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Vanadium dioxide as a material to control light polarization in the visible and near infrared

Patrick Cormier [a], Tran Vinh Son [b], Jacques Thibodeau [a], Alexandre Doucet [a], Vo-Van Truong [b], Alain Haché [a,*]

[a] Département de physique et d'astronomie, Université de Moncton, E1A 8T1, Canada
[b] Department of Physics, Concordia University, Montreal H3G 1M8, Canada

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ABSTRACT

We report on the possible use of vanadium dioxide to produce ultrathin (< 100 nm) adjustable phase retarders working over a wide spectral range. The refractive index of vanadium dioxide undergoes large changes when the material undergoes a phase transition from semiconductor to metal at a temperature of 68 °C. In a thin film, the resulting optical phase shift is different for s- and p-polarizations in both reflection and transmission, and under certain conditions the polarization state changes between linear or circular or between linear polarizations oriented differently when the material phase transitions. Specific ultrathin modulators are proposed based on the results.

1. Introduction

Vanadium dioxide (VO_2) is an insulator that acquires metallic properties when heated to temperatures above 68 °C, owing to a rearrangement of its crystalline structure [1]. This results in refractive index changes on the order of unity, which makes the material suitable for a variety of optical applications, including tunable metamaterials [2–4], spectrally selective filters [5,6], optical switches and limiters [7–10] and infrared imaging systems [11,12]. So far, VO_2 has been considered of interest only in the context of filtering and amplitude modulation, in particular at wavelengths above 1000 nm where optical properties vary the most during phase transition. Recently, we explored a different avenue by considering effects on the optical phase of light during the material's transition. We demonstrated optical phase control [13] and ultrathin flat lenses [14], the latter also suggesting applications of VO_2 may extend to the visible spectrum.

In this paper, we report VO_2 thin films as a way to control the polarization state of light, including switching from linear to circular and vice-versa, or to rotate linear polarization. We investigate the combination of material properties and optical conditions for which such control is possible. Using this effect in combination with polarizers could lead to highly efficient optical modulators working over a wide spectral range.

2. Modeling

We calculate changes in the polarization state of a light beam interacting with a layer of VO_2 as the material undergoes a phase transition. To this end, we assume a monochromatic plane wave incident on a uniform and homogeneous layer of VO_2 deposited on a semi-infinite dielectric substrate. Reflection and transmission coefficients at air/VO_2 and VO_2/substrate interfaces are given by Fresnel's equations and assume the refractive indices to be uniform throughout the film. We will also assume that the polarization of incident light can be prepared in any arbitrary state. Fig. 1 defines the parameters of the problem. Here θ_i is the incident angle, $\vec{E}_o$, $\vec{E}_r$ and $\vec{E}_t$ the complex electric field of the oncoming, reflected and transmitted waves, respectively. The VO_2 layer is assumed to have a complex refractive index $n + ik$ and be deposited on a dielectric substrate. The electric field component parallel to the plane of incidence is the p-polarization and the component perpendicular to it is the s-polarization. For convenience, we chose to express the electric field in the basis of s- and p-polarizations.

We first treat the case of reflection, then expand the results to

* Corresponding author.
E-mail address: hachea@umoncton.ca (A. Haché).

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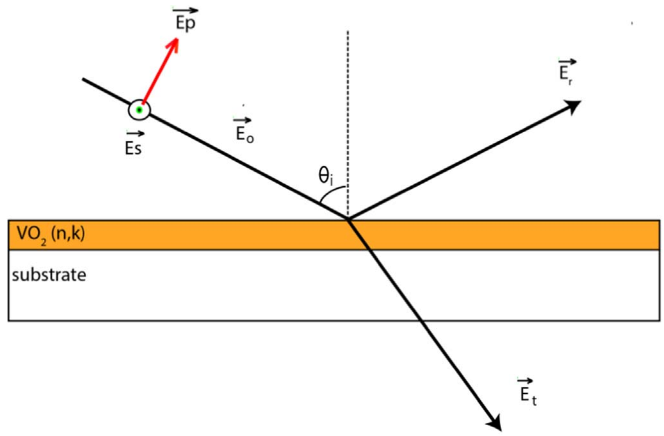

Fig. 1. Definitions of polarizations states and incoming and outgoing light beams on a film.

