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Temperature-driven tunability of a vanadium dioxide-based microcavity made of random sequences of layers

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ABSTRACT

Vanadium dioxide-based photonic devices show significant potential for a range of applications, such as smart windows and reconfigurable optical switches. In this study, we introduce a microcavity design featuring a vanadium dioxide layer positioned between two photonic structures composed of a random sequence of 32 alternating layers of silicon dioxide and zirconium dioxide. The temperature-dependent complex refractive index of vanadium dioxide has been thoroughly accounted for. Our findings reveal that even a temperature change of just 1 °C results in subtle variations in the optical response. These small changes can be detected through differential light transmission measurements, which can be performed using relatively simple and low-cost optical setups. Consequently, the proposed microcavity can serve as an effective temperature sensor or a highly sensitive photon detector, where incident photons induce a temperature rise in the material.

1. Introduction

Crystalline vanadium dioxide (VO₂) undergoes a thermochromic phase transition at approximately 68 °C (341 K) [1,2]. This transition corresponds to a structural shift in the crystal from a monoclinic insulating phase to a tetragonal (rutile) metallic phase [3,4]. Optically, this change transforms VO₂ from a semi-transparent insulator into a more reflective and lossy metallic material [4,5]. The unique characteristics of VO₂ phase transition enable a variety of potential applications, including smart windows, steep-slope devices for microelectronics, neuromorphic computing elements, reconfigurable radiofrequency switches, and THz and mid-infrared absorbers [6–10].

A major effort by the scientific community, responding to a real technological need, is focused on the creation of active photonic devices, and this work is evidenced by numerous reports that can be found in the literature [11–13]. An interesting and simple idea, both from the point of view of modelling the optical response and from the point of view of manufacturing the devices and characterizing them, is to introduce vanadium dioxide between photonic crystals [14–16] in order to create an optical microcavity. The literature on vanadium oxide based photonic crystals is vast. In 2001, Golubev et al. [17] have prepared a silicon dioxide based synthetic opal, i.e., a three-dimensional photonic crystal having a face-centered cubic lattice, they have filled the opal pore with V₂O₅ via chemical bath deposition technique, and they have reduced V₂O₅ to VO₂ by annealing. Golubev et al. have shown that the photonic

band gap of such opal-VO₂ composite is governed by the phase transition of vanadium dioxide. In 2002, Golubev et al. [18] have studied in detail the hysteresis of the temperature dependence of the opal-VO₂ composite, in terms of the photonic band gap peak shift and in terms of the electrical conductivity change. In 2008, Ibisate, Golmayo, and López [19] have fabricated VO₂-SiO₂ composite opals and VO₂ inverse opals, demonstrating their thermochromic behavior. In 2010, Pevtsov et al. [20] have fabricated opal-VO₂ composites that show switching, due to the VO₂ transition, of the photonic band gap in the range 1.3–1.6 μm, which is very interesting for telecommunications. In 2019, Wang et al. [21] have demonstrated tunable THz properties of three-dimensional VO₂/PDMS THz photonic crystals. Many interesting works are reported in a review on vanadium dioxide-based tunable photonics by Ko, Badloe, and Rho published in 2021 [11]. More recently, a deep study of the switching in vanadium dioxide-based opals has been reported by Peng et al. [22]. One-dimensional photonic crystals are very useful tools because of their relatively fabrication compatible with many layer-based processing [23]. The combination of a VO₂ layer and a one-dimensional photonic crystal has been studied in several publications [24–29]. Furthermore, Taherzadeh and Keshavarz [30] have proposed vanadium dioxide-based one-dimensional photonic quasicrystal. Finally, it is noteworthy the engineering of vanadium dioxide-based metasurfaces [31–34].

Here, we propose a microcavity in which a vanadium dioxide layer is sandwiched between two photonic structures with a randomized

