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Ultra-thin, single-layer polarization rotator

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We demonstrate light polarization control over a broad spectral range by a uniform layer of vanadium dioxide as it undergoes a phase transition from insulator to metal. Changes in refractive indices create unequal phase shifts on s- and p-polarization components of incident light, and rotation of linear polarization shows intensity modulation by a factor of 10^3 when transmitted through polarizers. This makes possible polarization rotation devices as thin as 50 nm that would be activated thermally, optically or electrically. [http://dx.doi.org/10.1063/1.4960552]

INTRODUCTION

The need for compact polarization rotators in displays and integrated optics is driving research for functional materials with optical activity and controllable anisotropy. The limiting factor on how thin a device can be made is the rotatory power, or the rotation angle per unit length, which depends on the amount of anisotropy induced in the material. For example, liquid crystals achieve 90 degrees polarization rotations over lengths of about one micrometer, and recent advances in transparent magneto-optic materials combined with photonic crystal technology has created devices with roughly the same thickness.[1,2]

In this study, we investigate vanadium dioxide as a candidate for ultrathin, controllable polarization rotating devices. In this material, a phase transition from insulator to metal occurs at the relatively low critical temperature of T_c = 68 °C, which coincides with large changes in refractive indices. Exploiting this effect, we demonstrate broadband, highly efficient polarization control by a single layer with thicknesses from 50 to 100 nm. Since the phase transition may be induced optically[3–5] or electrically driven,[6,7] it offers flexibility for device operation.

EXPERIMENTAL

Samples of vanadium dioxide (VO_2) were prepared for this study using a procedure described in Refs. 8 and 9. Layers were deposited by sputtering onto substrates of glass, quartz and Zerodur, a glass with low thermal expansion coefficient. Table I summarizes the properties and preparation conditions of samples used in this study. Vanadium dioxide is a complex material whose stoichiometry, morphology, optical and electrical properties are sensitive to the conditions of fabrication. Samples were therefore analyzed by spectrometry and ellipsometry at different temperatures to confirm their proper composition before use in experiments. For example, Figure 1 shows the real and imaginary parts of refractive indices of sample A changing as VO_2 is heated above its critical temperature. This refractive index change causes a light beam reflecting off the layer to experience a phase shift that is generally not the same for the s- and the p-component of the electric field, thereby altering the polarization state.[10] For example, a relative phase shift $\Delta = \pm\pi$ rotates linear polarization, while the transformation between linear and circular polarizations requires $\Delta = \pm\pi/2$. The

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TABLE I. Characteristics of samples used and preparation conditions.

Sample	Substrate	Thickness	Preparation conditions
A	Zerodur	50 nm	Metallic vanadium deposited by sputtering, post-treatement at 520 °C, 150 mtorr oxygen for 2 hours
B	Glass	110 nm	Metallic vanadium deposited by sputtering, post-treatement at 465 °C, 50 mtorr oxygen for 2 hours
C	Quartz	150 nm	Metallic vanadium deposited by sputtering, post-treatement at 465 °C, 50 mtorr oxygen for 2 hours

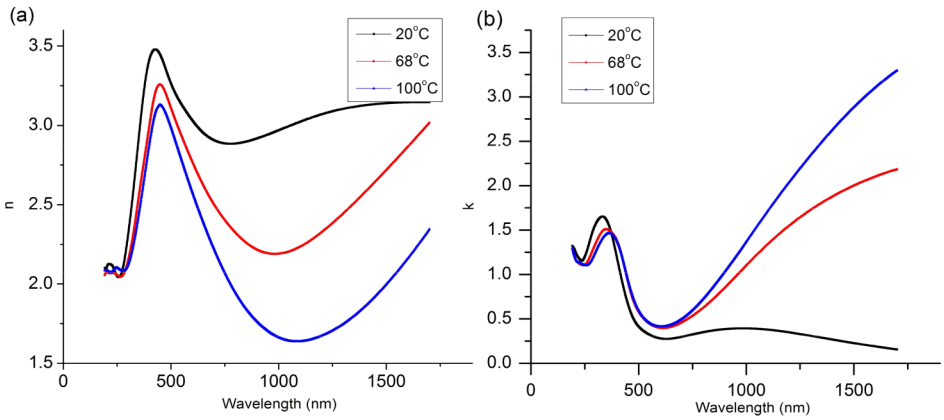

FIG. 1. (a) real and (b) imaginary refractive indices of VO_2 in its insulating state (20°C), its transition state (68°C) and its metallic state (100°C) for sample A.

