# All-solid-state tunable Bragg filters based on a phase transition material

**Xi Wang,[1] Zilun Gong,[1,2] Kaichen Dong,[1,3] Shuai Lou,[1] Jonathan Slack,[2] Andre Anders,[2] and Jie Yao[1,3,*]**
[1]*Department of Materials Science and Engineering, University of California, Berkeley, California 94720, USA*
[2]*Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
*yaojie@berkeley.edu*

**Abstract:** We demonstrate an all-solid-state tunable Bragg filter with a phase transition material as the defect layer. Dynamic tunability and hysteresis properties of the Bragg filter promise more applications by combining phase transition materials and optical cavities.
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## 1. Introduction

Bragg gratings, as famous one-dimensional photonic crystals, are formed by alternating dielectric layers with different refractive indices [1]. With the introduction of a defect layer to break the symmetry, phase-shifted Bragg gratings exhibit unique behaviors as ultra-narrow band-pass filters [2], namely Bragg filters. While the majority of light near the Bragg wavelength is reflected, a narrow band (known as a defect mode) gives rise to a reflection. Bragg filters with tunable defect modes attract much attention due to their potential abilities for laser cavities, sensing, communications, and spectroscopy applications. By changing the property of a defect layer, such as its refractive index or thickness, the reflection dip (transmission peak) can be tuned accordingly. However, once the structure of a Bragg filter is determined during the fabrication process, the defect mode is spectrally fixed in most designs. To date, tuning mechanisms for planar Bragg filters have been theoretically proposed using piezoelectric materials, doped semiconductors, and magnetic materials as defect layers, only liquid-crystal-based tunable Bragg filters have been realized in laboratories [3]. Moreover, devices containing liquid crystal layer(s) require additional fabrication processes for confinement and stabilization.

Here, we experimentally demonstrate an all-solid-state tunable Bragg filter with a phase transition material as the defect layer [4]. Phase transition materials, especially insulator-metal transition (IMT) materials, exhibit huge changes in electrical, mechanical and optical properties as a function of temperature and/or strain, which could give optical devices extra tunability. Without loss of generality, we use vanadium dioxide ($VO_2$) as the phase transition material for a defect layer because its phase transition temperature (~68 ℃) is close to room temperature.

## 2. Experiments

Bragg filters fabricated in our experiment consist of one $VO_2$ thin film (30 nm) with one silicon nitride ($Si_3N_4$) protection layer (9 nm) sandwiched between two Bragg gratings with 4 periods of alternating titanium dioxide ($TiO_2$) and silicon dioxide ($SiO_2$) layers. The schematic diagram with cross-section view can be found in Fig. 1(a). The whole sample was produced on a quartz substrate in a customized magnetron sputtering system. All the layers were deposited in one chamber continuously without breaking the vacuum, minimizing contamination.

Raman spectroscopy has been used to verify the composition of the defect film. The Raman spectrum of the Bragg filter sample at 25 ℃ is shown in Fig. 1(b) with the Raman spectrum of a single $VO_2$ layer on $SiO_2$/Si substrate as a reference. Typical Raman peaks of $VO_2$ in the Bragg filter match well with the Raman peaks of single $VO_2$ layer [5]. This means even being encapsulated between two multilayer gratings, the defect layer is still an active polycrystalline $VO_2$. Possible influence from strain on the material properties is small or negligible.

Our Bragg filter sample exhibits temperature-dependent tunability. The reflection spectra of the sample under different temperature are shown on Fig. 1(c)-1(d). At longer wavelength region, the reflectance, especially the position of defect mode, changes dramatically.

One prominent phenomenon in the IMT phase transition of $VO_2$ is the hysteresis behavior. In our experiment, optical hysteresis was also observed. Considering the sample and plotting the center wavelengths of defect mode versus temperatures during the whole heating and cooling cycle, a hysteresis curve is obtained (Fig. 2(a)).

Temperature dependent Raman spectroscopy verifies that the tunability of our Bragg filter originates from the phase transition of the $VO_2$ layer. The Raman shift at 612 $cm^{-1}$ is able to characterize the hysteresis of the $VO_2$ MIT phase transition [5]. Heights of 612 $cm^{-1}$ Raman shift of the Bragg filter sample are retrieved under different temperatures and plotted in red in Fig. 2(b). The hysteresis shape of this curve is almost identical to that of the defect mode shift shown in Fig. 2(a). More compelling evidence of the origin of hysteresis is given by plotting the reversed reflectance (-1×reflectance) at 795 nm during the whole heating and cooling cycle (blue curve in Fig. 2(b)). This reflection hysteresis curve perfectly matches the hysteresis curve of Raman spectra. The characterization results show that the Bragg filter is tuned by the phase transition of the $VO_2$ defect layer.

