two backward coherent pumps with using the six backward coherent pumps.

According to Figure 4.5, the comparison results are summarized in Table 4.1.

Table 4.1 The comparison results of the on-off gain and the DC RIN transfer with two backward coherent pumps or with the six backward pumps.

	Two backward pumps	Six backward pumps
Average on-off gain	10.78 dB	10.06 dB
On-off gain ripple	3.11 dB	0.59 dB
Average DC RIN transfer	8.34 dB	7.86 dB
DC RIN transfer ripple	2.55 dB	2.09 dB

In Table 4.1, the on-off gain ripple with the six backward coherent pumps is 2.52dB smaller than with the two pumps, but the DC RIN transfer ripple with the six backward coherent pumps is only 0.46dB smaller than with the two pumps. Increasing the number of coherent pumps can obtain much flatter the on-off gain, but the flatness of DC RIN transfer cannot be improved as much as the flatness of on-off gain. The main reason is that the longer wavelength signal has much greater RIN transfer from indirect pumps with the six backward coherent pumps as the analysis in Case 4. So the DC RIN transfer ripple is improved but not improved as the on-off gain when the number of coherent pumps is increased.

4.2 Comparisons of DC RIN transfer with or without considering the RIN transferring from the other signals

For multiple pumps, RIN transfer for FRAs in DWDM systems includes RIN transferring from indirect pump, from pumps to the reference signal and from the other signals to the reference signal as discussed before. Since the RIN transferring from indirect pumps has been investigated for backward pumping scheme in Section 4.1, now DC RIN transferring from the other C+L band signals to the reference signal is studied with two or six backward coherent pumps. Then for two forward pumping schemes, DC RIN transferring with or without considering the other C+L band signals to the reference signal will be compared.

Case 1: Comparison of DC RIN transfer with or without considering RIN transferring from the other signals using two or six pumps.

For two or six backward coherent pumps, DC RIN transfers for FRAs with or without considering RIN transferring from the other signals to the reference signal are compared.

The power of two backward pumps is 330mW and 218mW respectively. The wavelength of the two pumps is 1441nm and 1484nm respectively.

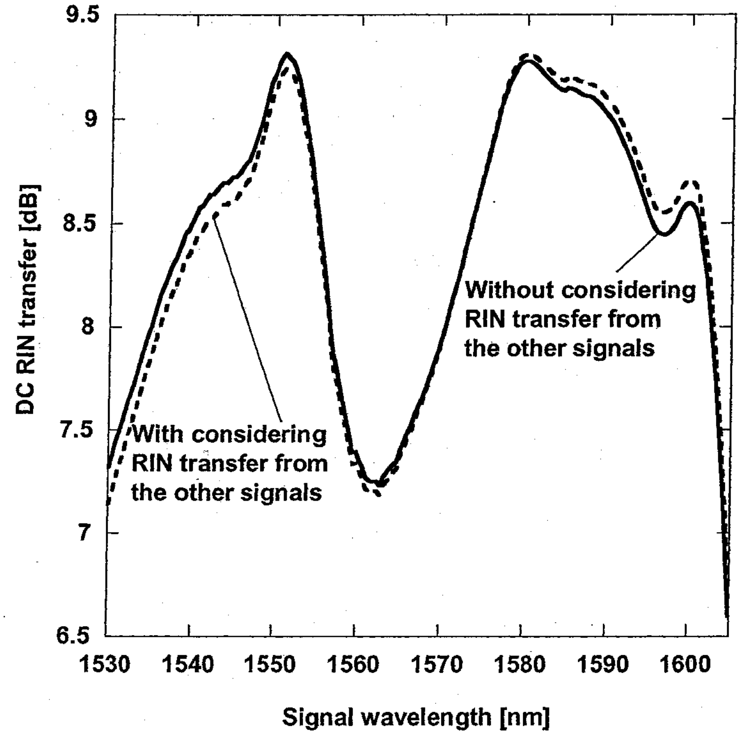

Figure 4.6 DC RIN transfer with or without considering RIN transferring from the other signals using two backward coherent pumps.

The wavelength of the six backward coherent pumps is 1425nm, 1436nm, 1447nm, 1461nm, 1485nm and 1500nm respectively. The power of the six backward coherent pumps is 150mW, 110mW, 79mW, 79mW, 97mW and 44mW respectively.

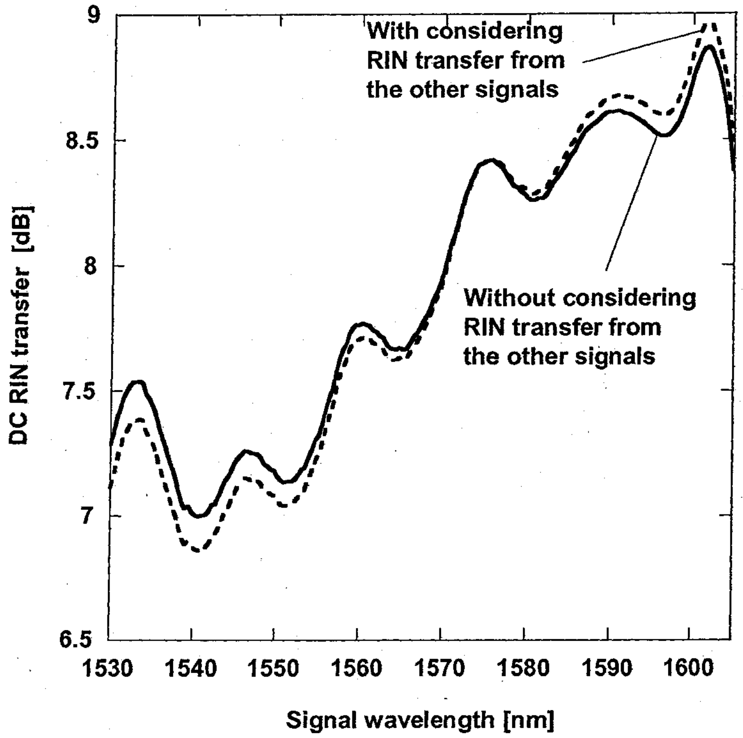

Figure 4.7 The DC RIN transfer with or without RIN transferring from the other signals using six backward coherent pumps.

As shown in Figure 4.6 and Figure 4.7, for FRAs, the wavelength difference of C+L band signals is 75nm, the DC RIN transfer of the shorter wavelength signal with considering RIN transferring from the other signals is smaller than without considering them. While on the other hand, the DC RIN transfer of the longer wavelength signal with considering the RIN transferring from the other signals is bigger than without considering them. The reason is that the DC RIN transfer of shorter wavelength signals is depleted by the longer wavelength signals; in other words, the DC RIN transfer of longer wavelength signals is pumped by the shorter wavelength signals. The difference is not big due to the small signal power.

Case 2: Comparison of DC RIN transfer with or without considering the other C+L band signals to the reference signal using two forward coherent pumps.

The wavelength and power of the two pumps are the same as Case1 only the direction of the pumps is different.

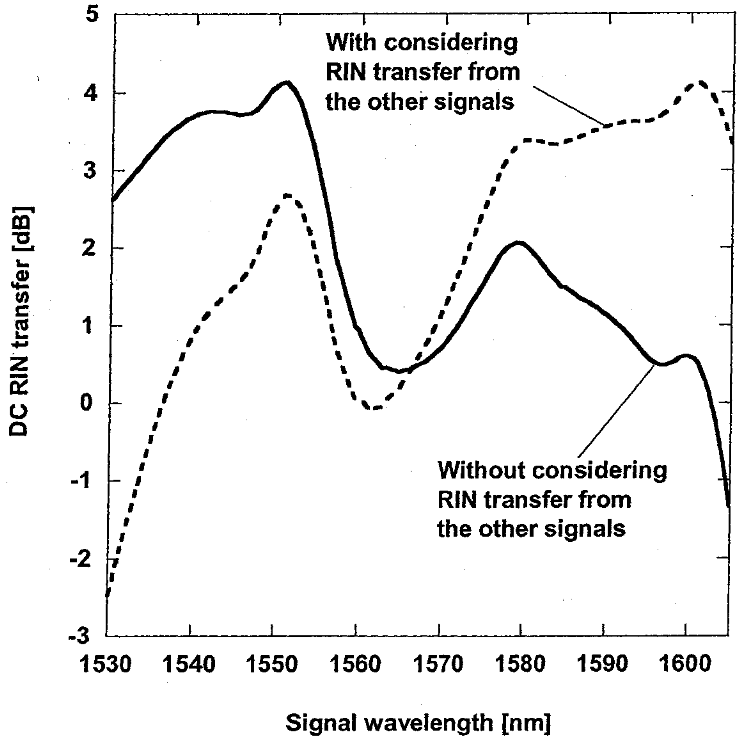

Figure 4.8 Using two forward coherent pumps, the DC RIN transfer with or without considering RIN transferring from the other signals.

As illustrated in Figure 4.8, the DC RIN transfer with or without considering RIN transferring from the other signals to the reference signal is much different for forward pumping scheme. This big difference is due to the FRAs work in depletion pump regime. The DC RIN transfer is totally different with the on-off gain and the average DC RIN transfer is small since FRAs work in pump-depleted regime (discussion in Chapter 6).

4.3 Comparison of the DC RIN transfer using forward pumps to using backward pumps

Since the forward pumping scheme is so different from the backward pumping scheme. The DC RIN transfer with two forward pumps and two backward pumps are compared. The power of two forward or backward pumps is 330mW and 218mW respectively. The wavelength of the two forward or backward pumps is 1441nm and 1484nm respectively. The fiber length is 60km.

