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Vanadium dioxide spatial light modulator for applications beyond 1200 nm

Phuong Anh Do [a], Ali Hendaoui [b], Ebrahim Mortazy [b], Mohamed Chaker [b], Alain Haché [a,*]

[a] Département de physique et d'astronomie, Université de Moncton E1A 3E9, Canada
[b] Institut National de la Recherche Scientifique, Varennes, Québec J3X 1S2, Canada

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ABSTRACT

Spatial light modulators based on vanadium dioxide are used to demonstrate all-optical spectral filtering in the near infrared, up to 1700 nm, with potential to application into the mid-infrared. By spectrally dispersing the shaped beam and transmitting the beam through a vanadium dioxide thin film, the transmission is modified by optically pumping the film locally with a laser beam. Heating causes the film to undergo an insulator-to-metal transition, along with a drop in transmission. The spectrum can be shaped by pumping with a beam at different location and/or different intensity profiles. The method is promising for longer wavelength since the film is more efficient further in the infrared.

Spatial light modulators (SLM) are extensively used to process optical data and to shape the spectrum, wave front, spatial profile and temporal profiles of light beams. Some SLMs are permanent (static) filters while others are made programmable (dynamic) by using acousto-optic effects [1–3], micro-electro-mechanical systems (MEMS) [4,5] and liquid crystals [6–8]. These techniques allow real-time control of the phase and/or amplitude of individual spectral components, an operation that is not only useful for simple applications like spectral filtering and beam shaping, but also for advanced processes such as femtosecond pulse shaping [1,3–5,9] and coherent control [10].

As one might expect, each technique has strengths and weaknesses with regard to spectral range, switching speed, efficiency, and hardware complexity and cost. For example, the most widespread commercially important SLMs use liquid crystal arrays, which offer an interesting combination of performance and simplicity. Yet there are limitations in the UV and the infrared because of molecular absorption bands. Although recent progress has been made in the near infrared [11,12], commercially available SLMs are still by and large limited to applications bellow 1600 nm. Given the widespread use of SLMs and the wide range of conditions under which they are used, there is always an interest in finding novel techniques with potentially new niche applications.

In this paper, we present an alternative method to achieve spatial light modulation by using light activated, high efficiency vanadium dioxide VO_2 films. When heated to above 68 °C, the transition metal oxide undergoes an insulator-to-metal phase transition that is accompanied by a sharp drop in optical transmission and electrical resistivity. By exploiting this thermochromic property, we demonstrate adjustable and reversible spectral filtering. Unlike previous studies that employed thermoelectric arrays [13] and micro-machined patterns [14] to locally activate a phase transition, we show that remote optical heating of a VO_2 film on a transparent substrate is an interesting method for its relative simplicity, usability for both transmission and reflection, high contrast switching, and suitability for applications deep into the infrared. Moreover, this work uses VO_2 films exhibiting some of the best infrared switching properties reported yet [15]. While the thermochromic properties of VO_2 have been known since the work of Morin [16], the fabrication of thin films with large areas, good optical quality, high transmission and switching contrast ratios has remained a topic of research until today. One of the challenges remains the oxide's tendency to take multiple stoichiometries, including V_2O_5 and V_2O_3, which don't share the same properties as VO_2 and tend to reduce performance. In this study, VO_2 films were grown according to a procedure that produces switching ratios of 10^4 at wavelengths above 1000 nm [17] and were used for energy efficient windows [15] and infrared imaging [18].

With the experiment layout of Fig. 1, spectral amplitude filtering between 900 and 1700 nm is demonstrated using VO_2 films as controllable shutters. A grating G and a lens L_1 spatially

* Corresponding author. Tel.: +1 506 858 4938; fax: +1 506 858 4541.
E-mail address: Alain.hache@umoncton.ca (A. Haché).

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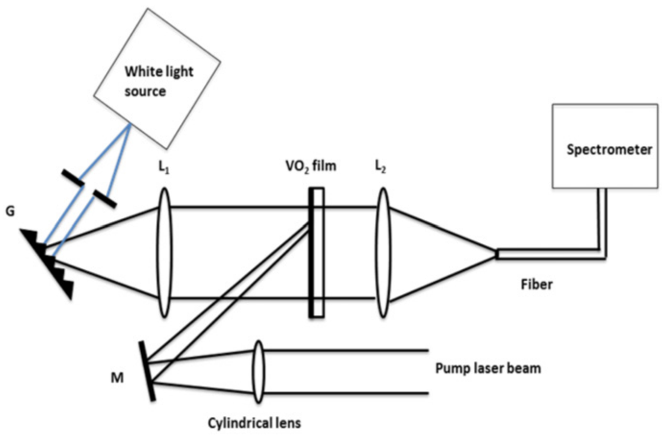

Fig. 1. A beam of white light (from a deuterium–tungsten source covering 215–2000 nm) is dispersed/collimated with a grating/lens system and passes through a VO_2 film. The pump laser beam is focused with a cylindrical lens to modulate optical transmission through the film.

disperse a beam of incoherent white light. A thin film of VO_2 on glass is placed on the Fourier plane, and a second lens L_2 focuses the light beam onto an optical fiber coupled to a spectrometer. When a laser beam heats the surface of the sample, a phase transition is induced inVO_2 and the film transmittance modified locally. The white light spectrum is filtered according to the transmission spatial profile. For example, with a narrow pump beam, a band $\Delta\lambda$ is removed or attenuated from the white spectrum. Although phase effects are not of concern here, note that the phase is also altered because of heat-induced changes in the substrate's refractive index. With $dn/dT = 2\times10^{-6}\,°C^{-1}$ in glass, a change of 50 °C, as needed to reach the transition point from room temperature, would induce a phase shift of 0.4 rad at 1500 nm through the 1 mm-thick substrate. If need be, this phase shift could be compensated with adaptive optics, e.g. with a deformable mirror moving by about 50 nm.