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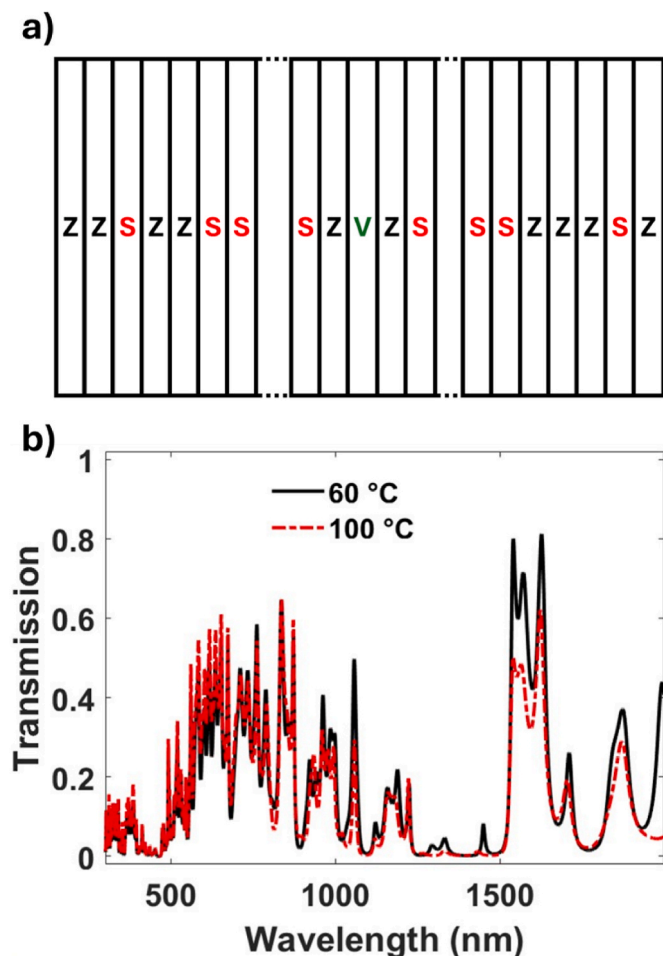


Fig. 1. (a) sketch of the disordered microcavity, in which Z, S, and V indicate zirconium dioxide, silicon dioxide, and vanadium dioxide, respectively. (b) Transmission spectra at 60 °C and 100 °C of the microcavity in which a vanadium dioxide layer is sandwiched between two photonic structures made by a random sequence of silicon dioxide and zirconium dioxide layers.

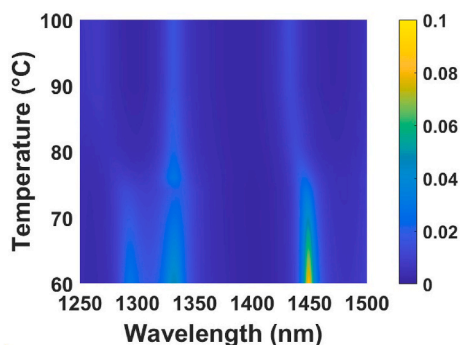


Fig. 2. Transmission of the random SiO₂/ZrO₂ cavity that embeds a VO₂ layer as a function of wavelength and temperature.

that the most significant changes in the transmission spectrum of the microcavity occur at the phase transition of vanadium dioxide.

Figure 3 (top) shows the transmission spectra at 77 °C and 78 °C of a microcavity in which a vanadium dioxide layer is sandwiched between two photonic structures made by a random sequence of silicon dioxide and zirconium dioxide layers, in the range 1100–1500 nm. Instead, Figure 3 (bottom) shows the differential transmission $\Delta T/T = (T_{t=78^\circ\text{C}} - T_{t=77^\circ\text{C}})/T_{t=77^\circ\text{C}}$. A measurement of the differential

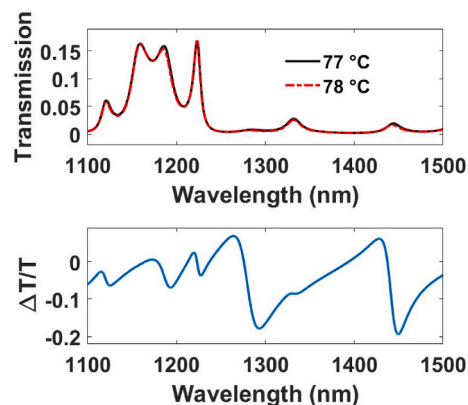


Fig. 3. (top) Transmission spectra at 77 °C and 78 °C of a microcavity in which a vanadium dioxide layer is sandwiched between two photonic structures made by a random sequence of silicon dioxide and zirconium dioxide layers, in the range 1100–1500 nm. (bottom) Differential transmission $\Delta T/T = (T_{t=78^\circ\text{C}} - T_{t=77^\circ\text{C}})/T_{t=77^\circ\text{C}}$.

transmission can be performed with different setups as in Ref. [44]. The mean value of the $\Delta T/T$ (absolute value) in the region 1100–1500 nm is 0.0584, while the standard deviation of the absolute value of $\Delta T/T$ in the region mentioned above is 0.0477. It is noteworthy to see a transmission decrease of almost 20 % at around 1450 nm with a temperature increase of a degree. Such difference is due to the significant variations in the real and imaginary parts of the refractive index of vanadium because of the change of temperature. In fact, by increasing the temperature, at 1450 nm the real part of the refractive index of vanadium dioxide is decreasing, while its imaginary part is increasing [36]. In Table 2 the position in the spectrum and the full width at half maximum (FWHM) of the transmission peak around 1450 nm are reported for the aforementioned temperatures, i.e., 77 °C and 78 °C. By increasing the temperature, together with the blue shift of the transmission peak, a slight peak broadening is remarkable.