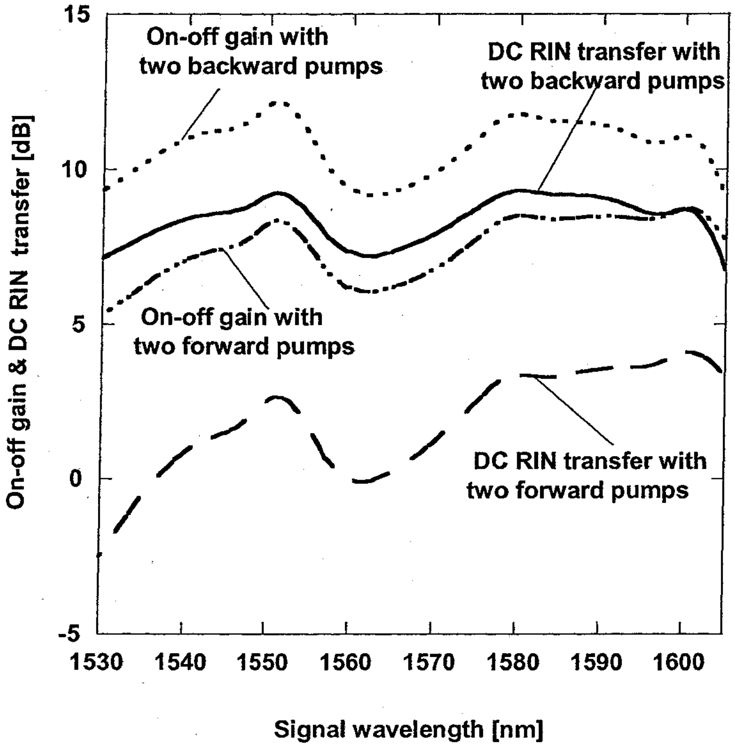

Figure 4.9 Comparison of the DC RIN transfer and the on-off gain using two backward pumps with two forward pumps.

The DC RIN transfer and the on-off gain for FRAs with two forward coherent pumps are compared with two backward coherent pumps as in Figure 4.9 as shown. The results are summarized in Table 4.2.

Table 4.2 The results of comparison using two forward coherent pumps with using two backward coherent pumps.

	Two backward pumps	Two forward pumps
Average on-off gain	10.78dB	7.50dB
On-off gain ripple	3.11dB	3.42dB
Average DC RIN	8.39dB	1.88dB
DC RIN ripple	2.55dB	6.58dB

According to Table 4.2, the 6.51dB difference of the average DC RIN transfer between using two forward pumps and with the two backward pumps. Although the two pumps power is the same, the average on-off gain with forward pumps is 3.28dB smaller than the backward pumps. The DC RIN transfer ripple is bigger with forward pumping scheme than backward pumping scheme. The DC RIN transfer with two forward pumps is not proportional to the on-off gain comparing with the case of two backward pumps. All these results are due to the forward pumps scheme made the FRAs work in pump depletion regime when the power of total input signals is 92mW. Although the same total input signal power, the backward pumping make the FRAs work in non-depletion regime due to the pumps and signals injected into the different sides of the fiber. So the backward pumping scheme is better than the forward pumping scheme due to more pump efficiency to the same pump power and less DC RIN transfer ripple.

CHAPTER 5 PERFORMANCE OF DC RIN TRANSFER FOR FIBER RAMAN AMPLIFIERS WITH INCOHERENT PUMPS

For incoherent pumping scheme, a flatter on-off gain can be obtained by comparing with multiple coherent pumps with the same number of pumps [19]. So the DC RIN transfer for FRAs with incoherent pumps needs to be investigated. In this chapter, first incoherent pump theory is introduced and the modeling of incoherent pump is presented in Section 5.1. While in Section 5.2, RIN transfers, using backward incoherent pump to C band signals, with different fiber length or different pump power are analyzed. The performances of DC RIN transfer with different FWHM bandwidth of forward or backward incoherent pumps are studied. Then DC RIN transfers with forward and backward incoherent pumps are compared. In Section 5.3, DC RIN transfer using one incoherent pump is compared with one coherent pump to C band signals. DC RIN transfer with two incoherent pumps is compared with six coherent pumps to C+L band signals. Modulation indexes are assumed as 1% pump powers in this chapter.

5.1 Incoherent pump theory and its modeling

An incoherent pump is a new Raman Amplifier pump source, which the Ahura Corporation invented and became the commercial product at the year 2003.

An incoherent pump beam is a pump that spreads its power within a broad bandwidth (up to 35nm), not within a very narrow bandwidth like a coherent pump beam. This broadband and high-power incoherent semiconductor pump sources were achieved through coupling of a low-power seed optical signal into a long-cavity semiconductor amplifier waveguide, which was optimized in design for CW power amplification. This seeded power-optical-amplifier (SPOA) concept relies on the design and fabrication semiconductor optical amplifiers. The resulting SPOA output can be efficiently coupled to SMF-28 fiber with a loss of <0.8 dB. Semiconductor optical amplifier is designed and fabricated to have saturated output power of > 250 mW currently [27], and could be further increased. Figure 5.1 is a photograph of high-power broad bandwidth Raman pump module [28]. Within the butterfly package, seeded source input, optical amplifier devices, isolators, detectors, and thin-film signal/pump WDM optics are integrated. Figure 5.2, is an optical spectrum of an on sale incoherent pump [28].

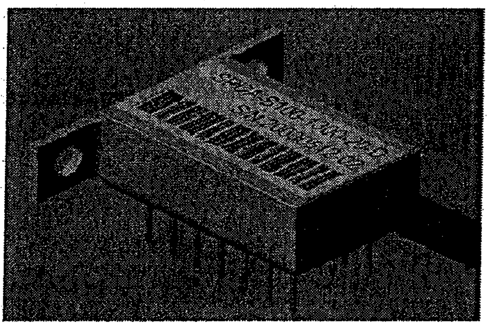

Figure 5.1 High power broadband Raman pump module

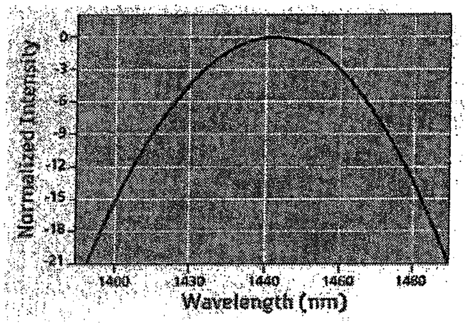

Figure 5.2 Optical-spectrum of an incoherent pump on sale

From the introduction given by Ahura, we know that by adjusting the central wavelength, and input current of the pump model, required incoherent pump can be achieved easily. At this moment, Ahura Corporation provides incoherent pumps with central wavelength between 1440 nm and 1460 nm, with FWHM bandwidth of greater than or equal to 35 nm, and minimum output power of 125 mW.

In the thesis, incoherent pumps are not restricted to the current commercial products.

Simply, we investigate FRAs with incoherent pumps that provide good performance.

Incoherent pump is modeled as follows. The Gaussian noise is generated in a broad bandwidth. After the noise passing through an approximate Gaussian filter, we obtain an approximate Gaussian-intensity spectrum. The incoherent pump is adjustable by changing the center wavelength, FWHM bandwidth of the filter and the power of Gaussian noise. Equation (5.1) is the referring approximate Gaussian filter equation.

$$H(\lambda) = \exp\left[-\frac{1}{2}\frac{(\lambda-\lambda_c)^2}{\lambda_0^{\,2}}\right] \tag{5.1}$$

Where, λ_c is the center wavelength and $\lambda_0 = \frac{FWHM}{\sqrt{2\ln 2}}$.

Figure 5.3 is an example of simulated incoherent pump. The filter is centered at 1453 nm, with FWHM bandwidth of equal to 35 nm. The Gaussian noise power is around 3.31 mW within 1 nm bandwidth. Let the Gaussian noise passes through the above filter; we obtain the incoherent pump shown in Figure 4.3. Its total power is 230 mW and spreads from 1404 nm to 1499 nm. Figure 4.4 shows the on-off Raman gain after a 50 km TW-Reach fiber, which is counter-pumped by the above incoherent pump and same power coherent pump located at 1453 nm.

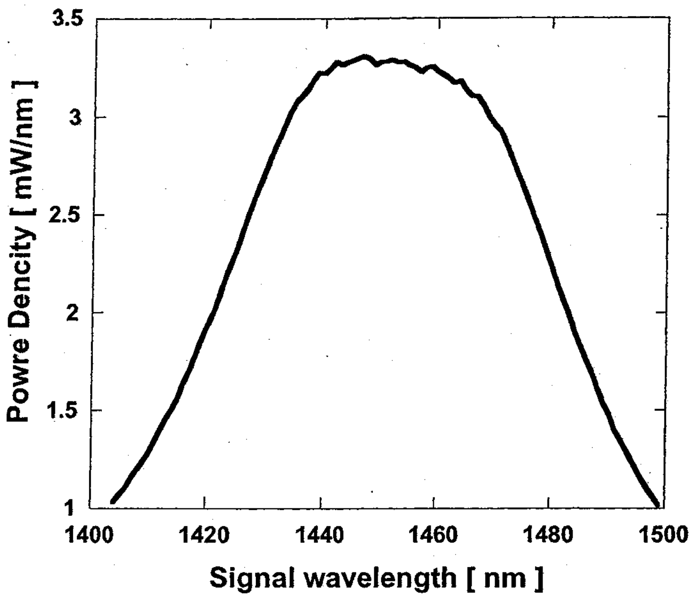

Figure 5.3 Incoherent pump example: central wavelength 1453 nm, FWHM bandwidth 35 nm, total power 230 mW.

