Ultra-Thin Absorber based on Phase Change Metamaterial Superlattice

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Abstract
In this paper, a superlattice VO\textsubscript{2}/SiO\textsubscript{2} metamaterial on a lossy substrate is designed to create a near perfect absorber with tunability across the infrared spectrum. We selected VO\textsubscript{2} as it presents a dielectric to metal-like phase change slightly above room temperature. Additionally, the slightly lossy nature of high-temperature VO\textsubscript{2} presents comparable and small components (real and imaginary) of the complex refractive index across portions of the visible and infrared. Coupled with a limited conductivity substrate, VO\textsubscript{2} has been employed to create highly absorbing/emitting structures where the thickness of the VO\textsubscript{2} is ultra-thin (t << \lambda/4n). Nevertheless, metal-like VO\textsubscript{2} does not possess comparable and small components of the complex refractive index across the entire infrared spectrum, which limits the universality of this ultra-thin VO\textsubscript{2} absorber design. Here we employ an ultra-thin superlattice of VO\textsubscript{2}/SiO\textsubscript{2} to create a composite metamaterial that is readily designed for high absorbance across the infrared spectrum.

Keywords—metamaterial, vanadium dioxide, absorber, emitter, superlattice, infrared

Introduction
A dielectric to metal-like phase change occurs for VO\textsubscript{2} at temperatures slightly above room temperature. This has sparked interest in VO\textsubscript{2} as a coating on windows of commercial buildings to reflect sunlight on warm days. Unfortunately, this high-temperature reflective state is inherently non-emitting, which is counter to applications such as radiators that need to eject heat at elevated temperatures. This phase change can be generated actively via an applied electric field or a local heating as well as passively via a temperature change of the entire structure or system.

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The use of slightly lossy material was recently proposed to create a single high absorbance layer that is much thinner than the traditional quarter wavelength design. [1] The key insight was to use a material with optical properties intermediate between a (lossless) dielectric and a (perfect electric conductor) metal on a partially lossy substrate. [2] Many semiconductors particularly metal oxides present this intermediate complex dielectric state across large portions of the infrared. The material VO\textsubscript{2} is particularly interesting as it undergoes a phase transition near 50°C. The material is a dielectric below the critical point and is metal-like above the transition point. This is of interest for a variety of applications including switchable antenna structures.

Design
Previous work on dielectrics with strong optical absorption deposited on metal-like materials with limited conductivity has leveraged the non-trivial reflection phase shift at the interfaces. [2] Specifically, the reflection phase shift is intermediate to 0 and π, when one of the materials has a complex refractive index, \( n_c = n + ik \), with comparable \( n \) and \( k \). Therefore, the
structure can accumulate a near-zero reflectance via multiple optical phase shifts at the interfaces. This is in contrast to the gradual phase change over the optical thickness as in traditional wavelength-scale film optics such as a quarter wavelength mirror.

The criteria to achieve near unity absorbance are a specific interplay of the VO$_2$ thickness, wavelength-dependent VO$_2$ refractive index, and the wavelength-dependent substrate refractive index. Fig. 1. displays the absorbance of a VO$_2$ layer as a function of thickness on a sapphire substrate. A high absorbance state is possible for a thickness of 37nm, which is remarkable as this corresponds to an optical thickness of $\lambda$/53n.

Although the absorbance is high with a 37nm film, examination of Fig. 2 shows that a significant fraction (approximately 10%) of the infrared light is reflected from this structure. For this particular complex dielectric constant of the VO$_2$ and the sapphire substrate at a wavelength of 11.75 µm, there is not a thickness that allows the reflection coefficients to return to zero.

Inspection of Fig. 3 reveals that a perfect absorbing refractive index condition theoretically exists for a 37nm film on sapphire at a wavelength of 11.75 µm. Unfortunately, this complex refractive index does not match the experimental VO$_2$ refractive index at this wavelength. A summary of Figs 1-3, is that a high absorbance state is available for an ultra-thin VO$_2$ layer on sapphire at this wavelength, but a perfect absorber/emitter is not available at any thickness.

A solution to this non-unity absorber limitation, is to form a superlattice with another layer. Fig. 4 show that 2nm VO$_2$ / 8 nm SiO$_2$ superlattice displays an absorbance of approximately 92%. As each individual VO$_2$ and SiO$_2$ layer thickness is
much less than the infrared wavelength, it is safe to describe the superlative as a composite layer.

$$e_1 = \frac{f e_{\text{Metal}} + (1-f) e_{\text{Dielectric}}}{d_{\text{Metal}} e_{\text{Metal}} + d_{\text{Dielectric}} e_{\text{Dielectric}}}$$

where the metal term refers to the metallic VO$_2$ and the dielectric term refers to the SiO$_2$.

Fig. 4. Absorbance of a 20x VO$_2$/SiO$_2$ superlattice as a function of VO$_2$ and SiO$_2$ layer thickness.

Fig. 5. Effective parallel and perpendicular permittivity of the VO$_2$/SiO$_2$ superlattice as a function of fill fraction. The parallel and perpendicular terms are relative to the surface of the superlative.

Viewing the superlattice as a single composite layer provides greater insight into the behavior of the material. In the superlattice the effective perpendicular permittivity can be expressed by

$$e_⊥ = \frac{f e_{\text{Metal}} + (1-f) e_{\text{Dielectric}}}{d_{\text{Metal}} e_{\text{Metal}} + d_{\text{Dielectric}} e_{\text{Dielectric}}}$$

where f is the fill fraction of the metallic VO$_2$. Additionally, in the superlattice the parallel permittivity can be expressed by

$$e_∥ = \frac{f e_{\text{Metal}} + (1-f) e_{\text{Dielectric}}}{d_{\text{Metal}} e_{\text{Metal}} + d_{\text{Dielectric}} e_{\text{Dielectric}}}$$
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