In Figure A2 of the appendix, a microcavity in which an uncertainty of 4 nm (following a uniform distribution) in each layer thickness has been considered, in order to simulate an experimental uncertainty in the deposition of each layer. It is evident that, also with this uncertainty, the difference in the spectra at 77 °C and at 78 °C can be detected.

In Figure A3 of the appendix, the angular dependence of the transmission spectrum at 77 °C of the vanadium dioxide-based microcavity has been reported. The simulation has been performed for transverse electric (TE) and transverse magnetic (TM) waves. A more in-depth study of the interrelationship between the optical response as a function of temperature and the optical response as a function of the angle of incidence of light is suggested for future work.

For a better comprehension of the physical mechanisms in the vanadium dioxide-based disordered microcavity, we have simulated the electric field distribution along the microcavity sample, following the methodology described in Wiersma et al. [45]. In Fig. 4a (top) we have reported a contour plot related to the light transmission along the sample at 78 °C, with the sample length in the x-axis and the wavelength in the y-axis. In Fig. 4a (bottom) we have reported the contour plot corresponding to the electric field, in logarithmic scale, along the sample at 78 °C. Finally, in Fig. 4b we have displayed the electric field, related to the wavelength of 1450 nm, along the sample at 77 °C (black solid

Table 2

Position and full width at half maximum (FWHM) of the transmission peak around 1450 nm at 77 °C and 78 °C.

Temperature (°C)	Transmission peak position (nm)	FWHM (nm)
77	1444.25	20.5
78	1442.75	22.75

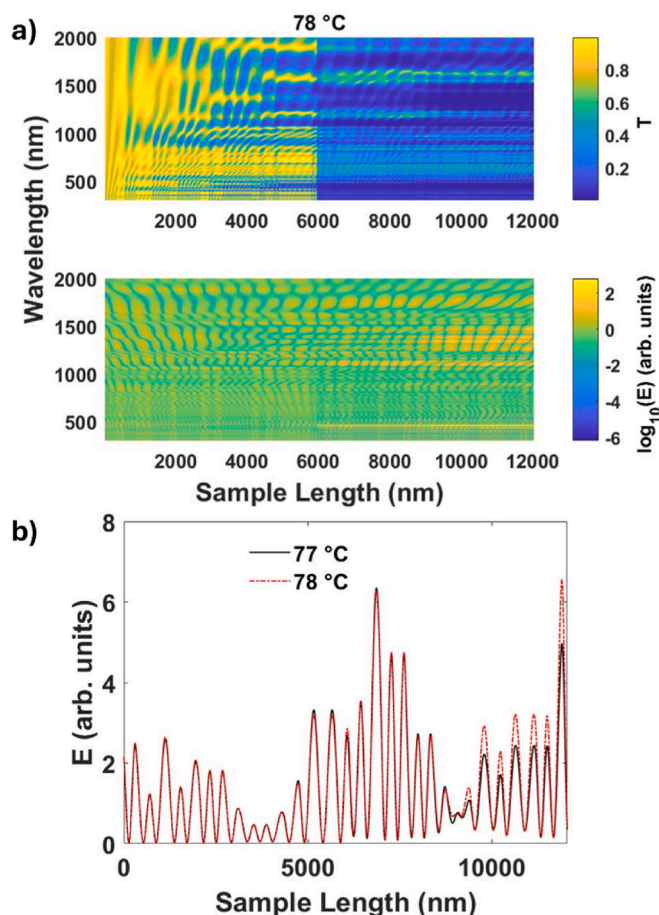


Fig. 4. (a, top) Contour plot of the light transmission along the sample at 78 °C, with the sample length in the x-axis and the wavelength in the y-axis; (a, bottom) Contour plot of the electric field, in logarithmic scale, along the sample at 78 °C. (b) Electric field, related the wavelength of 1450 nm, along the sample at 77 °C (black solid curve) and at 78 °C (red dashed curve).

curve) and at 78 °C (red dashed curve). We can observe that transmission is dramatically reduced in the middle of the sample, where the defect made of vanadium dioxide is placed, and this is due to the imaginary part of the refractive index of vanadium dioxide that is related to a light absorption contribution.

After the vanadium dioxide defect, in such microcavity we have observed stronger electric field peaks, and this could be ascribed to the possibility of local mode enhancements. However, a better understanding of the physical phenomenon and more investigations are necessary, and this could be the subject of future studies. Focusing at 1450 nm, we have observed that the electric field, after the vanadium dioxide defect, shows more intense peaks by increasing the temperature from 77 °C to 78 °C.