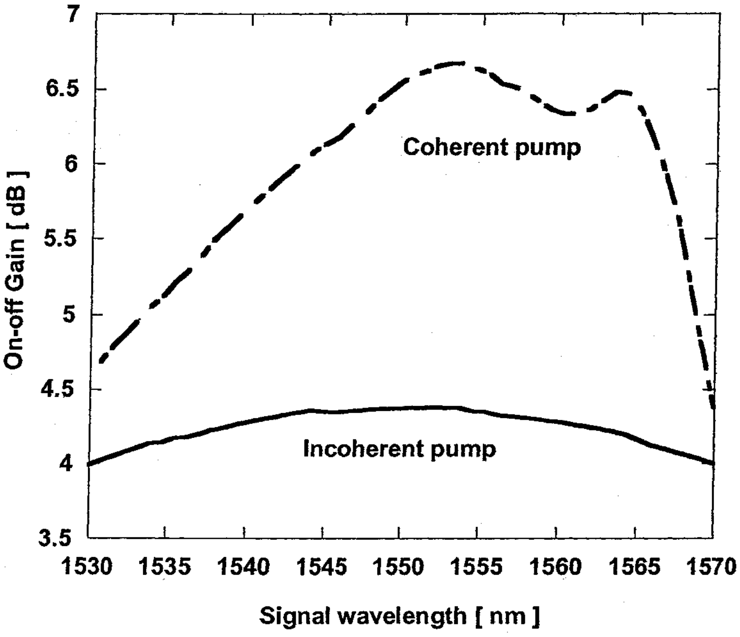

Figure 5.4 On-off gain comparisons: The pump power is 230 mW. Incoherent pump is solid curve. Dot-dash curve is coherent pump located at 1453 nm.

In Figure 5.4, incoherent pump provides a more flat gain than coherent pump with the same power. The example shows that gain ripple by incoherent pump is 0.4 dB, while the smallest gain ripple is 2.3 dB from a coherent pump with 230 mW. However, gain values resulting from incoherent pump are much smaller than the values from coherent pump. The reason for this phenomenon is that incoherent pump spreads its power in a broadband range and amplifies signals in a broader wavelength range. Consequently, gain becomes smaller.

5.2 Performance of DC RIN transfer for FRAs with incoherent pump

In this section, C band signals are 89 signals from 1530nm to 1565nm and have 50GHz channel spacing. Signal input power is 0.5mW per channel. The fiber is 60km TW-Reach fiber except extra illustration.

DC RIN transfer for FRAs is investigated from four aspects: with different pump power or different fiber length or different FWHM bandwidth of pumps or different direction pumping scheme.

Case 1: The DC RIN transfer with different pump power

The FWHM bandwidth of incoherent pump is 5nm; the central wavelength is 1449nm. The DC RIN transfer with one incoherent pump to C band signals at different pumps power is investigated. The total pump power is 321.5mW, 351.766mW and 442.509mW respectively.

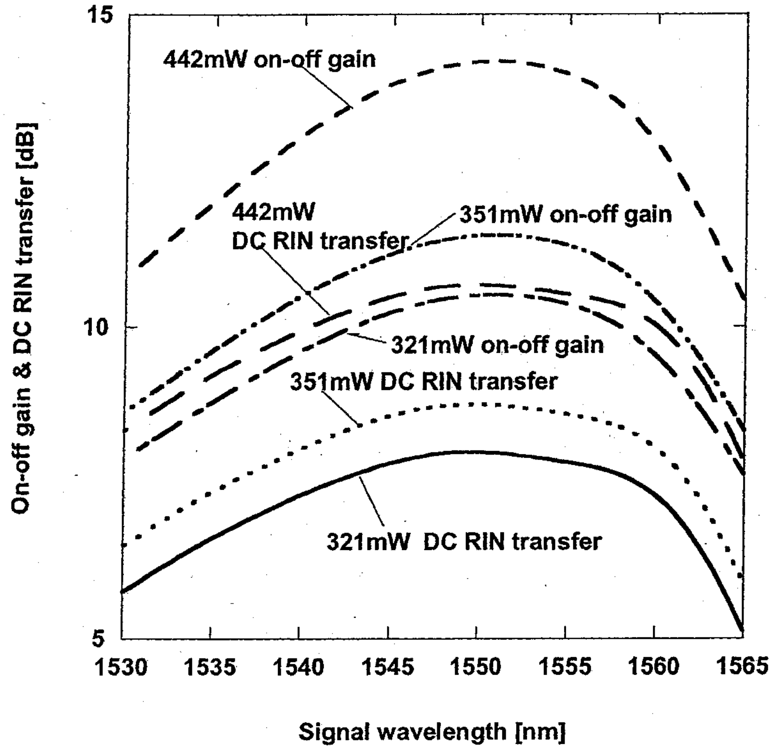

Figure 5.5 The on-off gain and the DC RIN transfer with different pump power.

In Figure 5.5, with the same FWHM bandwidth, average on-off gain and average DC RIN transfer increase along with the total incoherent pump power increasing. For backward pumping scheme, FRAs work in non-depletion pump regime although the input signal power is about 45mW for C band signals. The average on-off gain increases with the increasing of pump power. The DC RIN transfer is roughly proportional to the on-off gain in nondepletion pump regime, which will be discussed in Section 5.3 Case1. Therefore the average DC RIN transfer increases along with the pump power.

Case 2: The DC RIN transfer with the different fiber lengths.

The on-off gain and the DC RIN transfer are compared with different fiber length, which is 40km, 60km and 100km respectively. The DC RIN transfer is considered with

FWHM 20nm bandwidth of backward pump to each of C band signals. The total power of the incoherent pump is 429.12mW. The central wavelength of the incoherent pump is 1448nm.

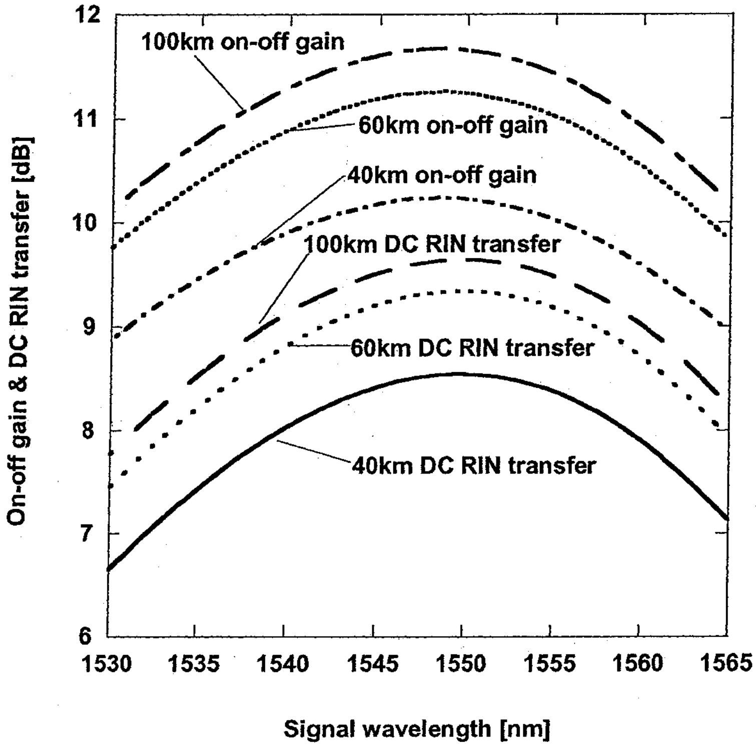

Figure 5.6 The on-off gain and the DC RIN transfer with different fiber length

The results of comparisons are summarized in Table 5.1.

Table 5.1 The comparison results with different fiber lengths

Fiber length	40km	60km	100km
Average on-off gain	9.76dB	10.73 dB	11.12 dB
On-off gain ripple	1.36 dB	1.50 dB	1.54 dB
Average DC RIN transfer	7.95 dB	8.74 dB	9.05 dB
DC RIN transfer ripple	1.90 dB	1.89 dB	1.87 dB

For the same pump power and the same FWHM bandwidth of incoherent pump, with the fiber length increasing, the average on-off gain and the average DC RIN transfer increases. For backward pumping scheme, the FRAs work in the non-depletion pump regime although the input signal power is about 45mW for C band signals. The DC RIN transfer is roughly proportional to the on-off gain in non-depletion pump regime, which will be discussed in Section 5.3 Case1. The average on-off gain increases along with the fiber length. Therefore the average DC RIN transfer increases with the fiber lengths increased.

Case 3: DC RIN transfer with different FWHM bandwidth of backward pump

The FWHM bandwidth of each backward incoherent pump is 5nm, 20nm and 35nm respectively. The total power of each incoherent pump is 351.77mW, 427.94mW and 515.47mW. The central wavelength of each pump is 1449nm, 1448nm and 1439nm. The fiber length is 60km.

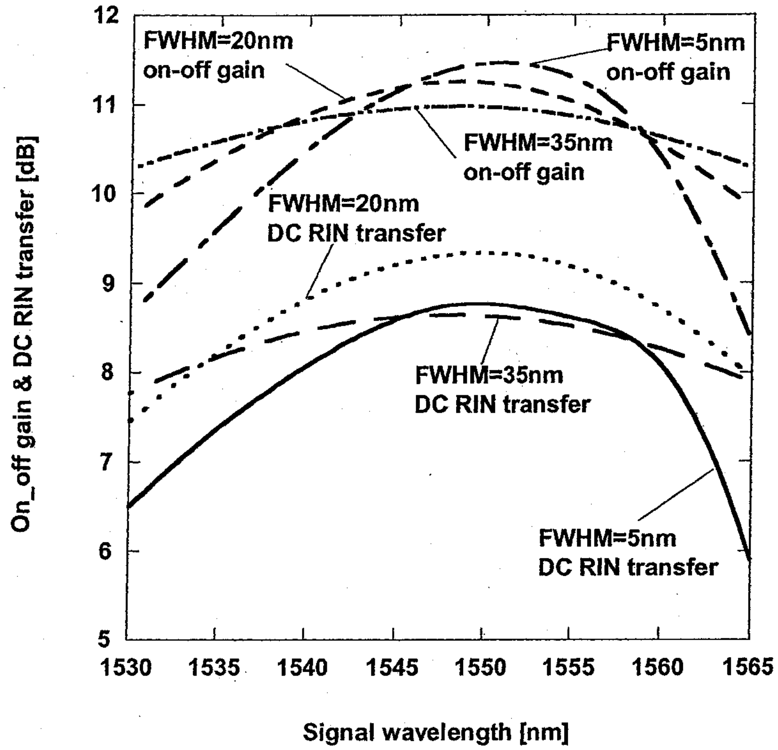

Figure 5.7 The on-off gain and the DC RIN transfer with different bandwidth of backward incoherent pump.