theory for this effect and its applications have been described in a recent article,[11] and results are found to depend on temperature, layer thickness, incidence angle and wavelength. For the reflected beam, the relative phase shift is

$$\Delta = \arg(z_r) \tag{1}$$

With

$$z_r = \frac{r_{Bs}}{r_{As}} \frac{r_{Ap}}{r_{Bp}} \tag{2}$$

where the r's are the overall Fresnel coefficients of reflection from the film on substrate, where subscripts s and p refer to polarization type and where subscripts and A and B refer to temperatures T_A and T_B.

From calculations done with VO_2 refractive indices reported by various studies, Ref. 11 suggested possible polarization control from 500 nm to 1600 nm and beyond if the appropriate layer thickness and angle of incidence are selected.

The experimental setup used to measure polarization rotation is depicted in Figure 2. Laser beams at wavelengths of 543, 633 or 1550 nm are sent through a polarizer and reflected off a VO_2 layer sample. Since the layer generally causes polarization to become elliptical, a birefringent crystal is used to prepare the incident polarization such that it become linear after reflection from the sample. This way, rotation of linear polarization may be possible for the reflected beam. As the sample is heated externally from 20°C to 100°C (in about one minute), reflected light is analyzed through a polarizer and a photodetector. The state of polarization then becomes apparent from polar plots of transmitted intensity through the polarizer as a function of the polarizer's angle of orientation.

Figure 3 shows results obtained at 633 nm with sample A. Polar plots of transmitted intensity are given for temperatures below and above the critical temperature. The incidence angle is set at $\theta_i = 76°$. At low temperature, the reflected beam is linearly polarized at $\varphi = 80°$, but at high

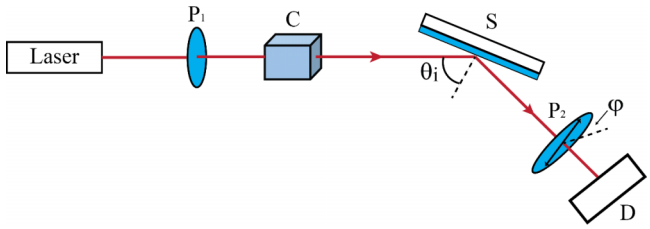

FIG. 2. Experimental setup for polarization rotation measurements. A laser beam is sent through a polarizer P_1 and a birefringent crystal (C) before reflecting off a sample S at an incident angle θ_i. Reflected light is analyzed through a second polarizer P_2 and a photodetector D. Polarizer P_2 is oriented at an angle φ relative to the plane of incidence.

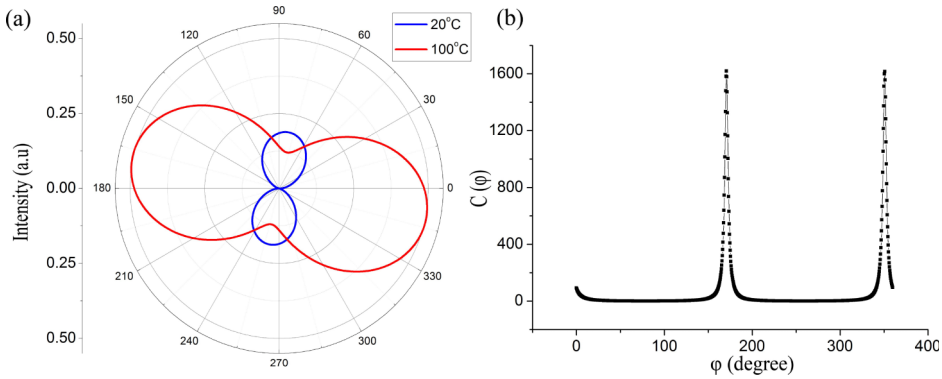

FIG. 3. (a) Reflected light intensity at 633 nm transmitted through polarizer P_2 with sample A in its insulator state (blue) and metal state (red), (b) Intensity ratio between the two results versus polarizer angle.

