Supplementary Information:

Ultra-thin perfect absorber using a tunable phase change material

Mikhail A. Kats¹, Deepika Sharma¹², Jiao Lin¹³, Patrice Genevet¹⁴, Romain Blanchard¹, Zheng Yang¹, M. Mumtaz Qazilbash⁵⁶, Dmitri Basov⁵, Shriram Ramanathan¹, and Federico Capasso¹

¹School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
²Department of Physics and Mathematics, University of Eastern Finland, Joensuu, Finland
³Singapore Institute of Manufacturing Technology, Singapore 638075, Singapore
⁴Institute for Quantum Studies and Department of Physics, Texas A&M University, College Station, Texas 77843, USA
⁵Department of Physics, University of California - San Diego, La Jolla, California 92093, USA
⁶Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA
Detailed reflection spectra

In Fig. 1(b), we plotted the measured reflectivity spectra from the vanadium dioxide (VO₂) film on a sapphire for several different temperatures. In Fig. S1, we re-plot this data, including more temperature data points, separating the spectra into those with temperatures up to 343 K (Fig. S1(a)), and those above 343 K (Fig. S1(b)).

![Fig. S1 Measured reflectance of VO₂ for increasing temperature](image)

Sample preparation

The ~180 nm VO₂ thin film was grown on a single-side-polished c-plane sapphire substrate (1mm thick) using magnetron sputtering from a vanadium pentoxide (V₂O₅) target at 550 ºC under 10 mTorr pressure with 100 sccm argon (Ar) gas flow rate at a power of 120 W. The thickness was checked with a scanning electron microscope (SEM) after milling a cross-section with focused ion beam (FIB).

Optical measurements

The sample was mounted on a temperature controlled stage (Bruker Optics A599, 1° temperature deviation) inside a mid-infrared (MIR) microscope (Bruker Optics Hyperion 2000). A reflective objective (15X, NA = 0.4) was used to focus an unpolarized beam from a MIR Globar source mounted in an Fourier transform infrared (FTIR) spectrometer (Bruker Optics Vertex 70) onto the sample from the VO₂ side, with the reflected light collected by the same objective and sent to a liquid nitrogen-cooled mercury-cadmium-telluride (MCT) detector. To normalize the reflectance spectra, a reference spectrum was taken in transmission mode utilizing a second
identical objective to collect the light. An additional sample was fabricated under different growth conditions and measured with the same setup; these measurements are presented in the next section.

**Various angles of incidence**

All of the calculated values for reflection presented in the main text (Fig. 2(d), Fig 3) were made for normally-incident illumination. It is useful to consider the behavior of our perfect absorber given oblique incident light. We used the 3-layer equations with angle dependence [15] to calculate the reflection spectra of our structure using the index for VO$_2$ at T = 342 K for various angles of incidence for s- and p-polarized light (Fig. S2(a) and (b), respectively). Very low reflectivity and high absorption values are observed over a broad range of angles around our wavelength of interest (~11.75 µm). Our calculations show that the reflectivity remains under 0.01 for incident angles of 0° ~ 30° for both s- and p-polarization. This low sensitivity to incident angle is a result of the small propagation distance for light inside the VO$_2$ film. We note that in our experiment, the numerical aperture (NA) of the objective is 0.4 (corresponding to an acceptance angle of ~24°), which is the likely source of the discrepancy between the calculated and measured reflection minima (0.0007 and 0.0025, respectively).

![Calculated reflection spectra from the 180nm VO$_2$ film on sapphire (T = 342 K) for (a) s-polarized and (b) p-polarized incident light at various angles of incidence](image)

Fig. S2 Calculated reflection spectra from the 180nm VO$_2$ film on sapphire (T = 342 K) for (a) s-polarized and (b) p-polarized incident light at various angles of incidence
Samples with different growth conditions

Because optical properties of VO₂ vary depending on material parameters, we performed an additional set of reflectance experiments identical to that of Fig. 1(a) on a second VO₂ film also grown on c-plane sapphire. This sample was grown by direct current (DC) sputtering with a Vanadium target, using gun power of 250 W in an atmosphere of 8.5% O₂ and 91.5% Ar, substantially different conditions from the sample measured in Fig. 1. The resulting sample was ~70nm thick as measured by FIB cross-section, though it had significant surface roughness (on the order of 15 nm), and displayed a four-order of magnitude change in DC resistivity across the phase transition. The experimental reflectance curves are plotted in Fig. S3(a), with the corresponding calculations for 70 nm VO₂ on sapphire shown in Fig. S3(b). The reflectivity minimum is once again visible when the VO₂ is in a transitional state between the purely insulating and metallic phases in both the experimental and calculated spectra, though the exact spectral position of the reflectivity minimum in the calculation is blue-shifted by ~0.8 µm compared to the experiment. We again attribute this to sample differences at different growth conditions. Nonetheless, the dynamically tunable reflectivity minimum is still visible despite the difference in the film thickness and the large surface roughness of the sample.

Fig. S3 Measured (a) and calculated (b) reflection spectrum from the ~70 nm VO₂ film on sapphire.