Table 5.2 The results with different FWHM bandwidth of backward incoherent pump.

	FWHM=5nm	FWHM=20nm	FWHM=35nm
Average on-off gain	10.43dB	10.73dB	10.73dB
On-off gain ripple	3.21dB	1.50dB	0.72dB
Average DC RIN	7.97dB	8.74dB	8.36dB
DC RIN ripple	2.99dB	1.89dB	0.88dB

With almost the same average on-off gain, the DC RIN transfer flatness is improved with the increasing of FWHM bandwidth of the incoherent backward pumping source. Apparently, the incoherent pump with 35nm FWHM bandwidth is the best choice for the consideration of the DC RIN transfer flatness. But it needs more pump power and the pump power efficiency is low.

Case 4: DC RIN transfer with different FWHM bandwidth of forward pump.

The FWHM bandwidth of each incoherent pump is 5nm, 20nm and 35nm respectively. The total power of each incoherent pump is 474.07mW, 611.67mW and 722.37mW. The central wavelength of each pump is 1447nm, 1442nm and 1428nm. DC RIN transfers are investigated with FWHM 5nm, 20nm and 35nm forward incoherent pump.

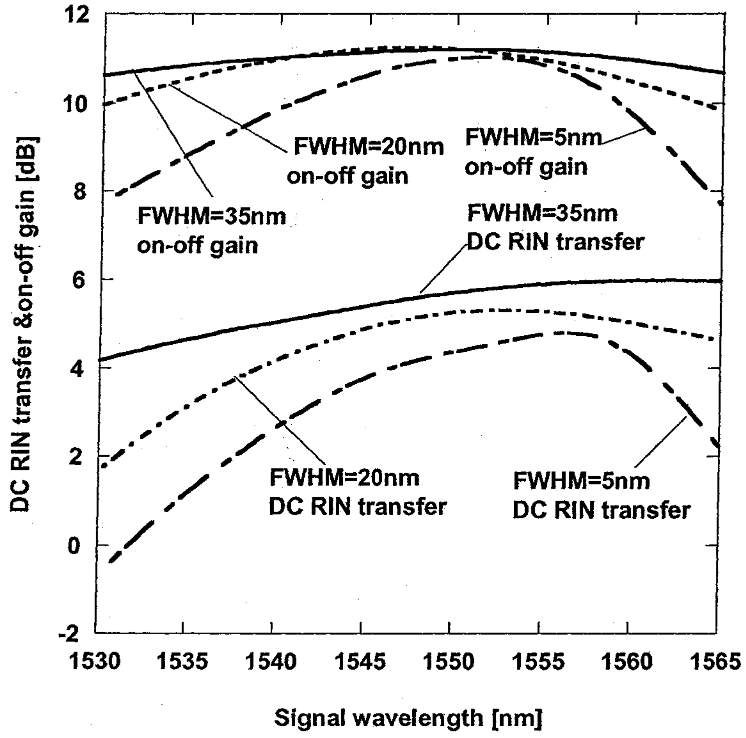

Figure 5.8 The on-off gain and the DC RIN transfer with different FWHM bandwidth of forward incoherent pump.

The results of comparisons from Figure 5.8 are summarized in Table 5.3.

Table 5.3 The results with different FWHM bandwidth forward incoherent pump

	FWHM 5nm	FWHM 20nm	FWHM 35nm
On-off gain ripple	3.31dB	1.30dB	0.58dB
DC RIN transfer ripple	5.47dB	3.64dB	1.80dB

The DC RIN transfer flatness is improved with the increasing of FWHM bandwidth of the incoherent forward pumping source. Apparently, the FWHM 35nm bandwidth incoherent pump is the best choice for the consideration of the DC RIN transfer flatness. These properties are the same as with different FWHM bandwidth of backward pumps in Case3. But for forward pumping scheme, it needs more pump power to get almost the same on-off gain comparing with backward pumping scheme. So the power efficiency is low with forward pumps.

Case 5: Comparison of the DC RIN transfer using forward incoherent pump with using backward incoherent pump.

The FWHM bandwidth of the pump is 35nm. The backward incoherent pump power is 515.47mW and its central wavelength is 1439nm. In order to get the approximate on-off gain, the forward incoherent pump power increased to 722.37mW and its central wavelength is 1428nm.

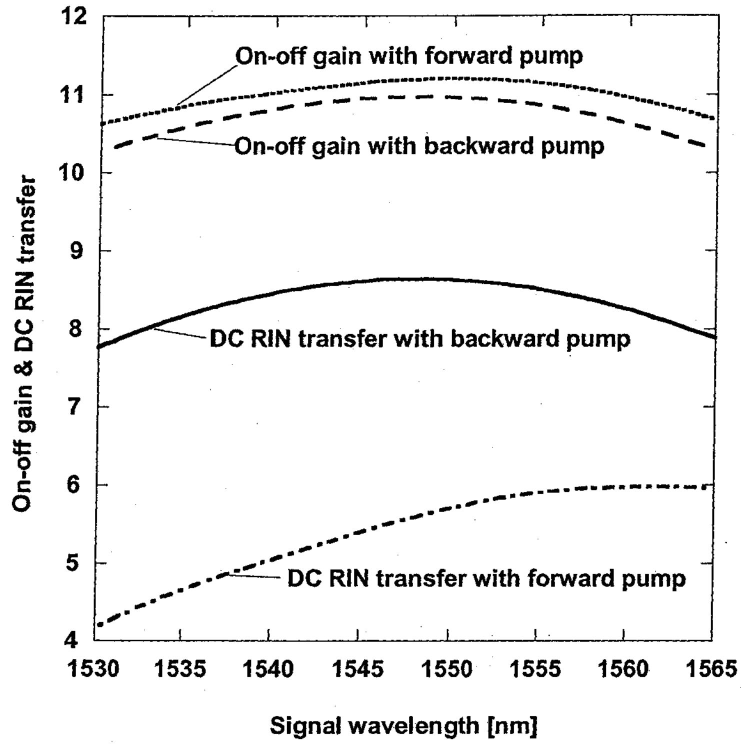

Figure 5.9 The on-off gain and the DC RIN transfer with different direction incoherent pump.

The results of Figure 5.9 are summarized in Table 5.4.

Table 5.4 The results with different direction pumping schemes.

	Backward incoherent pump	Forward incoherent pump
Average on-off gain	10.73 dB	11.01 dB
On-off gain ripple	0.72 dB	0.58 dB
Average DC RIN transfer	8.36 dB	5.40 dB
DC RIN transfer ripple	0.88 dB	1.80 dB

The forward pump power is 206.9mW more than backward pump power in order to get approximate on-off gain. Although the average on-off gain and the on-off gain ripple with forward and the backward incoherent pump are close to each other, the average DC RIN transfer with forward incoherent pump is 2.96dB smaller than with backward incoherent pump. This is due to FRAs working in depletion pump regime. The DC RIN transfer ripple with forward incoherent pump is 0.92dB bigger than with backward pump. So in terms of both the flatness DC RIN transfer and the pump power efficiency, backward pumping scheme is better than forward pumping scheme.

5.3 Comparison of DC RIN transfer using coherent pumps to using incoherent pumps

DC RIN transfer using one backward coherent pump is compared with one backward incoherent pump first. Then performance of DC RIN transfer with six backward coherent pumps is compared with one incoherent or two incoherent pumps.

Case 1: Comparison of the DC RIN transfers using one backward coherent pump to using one backward incoherent pump.

The coherent pump wavelength is 1450nm and its power is 353.5mW. The incoherent pump central wavelength is 1439nm, total power is 515.47mW and the FWHM bandwidth is 35nm.

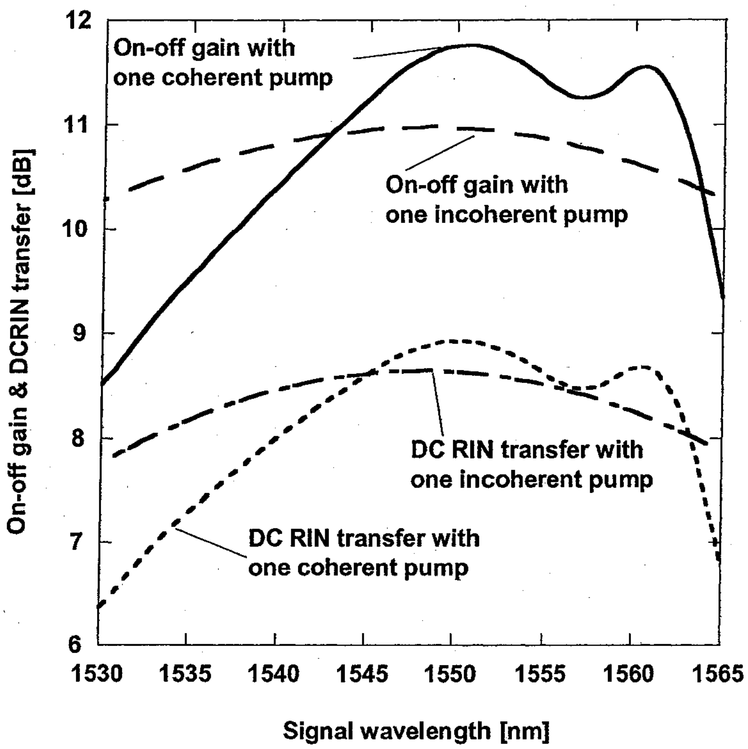

Figure 5.10 The on-off gain and the DC RIN transfer with backward incoherent pump and coherent pump to each of C band signals.

As shown in Figure 5.10, the DC RIN transfer is somewhat proportional to the on-off gain with one coherent or with one incoherent backward pump. One reason is that there is no RIN transferring from indirect pump for coherent pumping scheme, and very small RIN transferring from indirect pump for incoherent pumping scheme. The other reason is that the RIN transferring from the other signals is small since the signal input power is small. The results of comparisons are summarized in Table 5.5.

Table 5.5 The results with one coherent or incoherent backward pump.