In principle it is desirable to have the highest spectral resolution possible (i.e. $\Delta\lambda\to 0$), but there are three limiting factors. Firstly, the heated area has a width w which depends on the laser beam width and the sample diffusivity. This width overlaps with a spectral band given by

$$\Delta\lambda_1 = 1.87w/fD \tag{1}$$

where $D = d\theta/d\lambda$ is the angular dispersion parameter of the grating (a function of the diffraction order and angles of incidence and diffraction), and f is the focal length of lens L_1. In deriving Eq. (1) it is assumed that $w \gg f$. Secondly, the white beam having a finite width W on the grating, the spectral resolution on the Fourier plane is given by

$$\Delta\lambda_2 = W/[fD\,(L/f-1)] \tag{2}$$

where L is the distance between L_1 and the sample. Finally, the ultimate resolution is the Rayleigh limit of the grating at wavelength λ:

$$\Delta\lambda_3 = \lambda/(mN) \tag{3}$$

with m the diffraction order and N the number of grating grooves illuminated.

Our experiment used an argon ion laser at 514 nm as pump source, focussed down to 37 μm (FWHM) with a cylindrical lens (15 cm focal). The white light was provided by a deuterium–tungsten lamp. To analyze spectra in the near infrared, a silicon photodetector array was used (Ocean Optics PC 2000); for the measurements up to 1700 nm, an InGaAs array was used (Jobin Yvon IGA Triax 320). The grating G has 600 lines/mm, a dispersion parameter $D = 6.85\times10^5$ rad/m, and lens L_1 has a focal length $f = 5$ cm. The sample heated area was numerically calculated by solving the heat transfer equations, and results compared with those of Lax [19]. Both theories give steady-state temperature profiles with a width of 70 μm. From this result we obtain resolutions of $\Delta\lambda_1 = 2$ nm and $\Delta\lambda_2 = 35$ nm, much larger than the Rayleigh limit $\Delta\lambda_3 = 0.77$ nm. We therefore anticipate a spectral resolution of ~35 nm mainly limited by the resolving power of the light disperser. To test the resolution limit given by the heated area, the necessary condition is $\Delta\lambda_1/\Delta\lambda_2 > 1$. From Eqs. (1) and (2), we see that this ratio does not depend on the grating dispersion parameter D but rather on the system parameters f, L, W and w.

Three VO_2 samples were tested. Sample A was deposited on a glass substrate with the sputtering technique and prepared according to Ref. [15].It has a thickness of 200 nm and a high transmittance contrast in the infrared. Samples B and C are quartz substrates with VO_2 films of 80 and 110 nm in thickness, respectively, deposited with the pulsed laser deposition technique. When heated, the transmittance of these samples drops by 80% at 2000 nm. Fig. 2 shows the transmittance of each sample below and above the phase transition temperature. The better performance of sample A may be attributed to the thicker layer and perhaps to a better material stoichiometry, as other forms of vanadium oxides tend to form and need to be removed with post-deposition treatments [15].

Fig. 3 shows spectral filtering in the near-IR using sample A. The original spectrum has a three-peak structure, and one of the peaks is removed or added by focusing the pump laser at various locations on the VO_2 sample. As an example, Fig. 3a shows the removal of the 928 nm peak, while Fig. 3b plots the relative change in transmittance with the pump beam at different positions on the sample. Because the spectral components are angularly dispersed by the grating, focusing the pump beam at various points on the Fourier plane selectively removes certain bands of the white light. The pump power is steady at 93 mW and corresponds to an intensity of 200 W/cm^2.

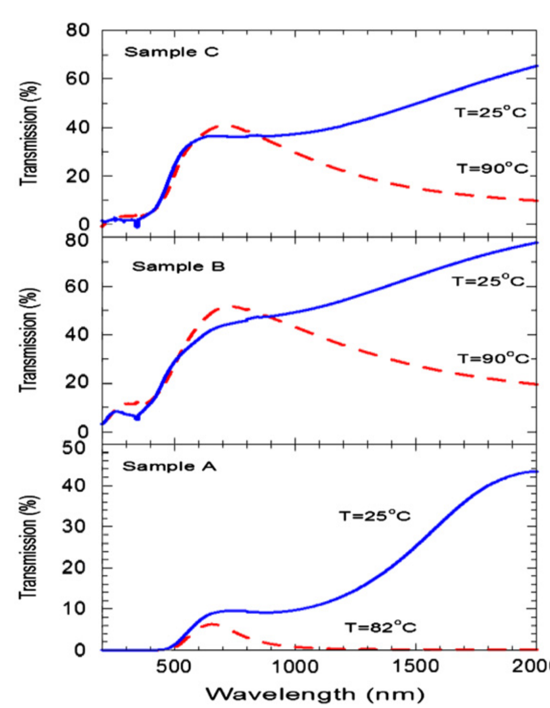

Fig. 2. Transmission spectra of three VO_2 thin film samples. The phase transition temperature is 68 °C.