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Polarization modulation by vanadium dioxide on metallic substrates

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ABSTRACT

Vanadium dioxide (VO_2) undergoing phase transition is known alters the polarization state of light in reflection owing to large changes in complex refractive indices. While this effect is promising for optical modulation applications, the usual VO_2 films on dielectric substrates tend to offer limited tunability for polarization modulation. In this paper, we show that metallic under-layers greatly enhance the performance by widening the spectral range and include visible wavelengths, by increasing the polarization modulation amplitude, and by widening the range of workable incidence angles. The imaginary part of the refractive index in the metallic layer is found to increase the relative phase shifts between s- and p-components of polarization as well as increasing the reflectance.

1. Introduction

Vanadium dioxide (VO_2) has found many applications in optics owing to its large refractive index variations when it transitions from an insulating to a metallic state. The phase transition can be activated thermally, by heating to a temperature of 68 °C [1], or on faster time scales by optical excitation [2–5]. Changes in optical properties have been useful mostly for applications of spectral filtering and field-amplitude modulation of infrared light, but recently, applications have also been found for phase and polarization modulation of visible and infrared light [6–10]. Phase and polarization modulations rely on the principle that in a material with complex-valued refractive indices like VO_2, optical phase shifts are generally unequal in s- and p-polarizations. A beam of light reflecting off a VO_2 layer therefore sees its polarization state change as the material undergoes a phase transition, making possible the rotation of linear polarization, among other possibilities [9,10].

One advantage of phase and polarization modulation over field amplitude modulation is a greater sensitivity over a wider spectrum: whereas applications of VO_2 were traditionally limited to wavelengths above 1000 nm [11,12], phase modulation has extended to range to include parts of the visible spectrum (>500 nm). However, preliminary studies [7,9,10] showed that VO_2 layers on dielectric substrates only enable substantial polarization modulation for incident angles near Brewster's angle, i.e. ~70° in the case of VO_2. While we should not expect such applications to be possible at near normal incidence angles, where s- and p-polarizations become indistinguishable, it would be desirable to lower the angle for some applications.

In this paper, we study the effect of metallic substrates on polarization modulation of light by a VO_2 layer, a system which so far has only been studied in the context of perfect absorbers [13]. Here we show that not only a VO_2/metal interface makes polarization modulation possible at lower incidence angles and over a wider spectral range compared with VO_2-on-dielectric layouts, it also increases reflectance significantly. Note that the term "metallic substrate" does not imply that the substrate should be made of bulk metal, only optically thick. In most cases, metal layer thicknesses greater than 100 nm would be sufficient.

2. Theory

The parameters relevant to the problem are defined in Fig. 1. A beam of light with s- and p-polarization components arrives at an angle θ_i on a VO_2 layer of thickness d in contact with an optically thick layer of metal. Looking at the properties of the reflected light, we define $\delta = \phi_p - \phi_s$ as the phase difference between the two polarization components in reflection. This phase difference, along with the amplitudes of each polarization components, determine the polarization state of the reflected light. Since we are interested in how polarization is changed by the phase transition of VO_2, we need to consider $\Delta = \delta_1 - \delta_0$, the change in relative phase occurring during the phase transition, with δ_1 the relative phase when VO_2 is activated (metallic state) and δ_0 the relative phase when it is not activated (insulating state).

Two cases are of particular interest: (1) if $\Delta = \pm\pi$, linearly polarized light may rotate by some angle while remaining linearly polarized, and

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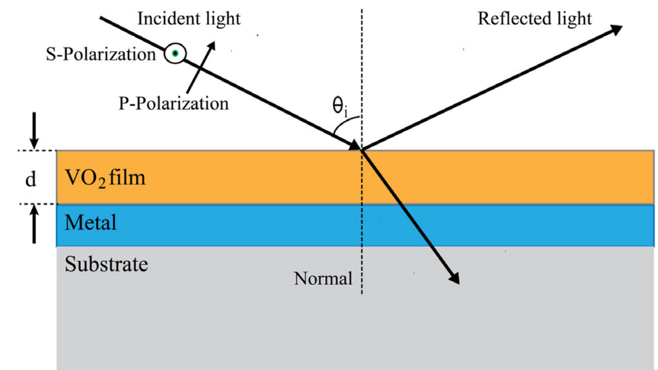

Fig. 1. Sample geometry and definition of optical parameters.

(2) if $\Delta = \pm\pi/2$, linear polarization may become circular, or vice-versa. The first case is useful for producing large modulation amplitudes in transmission through polarizers.