	One coherent pump	One incoherent pump
Average on-off gain	10.73dB	10.73 dB
On-off gain ripple	3.25dB	0.71 dB
Average DC RIN transfer	8.13 dB	8.36 dB
DC RIN transfer ripple	2.55 dB	0.88 dB

In Table 5.5, the average on-off gain with one coherent pump is the same as with one incoherent pump, and the average DC RIN transfer with coherent pump is 0.24 dB smaller than with the incoherent pump. The incoherent pump provides not only flatter on-off gain but also flatter DC RIN transfer to C band signals than the coherent pump dose. So the incoherent pumping scheme is better than coherent pumping scheme in terms of the flatness of DC RIN transfer.

Case 2: Comparison of DC RIN transfers using six backward coherent pumps to using one incoherent pump.

The wavelength of six coherent pumps is 1425nm, 1436nm, 1447nm, 1462nm, 1485nm and 1500nm respectively. The power of six pumps is 150mW, 110mW, 79mW, 79mW, 97mW and 44mW respectively. The fiber length is 60km. The one incoherent pump central wavelength is 1439nm and the total power is 515.48mW. The FWHM bandwidth of this incoherent pump is 35nm. Figure 5.11 shows power density of the incoherent pump.

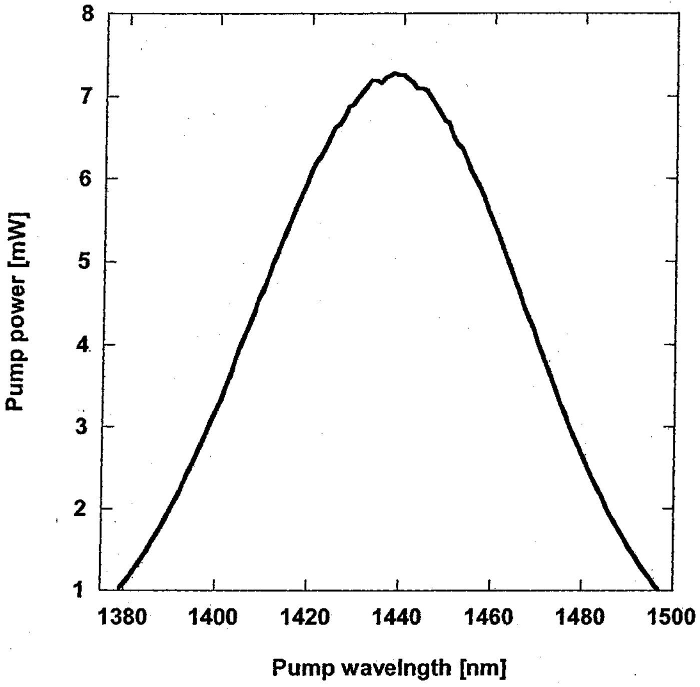

Figure 5.11 The FWHM bandwidth 35nm incoherent pump power density.

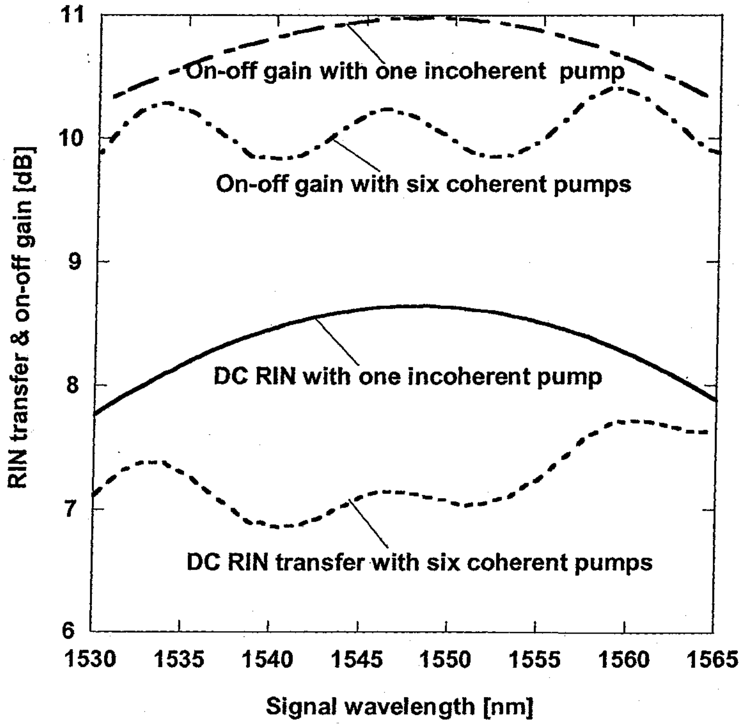

Figure 5.12 The on-off gain and the DC RIN transfer using one incoherent backward pump comparing with using six coherent backward pumps.

The on-off gain ripple is 0.71 dB with one incoherent pump and the on-off gain ripple is 0.58 dB with six coherent pumps. The DC RIN transfer is 0.88 dB with one incoherent pump and the DC RIN transfer is 0.85dB with six coherent pumps. Although using six coherent pumps can get the almost same results as using one incoherent pump, the system will be more complexity. So one incoherent pumping scheme is better than six coherent pumping scheme in terms of the simplification of system and easy implementation.

Case 3: Comparison of the DC RIN transfers using six coherent backward pumps to using two incoherent backward pumps.

The wavelength of six coherent pumps is 1425nm, 1436nm, 1447nm, 1462nm, 1485nm and 1500nm respectively and the power of six pumps is 150mW, 110mW, 79mW, 79mW, 97mW and 44mW respectively. The FWHM bandwidths of both two incoherent pumps are 20nm. The first incoherent pump central wavelength is 1433nm and the second incoherent pump central wavelength is 1489nm. The total power of the two incoherent pumps is 596.71mW.

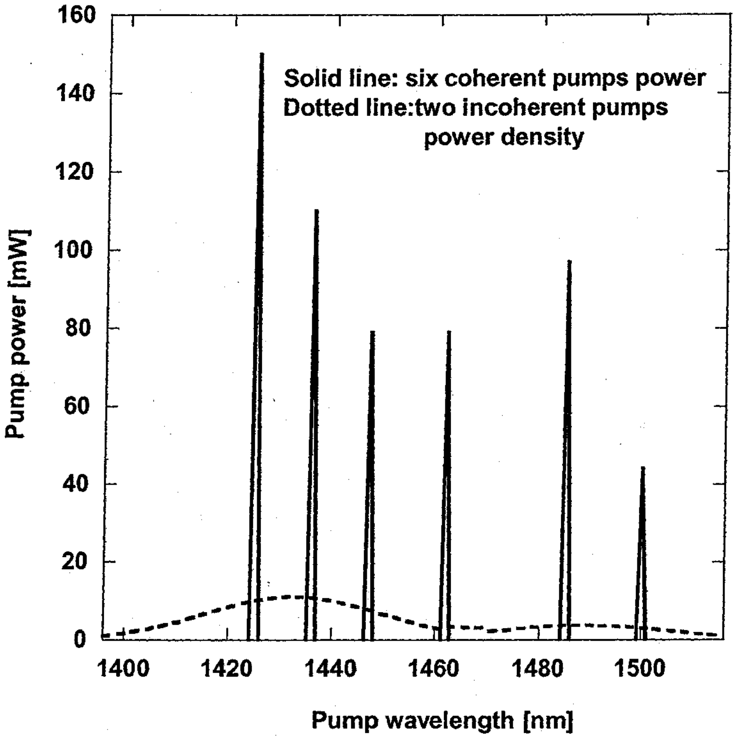

Figure 5.13 Six coherent pumps power and two incoherent pumps power density.

Figure 5.13 illustrates that using two incoherent pumps with small power pump lasers has advantages of not only implementation easily but also small RIN transferring from indirect pumps comparing with six coherent pumps.

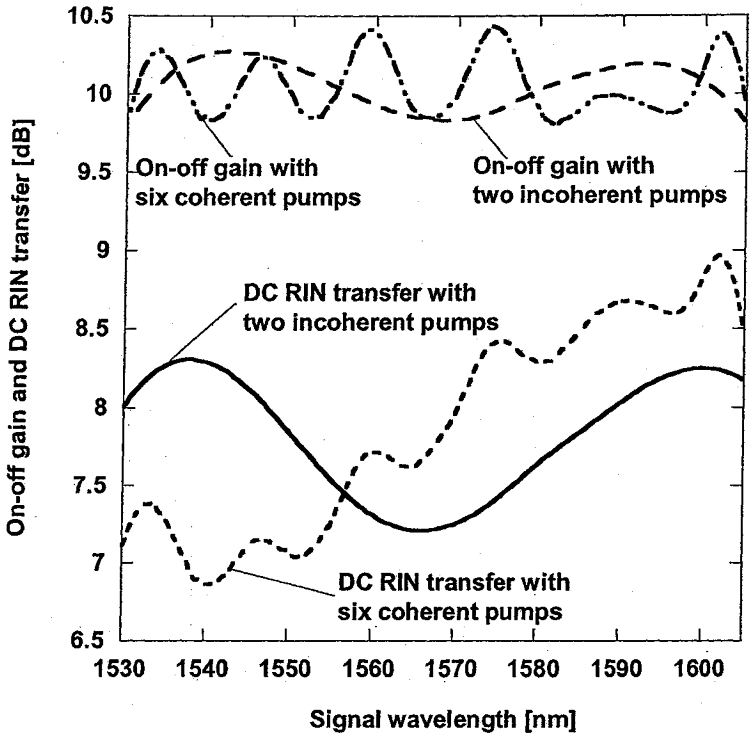

Figure 5.14 The on-off gain and the DC RIN transfer with two incoherent pumps and with six coherent pumps.

According to Figure 5.14, the DC RIN transfer with six coherent pumps is bigger at longer signal wavelengths and smaller at shorter signal wavelengths within C+L band signals comparing with its on-off gain. The main reason is that the RIN transferring from indirect pumps is big. This has already been discussed in Chapter 4. The DC RIN transfer with two incoherent pumps has small RIN transferring from indirect pump because the pump power is obtained by coupling of a low-power seed optical signal into a long-cavity semiconductor amplifier waveguide (see Figure 5.13) and each pump power is small.