temperature it shows the signature of elliptical polarization with the long axis oriented at 170°. From the shape of the plots we calculate a relative phase shift $\Delta = 0.64\ \pi$ between the two states, a result that is comparable to $\Delta = 0.9\pi$ predicted by theory using the data of Figure 1.[11] The discrepancy may be due to measurement error on θ_i, as Δ tends to be sensitive to angle of incidence.

A quantity of interest for optical switching applications is the contrast ratio, or the relative signal strength between the high- and low-temperature states at a given polarizer angle:

$$C(\varphi) = \frac{S(T_H, \varphi)}{S(T_L, \varphi)} \tag{3}$$

where S is the photodetector signal, φ is the polarizer angle, and $T_H > T_c$ and $T_L < T_c$. The contrast ratio $C(\varphi)$ is plotted in Figure 3(b), revealing a large modulation peak at $\varphi = 170°$, where the polarizer is orthogonal to the linearly polarized light at low temperature. Contrast ratios in excess of 1500 are measured at the best conditions. Note that the contrast ratio is enhanced by the increase in reflectance as VO_2 becomes metallic, as is apparent in Figure 3(a): the long axis increases by a factor 3 at high temperatures. Nonetheless, even normalizing for this enhancement, the switching ratio is more than two orders of magnitudes.

In Figure 4, results obtained with sample C at 633 nm and $\theta_i = 68°$ shows transformation between linear and circular polarization. This implies a $\pi/2$ relative phase shift between reflected s and p-polarization components at $> T_c$.

Experiments using a 1550 nm laser beam produced better switching performances, and linear polarization could be maintained during rotation. Figure 5(a) shows polar intensity plots obtained with sample A, exhibiting linear polarizations in both material states, but orthogonal to each other. Here $\theta_i = 72°$ and the linear polarization of the reflected light was oriented at 55° with respect to the plane of incidence. Based on ellipsometric data, theory predicts $\Delta = 0.9\ \pi$, close to the measured $\Delta = \pi$. As seen in Figure 5(b), modulation amplitudes upwards of 200 are measured in this configuration. The lower contrast ratio (compared with that of 633 nm) can be explained by the lesser efficiency of polarizer P_2 at that wavelength.

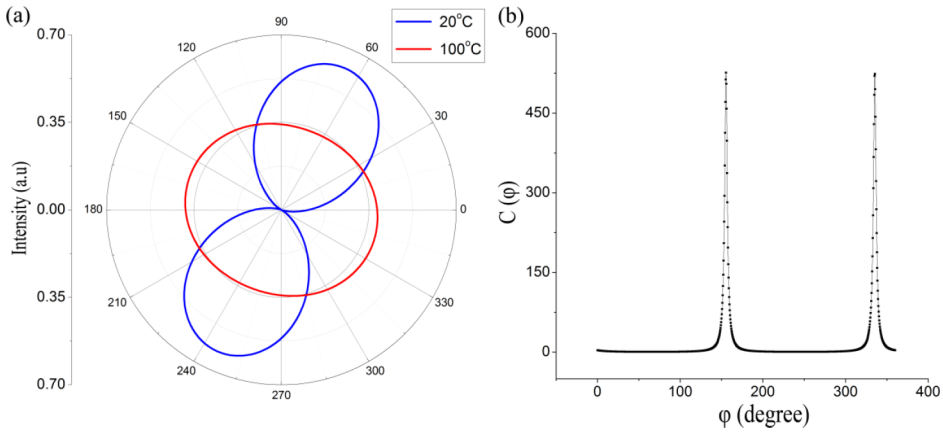

FIG. 4. (a) Polarization state of reflected light at 633 nm using sample C and (b) the corresponding contrast ratio.