4. Conclusion

In this study, we modeled a microcavity incorporating a vanadium dioxide layer positioned between two photonic structures composed of a random sequence of 32 alternating silicon dioxide and zirconium dioxide layers. The complex refractive index of vanadium dioxide was rigorously considered, accounting for both its wavelength and temperature dependencies. While the distinct optical responses of the cavity with vanadium dioxide in its insulating and metallic phases are clearly pronounced, our findings demonstrate that even a temperature variation as small as 1 °C induces subtle yet measurable changes in the optical

response. These minor variations can be detected using differential light transmission measurements, which can be performed with relatively simple and cost-effective optical instrumentation. One notable thing is that the relationship between refractive index and temperature is different when the sample is heated or cooled [36]. In this work, we limited ourselves to the case of heating. The studied vanadium oxide-based random microcavity can be employed as a temperature sensor. Alternately, the microcavity can be used as a photon detector, because photons striking such microcavity cause a temperature change in the material.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

In Figure A1 the transmission spectra at 60 °C of the vanadium dioxide-based random photonic structures for five different permutations of the random sequence of silicon dioxide and zirconium dioxide layers are shown. It is evident that each permutation leads to a completely different transmission spectrum.

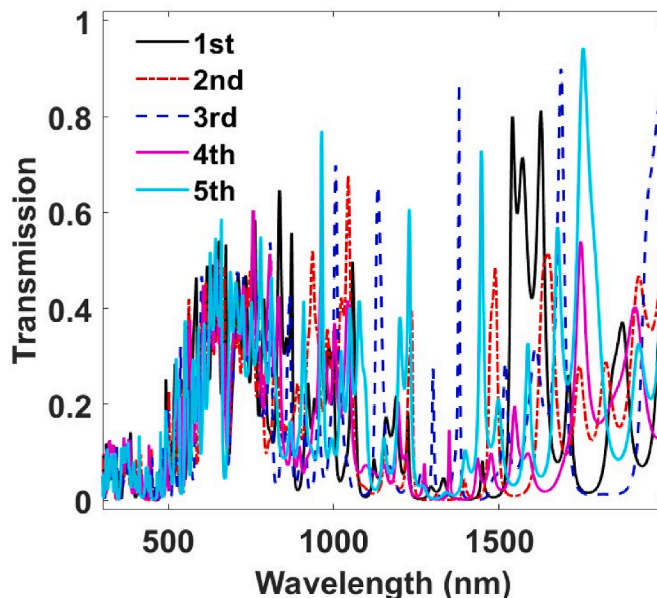


Fig. A1. Transmission spectra at 60 °C of the vanadium dioxide-based random photonic structures for five different permutations of the random sequence of silicon dioxide and zirconium dioxide layers.

In Figure A2 there are shown the transmission spectra at 77 °C and 78 °C, in the range 1100–1500 nm, of the vanadium dioxide-based microcavity with an uncertainty of 4 nm for each layer thickness (e.g., the thickness of silicon dioxide layers is 220 ± 2 nm).

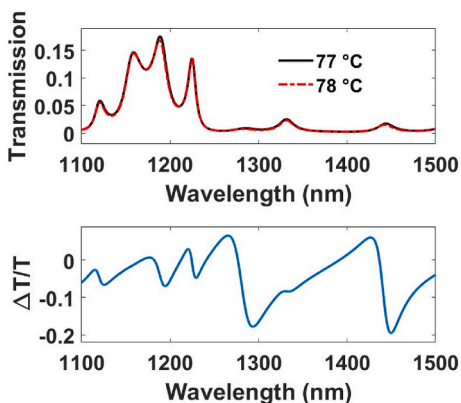


Fig. A2. Transmission spectra at 77 °C and 78 °C, in the range 1100–1500 nm, of the vanadium dioxide-based microcavity with an uncertainty of 4 nm for each layer thickness.

In Figure A3 the angular dependence of the transmission spectrum at 77 °C of the vanadium dioxide-based microcavity is shown. Figure A3 top shows the transverse electric (TE) waves, while figure A3 bottom shows the transverse magnetic (TM) waves. The method followed is described in Ref. [46].

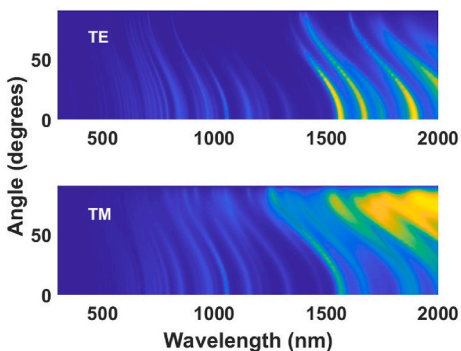


Fig. A3. Angular dependence of the transmission spectrum at 77 °C of the vanadium dioxide-based microcavity. Top: transverse electric (TE) waves; bottom: transverse magnetic (TM) waves.

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