From Figure 5.14, the results are summarized in Table 5.6.

Table 5.6 Results of comparison using six coherent backward pumps with using two incoherent backward pumps.

	Six coherent pumps	Two incoherent pumps
Average on-off gain	10.53dB	10.06dB
Average DC RIN transfer	7.86dB	7.82dB
On-off gain ripple	1.10dB	0.48dB
DC RIN transfer ripple	2.10dB	1.10dB

As shown in Table 5.6, to get the almost same on-off gain, the ripples of on-off gain and the DC RIN transfer with two incoherent pumps are smaller than with six coherent pumps. So the incoherent backward pumping scheme is better than coherent backward pumping in terms of not only the easy implementation but also the flatness of the on-off gain and the DC RIN transfer.

CHAPTER 6 PERFORMANCE OF RIN TRANSFER FOR FIBER RAMAN AMPLIFIERS

RIN transfer for FRAs is investigated from two aspects. One is DC RIN transfer and the other is bandwidth of RIN transfer. The DC RIN transfer has been investigated in the previous chapters. The bandwidth of RIN transfer will be investigated in this chapter. In Section 6.1, RIN transfers are analyzed with different direction multiple pumps to only one or to one of C band signals. Then in the same way RIN transfers with one incoherent pump are studied in Section 6.2. In Section 6.3, RIN transfer with one backward coherent pump is compared with one backward incoherent pump to one of C band signals.

6.1 RIN transfer with forward or backward multiple coherent pumps

RIN transfer with six forward or backward pumps is investigated to one signal or one of C band signals. Then for forward pumping scheme, RIN transfer to one signal is compared with to one of C band signals.

Case 1: The RIN transfer with six forward or backward coherent pumps to one signal.

TW-Reach Fiber is considered and the fiber length is 60km. The parameters of six forward and backward pumps are the same. The power of the pumps is 110mW, 87mW, 60mW, 65mW, 85mW and 40mW respectively. The corresponding central wavelength is 1425nm, 1436nm, 1447nm, 1461nm, 1485nm and 1500nm. The total input signal power is 0.5mW.

These pumps are adjusted to get flatter on-off gain for the whole C band signals and get the same on-off gain 8.5dB at the reference signal wavelength 1539.43nm. The RIN transfer is studied with six coherent pumps to the reference signal.

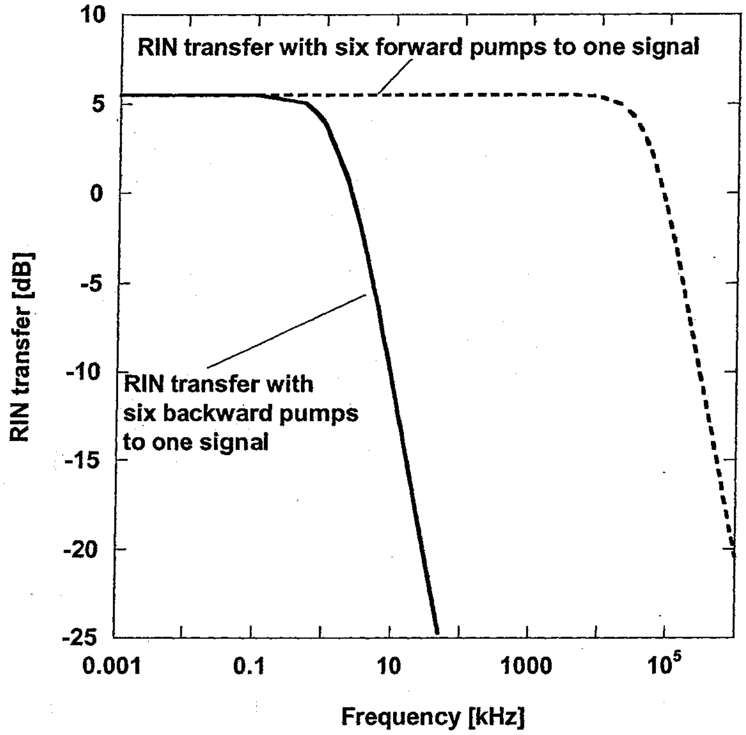

Figure 6.1 The RIN transfer with six forward or backward coherent pumps to only one signal at wavelength 1539.43nm.

In Figure 6.1, the RIN transfer with six coherent pumps to one signal has the same trend as RIN transfer with one pump to one signal as shown in the research [11]. It has the same low frequency RIN transfer for forward or backward pumps. The RIN transfer from the forward pumps has much wider bandwidth than from the backward pumps. The -3dB corner frequency is around 1.4 kHz for backward pumping scheme and around 50MHz for forward pumping scheme. The backward pumping scheme is better than forward pumping scheme in terms of narrower bandwidth.

Case 2: The RIN transfer with six forward or backward coherent pumps to one of C band signals

The C band signals have 89 channels with 0.5mW input power per channel and 50GHz channels spacing, RIN transfer is analyzed to one of these signals. For FRAs, these six pumps pump the whole C band signals and the on-off gain is the same at 1549.43nm wavelength signal for both forward and backward pumping scheme. The total input signal power is 44.5mW. The parameters of these pumps are in Table 6.1.

Table 6.1 The parameters of six forward and backward pumps.

Six forward coherent pump		Six backward coherent pump	
Central wavelength	Pump power	Central wavelength	Pump power
1425nm	150mW	1425nm	110mW
1436nm	110mW	1436nm	87mW
1447nm	79mW	1447nm	60mW
1461nm	79mW	1461nm	65mW
1485nm	97mW	1485nm	85mW
1500nm	44mW	1500nm	40mW

From the Table 6.1, the total power of the forward pumps is higher than backward pumps to get the same on-off gain. So the pump power efficiency of backward pumping scheme is higher than forward pumping scheme.

RIN transfer is investigated with these six backward or forward pumps to 1539.43nm wavelength signal, which is the reference signal.

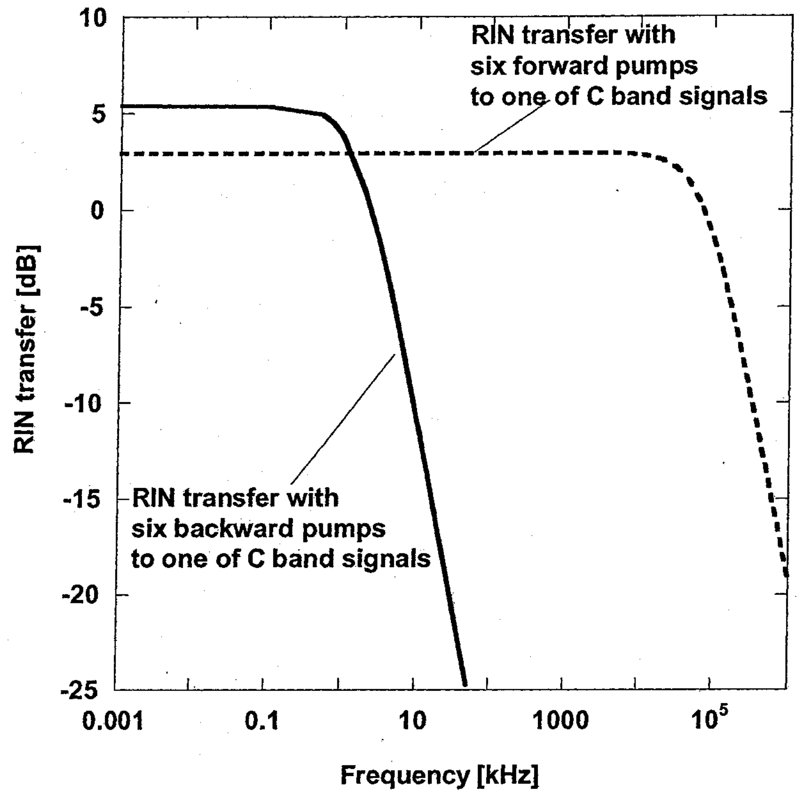

Figure 6.2 The RIN transfer with six forward or backward coherent pumps to one of C band signals.

As shown in Figure 6.2, the low frequency RIN transfer with six forward pumps is not as the same as six backward pumps. The RIN transfer with forward pumps has lower frequency RIN transfer. The reason is that the FRAs work in depletion pump regime with forward pumps. The RIN transfer with forward pumps has much wider bandwidth than with the backward pumps. The -3dB corner frequency is around 1.4 kHz for backward pumping scheme and around 70MHz for forward pumping scheme. The backward pumping scheme is better than forward pumping scheme in terms of narrower bandwidth and higher pump efficiency. But the DC RIN transfer with backward pumps is higher than with forward pumps at the same on-off gain.

Case 3: Comparison of the RIN transfers to one signal with to one of C band signals for six forward coherent pumping schemes.

For backward pumping scheme, the low frequency RIN transfer is 5.5dB and RIN transfer bandwidth is around 1.4 kHz to both one signal and one of C band signals as shown in Figure 6.1 and Figure 6.2. But for forward pumping scheme, the low frequency and the bandwidth of the RIN transfer with one signal is not the same as with one of C band signals. So it is necessary to compare the RIN transfer to one signal with to one of C band signals. These pumps are adjusted to make the on-off gain is almost same around 8.5dB in both considering one signal and considering one of C band signals.

Table 6.2 The parameters of six forward pumps to one or one of C band signals.

Six forward pumps to one of C band signals		Six forward pumps to one signal	
Central wavelength	Pump power	Central wavelength	Pump power
1425nm	150mW	1425nm	110mW
1436nm	110mW	1436nm	87mW
1447nm	79mW	1447nm	60mW
1461nm	79mW	1461nm	65mW
1485nm	97mW	1485nm	85mW
1500nm	44mW	1500nm	40mW

For forward pumping scheme, as shown in Figure 6.3, the DC RIN transfer is 5.5dB and RIN transfer bandwidth is 50MHz when considering one signal. While the DC RIN transfer is 2.9dB and the RIN transfer bandwidth is 70MHz at the time considering one of the whole C band signals. The RIN transfer to one of C band signals has a lower DC RIN transfer and broader bandwidth than to only one signal when the on-off gain is almost same. These properties are the same as from one pump to one signal of RIN transfer when the input signal power is big enough [22]. The reason is that the FRAs work in pump depletion regime when the forward pumps pump the whole C band signal and input signal power is around 44.9mW.