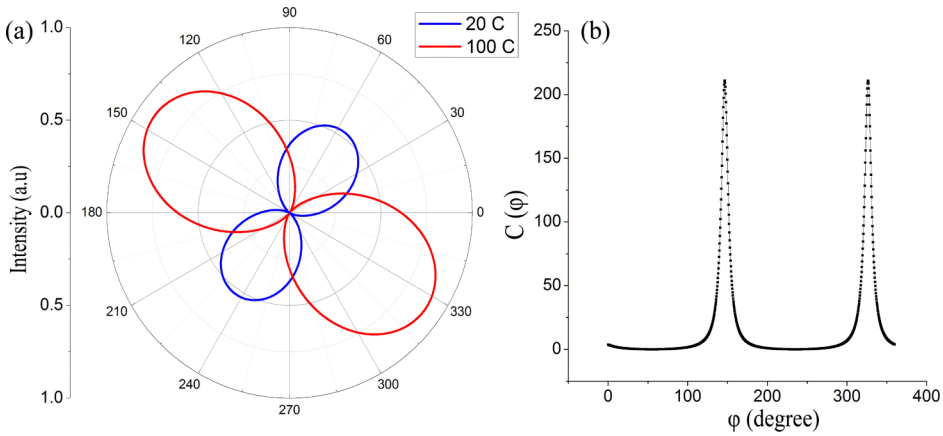

FIG. 5. (a) Polarization state of reflected light at 1550 nm using sample A and (b) the corresponding contrast ratio.

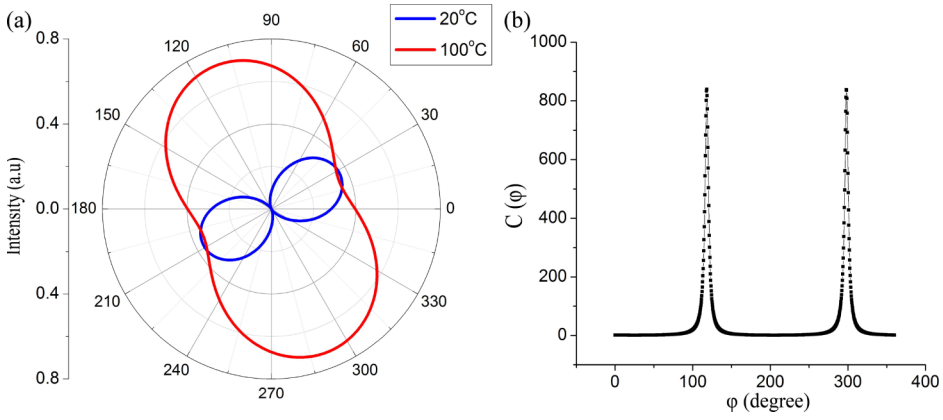

FIG. 6. (a) Polarization state of reflected light at 1550 nm using sample B and (b) the corresponding contrast ratio.

Experiments with samples B and C at 1550 nm are reported in Figures 6 and 7, respectively. In both these films, the thickness is not optimal for rotation of linear polarization. Nonetheless, contrast ratios are still high, owing to the low signal through polarizer P_2 when it is cross-polarized with the reflected light at low temperature.