From the values of the refractive indices of VO_2 and the metal, we can calculate the reflection amplitudes for either s- or p-polarizations and for the two states of VO_2, namely $r_{p,0}$, $r_{p,1}$, $r_{s,0}$ and $r_{s,1}$. These quantities are complex and contain the phase information of each polarization component relative to that of incident light. We then obtain the phase modulation term with

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

where

$$z_r = \frac{r_{p,1} r_{s,0}}{r_{p,0} r_{s,1}} \tag{2}$$

Since the film's Fresnel coefficients $r_{p,0} \dots r_{s,1}$ are functions of incidence angle θ_i and film thickness d, and since refractive indices depend on wavelength, the phase modulation term Δ also depends on all three parameters. As a result, at a given wavelength, there could be many sets of conditions where $\Delta = \pi$ is possible, for example.

3. Theoretical results

To better visualize the role of each parameter and capture the full range of possibilities, we calculated Δ for many combinations of incidence angles and VO_2 film thicknesses. As a reference, we first calculate for the case of VO_2 deposited on amorphous silica. Fig. 2 shows the result, with θ_i varied from 0 to 90° and d from 0 to 300 nm (the typical range of achievable VO_2 film thicknesses). Calculations use refractive index of VO_2 and amorphous silica experimentally measured by ellipsometry.

We note that VO_2 film thicknesses of less than 100 nm are sufficient. However, there is a narrow range of incidence angles, between 60 and 70°, where substantial phase modulation is possible, and modulation is much less pronounced in the visible spectrum as it is in the near infrared. Calculations for VO_2 on gold, on the other hand, reveal an entirely different picture, as Fig. 3 shows. Modulation is possible in the visible spectrum and the range of possible incidence angle reduced to 10° in some cases. While the required thicknesses to achieve $\Delta = \pi$ tend to increase, a side benefit is an enhanced reflectance due to the metallic layer. By calculating reflectance for all incidence angles, polarizations, and wavelengths from 400 nm to 2000 nm, an averaged reflectance of 0.2 is obtained for VO_2 layers (all thicknesses) on glass, whereas it increases to 0.4 for a 75 nm of VO_2 on gold, and to 0.6 for 50 nm of VO_2 on gold. If the VO_2 layer is thick (say, more than 200 nm), a metallic substrate has negligible effect because only a small fraction of incident light reaches it.

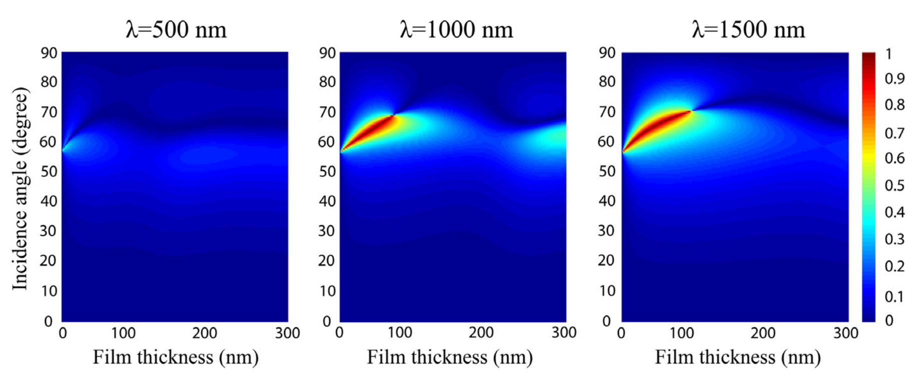

Fig. 2. Relative phase modulation Δ during phase transition as a function of incidence angles and film thickness for VO_2 on amorphous silica. The color code is normalized to $\Delta = \pi$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

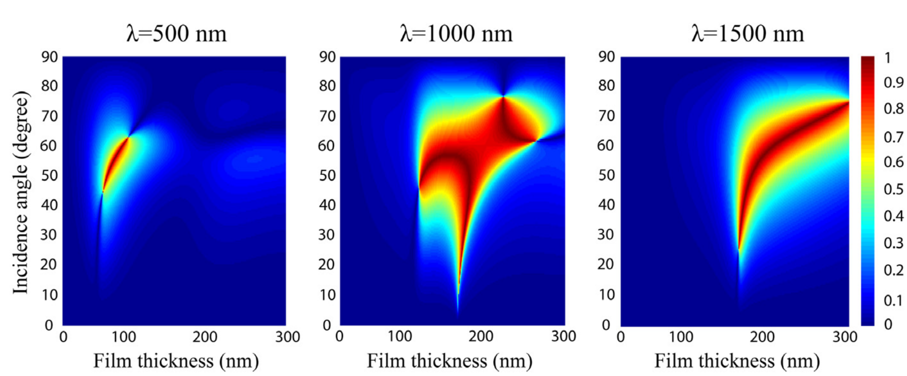

Fig. 3. Relative phase modulation Δ during phase transition as a function of incidence angles and film thickness for VO_2 on gold. The color code is normalized to $\Delta = \pi$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)