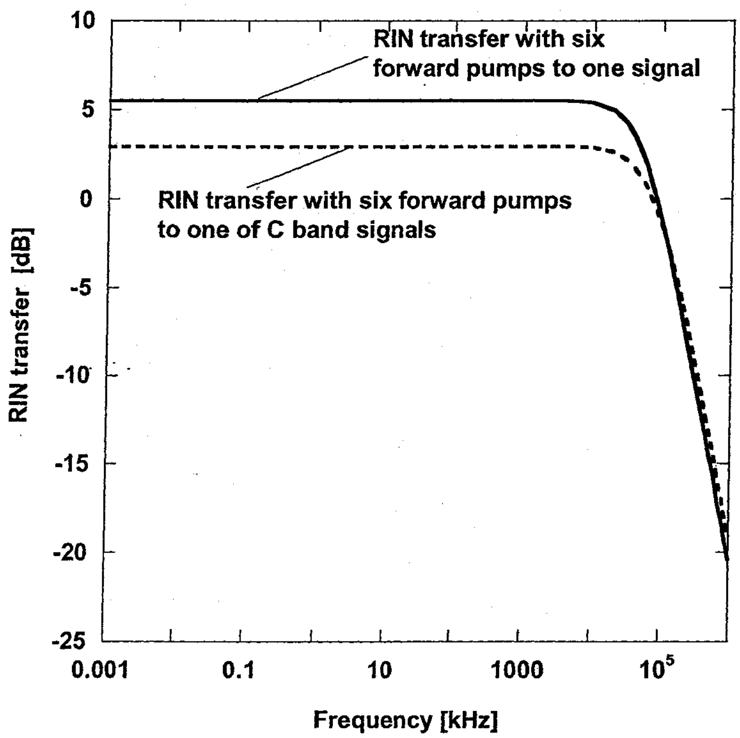

Figure 6.3 The RIN transfer with six forward coherent pumps to one of C band signals or to only one signal.

From above illustrations, with multiple pumps pumping multiple signals in DWDM system, the forward pumping scheme makes the FRAs work in the pump depletion regime, so the backward pumping scheme is better than the forward pumping scheme because of the higher pump power efficiency and narrower bandwidth.

6.2 RIN transfer with one forward or backward incoherent pump

The RIN transfer with one forward or backward incoherent pump is investigated to one signal or to one of C band signals respectively. For forward pumping scheme, the RIN transfer to one signal is compared with to one of C band signals. The parameters of the signals and the fiber are the same as the Section 6.1. The incoherent pump has FWHM 35nm bandwidth and the central wavelength is 1439nm.

Case 1: The RIN transfer with one forward and backward incoherent pump to only one signal.

The pump power is about 380mW to get the almost same on-off gain, which is around 9.12dB at the considering signal wavelength 1539.43nm.

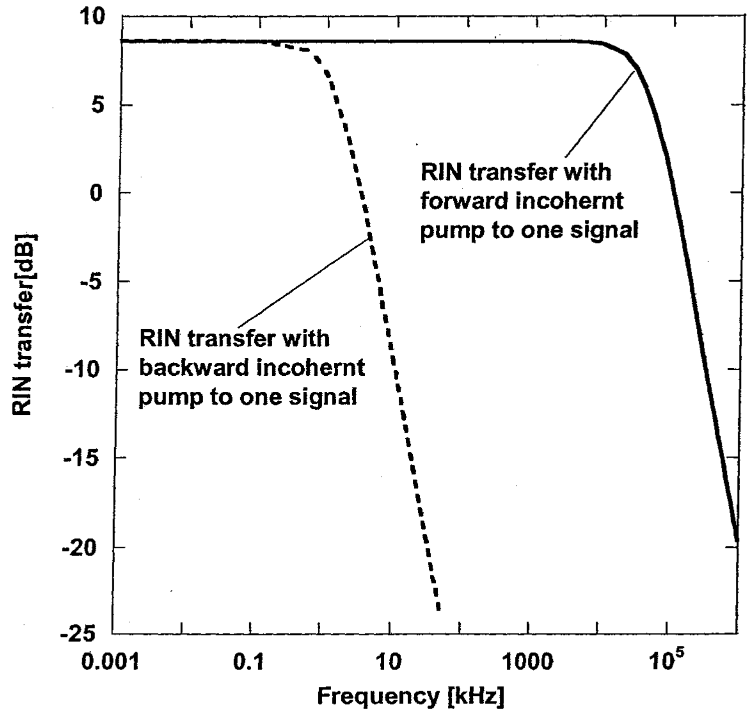

Figure 6.4 The RIN transfer with one forward or backward incoherent pump to only one signal at 1539.43nm.

In Figure 6.4, the low frequency RIN transfer is the same for both directions pumps. The RIN transfer from the forward pump has much wider bandwidth than the RIN transfer from the backward pump. The -3dB corner frequency is around 1.4 kHz for backward pumping scheme and around 40MHz for forward pumping scheme. The backward pumping scheme is better than forward pumping scheme in terms of narrower bandwidth.

Case 2: The RIN transfer with one forward and backward incoherent pump to one of C band signals.

The C band signals have 89 channels with 0.5mW input power per channel and 50GHz channels spacing, the RIN transfer is only analyzed to one of these signals. The total input signal power is 44.5mW. For FRAs, the whole C band signals are pumped by one incoherent pump. The pump power of forward or backward pump is optimized to obtain the same on-off gain at the reference signal which wavelength is 1549.43nm. For backward pumping the total pump power is about 398.93mW and for forward pumping the pump power is 515mW.

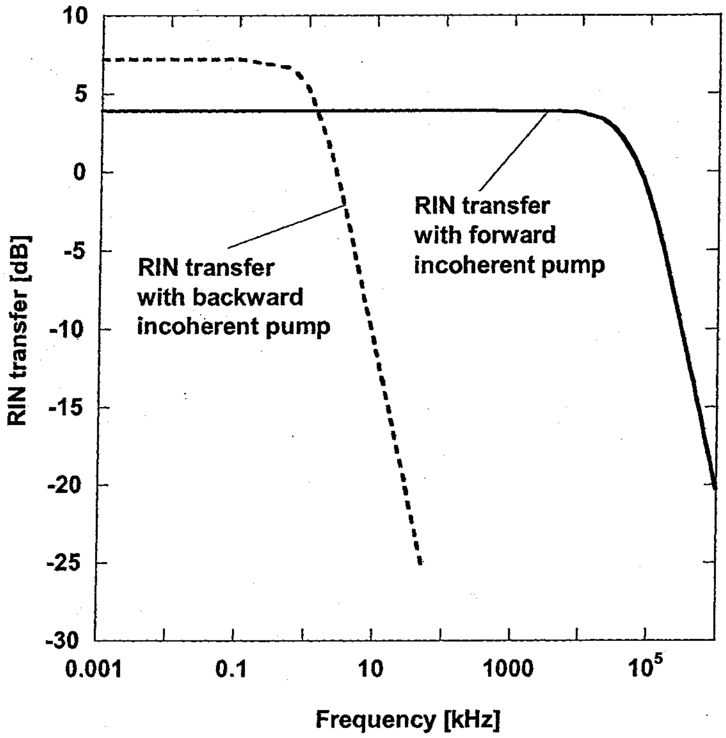

Figure 6.5 The RIN transfer with one forward or backward incoherent pump to one of C band signals.

The forward pump power is bigger than the backward pump power when the reference signal has the same on-off gain. The low frequency of RIN transfer with forward pump is smaller than the backward pump from Figure 6.5. The reason is that the power of input signals is big enough to make the FRAs work in depletion pump regime for forward pumping scheme. The -3dB corner frequency is around 1.4 kHz for backward pumping scheme and around 60MHz for forward pumping scheme. The backward pumping scheme is better than forward pumping scheme in terms of narrower bandwidth.

Case 3: Comparison of the RIN transfers to one signal with to one of C band signals using one forward incoherent pumping scheme.

The RIN transfer with one forward FWHM 35nm bandwidth of incoherent pump to one signal is compared with to one of C band signals. The reference signal wavelength is 1539.43nm and the on-off gain at this signal wavelength is around 8.5dB with adjusting the pump power. The power of incoherent pump is 374.90mW for pumping one signal and 515.48mW for pumping the whole C band signals.

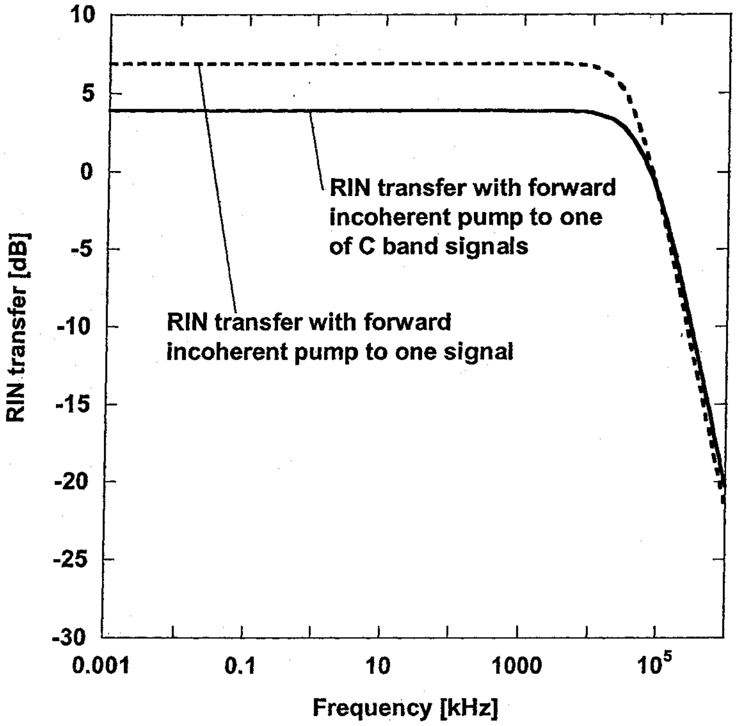

Figure 6.6 The RIN transfer with one forward FWHM 35nm bandwidth incoherent pump to only one signal or to one of C band signals.