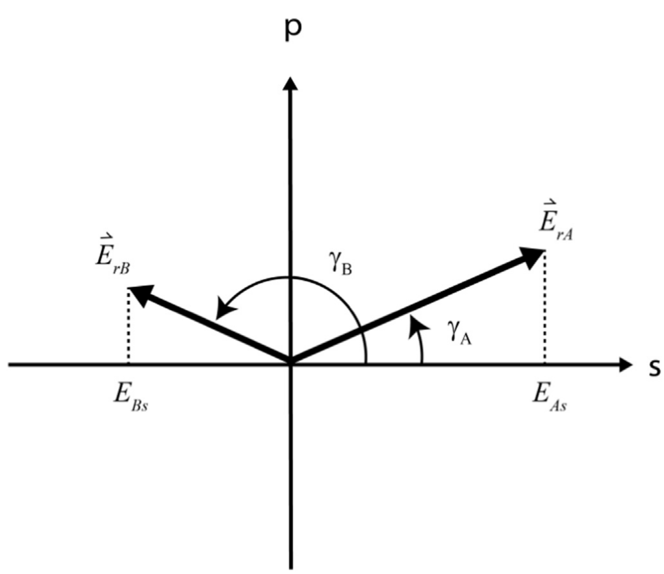

Fig. 2. Reflected electric fields at temperatures T_A and T_B in the p- and s-polarization basis.

transmission. Let's call $\vec{E}_{rA}$ the reflected electric field when the VO_2 film is at low temperature T_A and $\vec{E}_{rB}$ the corresponding field at some higher temperature T_B. In the Jones matrix formalism, the electric field in the basis of s- and p-polarizations is written

$$\vec{E} = \begin{pmatrix} E_p \\ E_s \end{pmatrix}. \tag{1}$$

The reflected field is related to the incident field via

$$\vec{E}_{rA} = r_A \vec{E}_o \tag{2}$$

$$\vec{E}_{rB} = r_B \vec{E}_o \tag{3}$$

where r_A is the thin film's reflection matrix at temperature T_A which takes the form

$$r_A = \begin{pmatrix} r_{Ap} & 0 \\ 0 & r_{As} \end{pmatrix}, \tag{4}$$

where r_{Ap} and r_{As} are the (complex) coefficients of reflection of the VO_2 layer for the p- and s-polarizations, respectively, at temperature T_A. Matrix r_B has the same structure but with coefficients for temperature T_B.

Of particular interest is the difference between $\vec{E}_{rA}$ and $\vec{E}_{rB}$ in terms of their polarization state. If the phase between the s- and p-components varies with the thin film's temperature, the polarization state will be altered. We can express the difference between $\vec{E}_{rA}$ and $\vec{E}_{rB}$ in terms of a "switching matrix" r_{AB} defined as

$$\vec{E}_{rB} = r_{AB} \vec{E}_{rA} \tag{5}$$

where

$$r_{AB} = r_B r_A^{-1} = \begin{pmatrix} \frac{r_{Bp}}{r_{Ap}} & 0 \\ 0 & \frac{r_{Bs}}{r_{As}} \end{pmatrix}. \tag{6}$$

We can write this matrix in the form

$$r_{AB} = a_r \begin{pmatrix} 1 & 0 \\ 0 & z_r \end{pmatrix}, \tag{7}$$

with

$$a_r = \frac{r_{Bp}}{r_{Ap}} \tag{8}$$

and

$$z_r = \frac{r_{Bs}}{r_{As}} \frac{r_{Ap}}{r_{Bp}}. \tag{9}$$

Since a_r affects both the s- and p-components of $\vec{E}_{rA}$ equally, it does not change the relative phase between the two and the polarization state remains the same. On the other hand, the phase of z_r (or $\arg(z_r)$) will have an effect on the polarization state.

Note that parameter z_r is related to the commonly used ellipsometry parameters Ψ and Δ defined as

$$\frac{r_p}{r_s} = \tan\Psi e^{i\Delta}, \tag{10}$$

and

$$z_r = \frac{\tan\Psi_A}{\tan\Psi_B} e^{i(\Delta_A - \Delta_B)}. \tag{11}$$

In the most general case, the effect of r_{AB} would be to transform an elliptically polarized field $\vec{E}_{rA}$ into differently polarized but still elliptical $\vec{E}_{rB}$. Indeed, since the phase difference between r_s and r_p in a VO_2 layer is generally not a multiple of 2π, the reflected field is generally not linearly polarized even if $\vec{E}_o$ is linearly polarized. But in order to attain the greatest contrasts of modulation using polarizers, it is best to operate with linear polarizations. To this end, a phase compensator (e.g. birefringent crystal) can be used to prepare $\vec{E}_o$ in such a way that $\vec{E}_{rA}$ (or $\vec{E}_{rB}$) is linearly polarized, in which case high-contrast modulation through polarizers would be possible.

If $\vec{E}_{rA}$ is linearly polarized, two options are particularly promising: rotation of the linear polarization by some angle when $\arg(z_r)=\pi(1+2m)$ with $m = 0, \pm 1, \pm 2\ldots$ and conversion to circular polarization when $\arg(z_r) = \pi(1/2+m)$ with $=0, \pm 1, \pm 2\ldots$. We examine these two situations in more details in the following sections.

2.1. Rotation of linear polarization

Fig. 2 draws $\vec{E}_{rA}$ in the s–p plane, thus defining γ_A the angle of the field with respect to the s-axis. (Note that γ_A should not take values of 0 or $\pi/2$ as they represent polarization states purely in s or p, a condition that does not allow polarization control). A phase