Experiments were carried out near the center of the visible spectrum, at a wavelength of 514 nm, where theory predicts it to be difficult to alter polarization because of small changes in

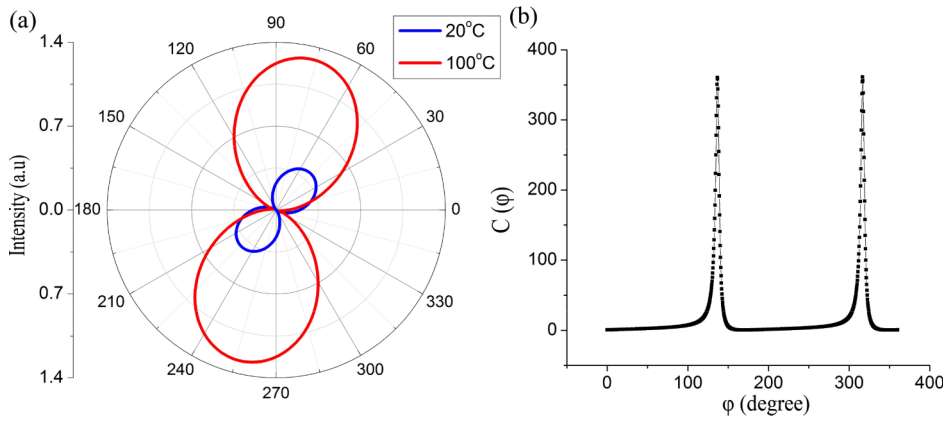

FIG. 7. (a) Polarization state of reflected light at 1550 nm using sample C and (b) the corresponding contrast ratio.

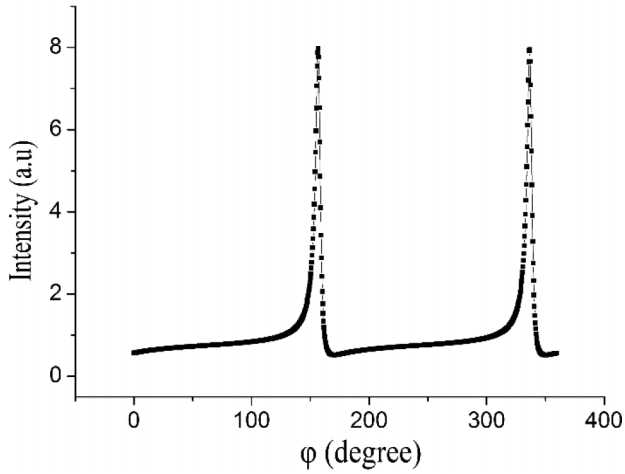

FIG. 8. Contrast ratio at 514 nm obtained with sample A.

refractive indices. Several VO_2 samples were tested and a maximum contrast ratio of almost 10 was obtained, shown in Figure 8. The angle of incidence is $\theta_i = 74°$, and polarization goes from linear to elliptical with the long axis oriented 5° relative to it. Theory predicts $\Delta = 0.08\pi$. Nonetheless, these constitute the first demonstration of optical modulation by VO_2 in the visible spectrum.

When measuring polarization rotation effects on light transmitted through VO_2 samples, we found the effect to much weaker than in reflection. This also concords with theory,[11] as the relative phase shift between s- and p-polarizations tends to be much lower in transmission than in reflection. Interference effects appear to influence the phase of reflected light more than in transmission.

The method of VO_2 activation by ambient heating is suitable for some optical applications, but too slow for others, such as dynamic imaging and optical modulation. Although heating of VO_2 has been demonstrated on timescales of less than 1 ms,[12] thus making it comparable to LCD devices,[13,14] it is still far from the nanosecond timescale obtained with electro-optic and ferroelectric materials such as quartz, $BaTiO_3$ or KH_2PO_4 (KDP).[15] So a promising direction for research is optical activation (optical pumping) of VO_2 by short laser pulses, which are known to induce phase transitions over times as short as 100 femtoseconds.[3–5]

CONCLUSIONS

In conclusion, we have demonstrated control and rotation of light polarization by using thin films of VO_2 with thicknesses between 50 and 150 nm. Large refractive index changes during the

material's phase transition at a temperature of 68°C alter the relative phase between the s- and p-polarization components of incident light, thereby altering its polarization state. The concept works especially well in reflection, and over a wide spectral range from the mid-visible to the infrared, and possibly beyond. Moreover, devices don't require nanoscale patterning but use uniform films on a variety of substrates. These results suggest new possibilities new ultra-thin polarization elements which could potentially operate at high speeds by optical pumping.

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