For forward pumping scheme, the low frequency RIN transfer is 7.0dB and RIN transfer bandwidth is 40MHz when the pump only pumps one signal. The low frequency RIN transfer is 3.9dB and the RIN transfer bandwidth is 60MHz when the pump pumps the whole C band signals and only considered one of C band signals as reference signal which wavelength is 1539.43nm. The forward pump that pumps the whole C band signals makes the FRAs work in depletion pump regime since the input signal power is around

44.9mW. For backward pumps, the FRAs work in non-depletion pump regime with the same input signal power because the signals and the pump are injected into the fiber at different sides. The RIN transfer has lower DC RIN transfer and broader bandwidth with forward pump. These properties are the same as with one forward pump to one small or big power signal [22] and also as with multiple forward coherent pumps to one signal or one of C band signals, which is discussed in Section 6.1. In DWDM system, with incoherent pump pumping multiple signals, the backward pumping scheme is better than the forward pumping scheme because of narrower RIN transfer bandwidth.

6.3 RIN transfer using one coherent pump compared to using one incoherent pump

The RIN transfer from one coherent backward pump is compared with from one incoherent backward pump to one of C band signals. The signal wavelength is 1555nm. The coherent pump wavelength is 1450nm and the power is 345mW. The incoherent pump central wavelength is 1450nm and the total power is 427.9mW. The incoherent FWHM bandwidth is 20nm. Figure 6.7 indicates the on-off gain of the whole C band signals with the coherent pump or the incoherent pump.

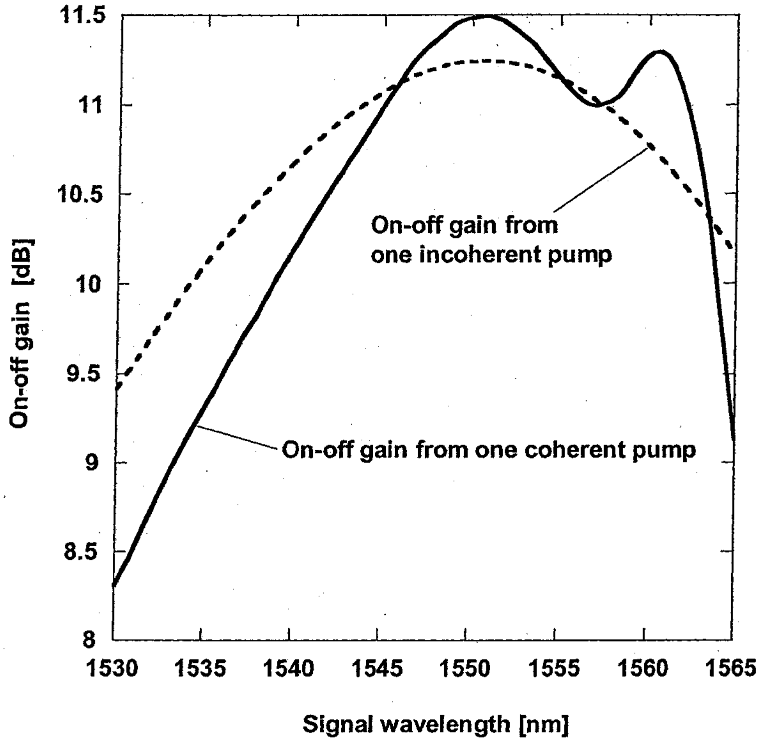

Figure 6.7 The on-off gain from the coherent pump and incoherent pump to one of C band signals.

In Figure 6.7, the on-off gain is the same at the reference signal which wavelength is 1555nm. The RIN transfer is investigated at this reference signal with one coherent pump or with one incoherent pump as shown in Figure 6.8.

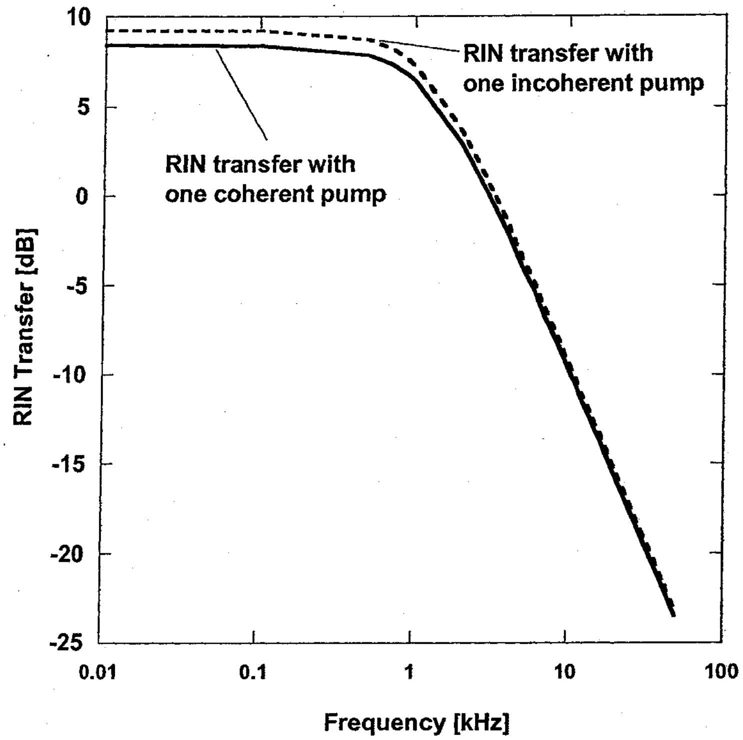

Figure 6.8 The RIN transfer with the coherent pump and with the incoherent pump to the reference signal, which is one of C band signals.

As shown in Figure 6.7 and Figure 6.8, the reference signal is chosen with the same on-off gain for these two pumping schemes, but the RIN transfers are somewhat different. The low frequency RIN transfer with incoherent pump is 0.85dB higher than with coherent pump. The –3dB corner frequency has a small difference. When considering the ripple of the DC RIN transfer, the incoherent pumping scheme is better than the coherent pumping scheme. Moreover, the incoherent pumping scheme can be implementation easier than coherent pumps.

CHAPTER 7 CONCLUSIONS

7.1 Contributions of this thesis

RIN transfer with one or dual order pump to one signal has been investigated in the previous papers [11] [22]. Nowadays, in DWDM systems the multiple coherent and incoherent pumps are used to get the flatness of on-off gain for multiple signals. Therefore investigations and explorations of RIN transfer with multiple coherent or incoherent pumps in DWDM system are necessary.

A RIN transfer model for multiple pumps to multiple signals has been established in Chapter 2. The model verifications are done by different cases in Chapter 3. Having this model, RIN transfers are investigated with multiple coherent or incoherent pumps to multiple signals from the following aspects.

For multiple coherent pumping schemes, DC RIN transfer is not only relative to its on-off gain but also relative to RIN transferring from indirect pumps and from the other signals. The ripple of DC RIN transfer decreases with increasing the number of coherent pumps and average DC RIN transfer increases along with the fiber length when FRAs work in non-depletion pump regime. The ripple of DC RIN transfer with backward pumping scheme is smaller than with the forward pumping scheme.

For one incoherent pumping scheme, since the pump is consisted with seeded power optical amplifiers, the seeded power is so small that RIN transferring from indirect pumps can be negligible. The ripple of DC RIN transfer with backward pumping is smaller than with forward pumping. Through increasing FWHM bandwidth of incoherent pump, the ripple of DC RIN transfer is decreased. Average DC RIN transfer increases along with the fiber length or pump power for backward pumping scheme when FRAs work in non-depletion pump regime. The ripple of DC RIN transfer with two incoherent backward pumps is smaller than with six coherent backward pumps because RIN transferring from indirect pump is small with incoherent pumping scheme. To achieve the same DC RIN transfer flatness, the number of pumps for FRAs with incoherent pumping can be significantly reduced comparing with coherent pumping.

In DWDM system, forward pumping scheme can make FRAs work in depletion pump regime. For considering multiple signals, low frequency RIN transfer is smaller and the bandwidth is broader than considering only one signal.

For incoherent pumping scheme, the ripple of DC RIN transfer is smaller but the average low frequency RIN transfer and the bandwidth of RIN transfer are not big different comparing with the coherent pumping scheme.

The backward pumping scheme is more suitable for DWDM system because the smaller DC RIN transfer ripple and narrower RIN transfer bandwidth. Moreover, the backward pumping scheme can get the higher pump efficiency due to the FRAs working in nondepletion pump regime.

7.2 Future works

Having done all these analysis, future works related to this thesis could be focused on with the following aspects:

(i) Research of the RIN transfer with bi-direction pumping scheme.

Since the RIN transfer has been studied with forward or backward pumps respectively and nowadays for FRAs bi-directional pumping scheme is used, investigated the RIN transfer with bi-directional pump has practical meaning.

(ii) Research of the RIN transfer with the crystal fiber.

So far we considered only the RIN transfer with TW-Reach fiber, the performance and properties of the RIN transfer need to be explored with crystal fiber, which is a new high nonlinearly coefficient FRAs.

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Acronyms

RIN	relative intensity noise
DFRAs	distributed fiber Raman amplifiers
DWDM	dense wavelength division multiplexing
DisFRA	discrete fiber Raman amplifier
DC RIN	dc level of RIN
FWHM	full-width at half-maximum
FRAs	fiber Raman amplifiers
EDFAs	erbium-doped fiber amplifiers
O-E-O	optical-electrical-optical
SOAs	semiconductor optical amplifiers
FPA	Fabry-Perot Amplifier
TWA	Traveling Wave Amplifier
SRS	stimulated Raman scattering
OSNR	optical signal to noise ratio
SPOA	seeded power-optical-amplifier