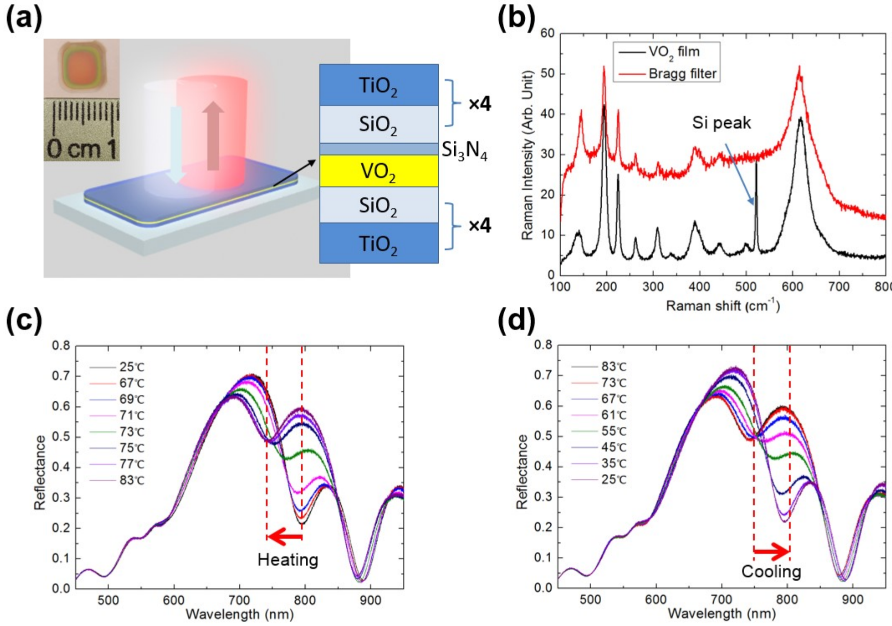


Fig. 1. (a) Schematic diagram with cross-section view and photo (inset) of a typical tunable Bragg filter sample. The figure is not drawn to the scale; (b) The Raman spectrum of the Bragg filter sample at 25 ℃ (red) and the Raman spectrum of a single layer $VO_2$ on $SiO_2$/Si substrate (black). The Raman peak of silicon substrate is indicated by an arrow; the reflection spectra of sample A during (c) heating and (d) cooling processes. Red arrows indicate shifts of reflection dips during heating and cooling respectively.

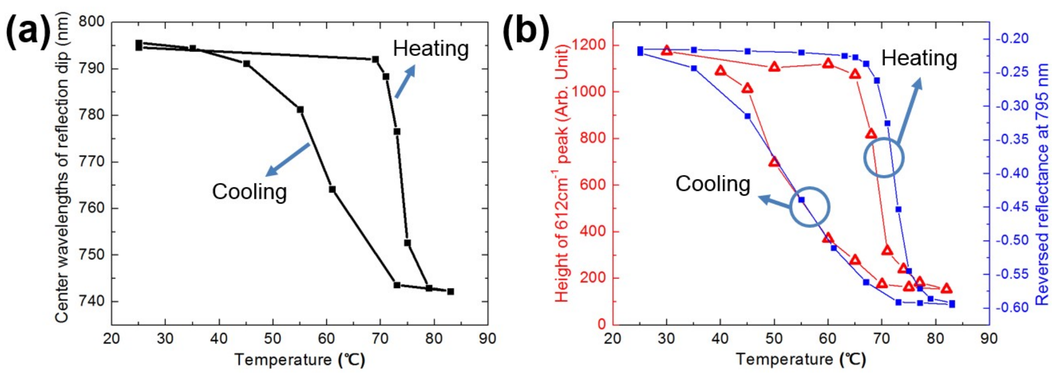


Fig. 2. (a) A hysteresis curve of the center wavelengths of defect modes (reflection dips); (b) Heights of 612 $cm^{-1}$ Raman shift of the Bragg filter sample retrieved from Raman spectra (red) and reversed reflectance at 795 nm (blue) as a function of temperature.

## 3. Conclusions

In conclusion, we have experimentally demonstrated a tunable Bragg filter using a phase transition material, i.e. $VO_2$, as the defect layer. Temperature-dependent Raman spectroscopy verified that this device is tuned by the phase transition of $VO_2$. This work promises more applications by combining phase transition materials and optical cavities in different ways.


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