A reflective mm-wave photonic limiter

Rodion Kononchuk,¹,² Suwun Suwunnarat,² Martin S. Hilario,³
Anthony E. Baros,³ Brad W. Hoff,³ Vladimir Vasilyev,⁴
Ilya Vitebskiy,⁴ Tsampikos Kottos,² and Andrey A. Chabanov¹

¹Department of Physics and Astronomy,
University of Texas at San Antonio, San Antonio, TX 78249, USA
²Department of Physics, Wesleyan University, Middletown, CT 06457, USA
³Air Force Research Laboratory, Directed Energy
Directorate, Kirtland AFB, NM 87117, USA
⁴Air Force Research Laboratory, Sensors Directorate,
Wright-Patterson AFB, OH 45433, USA

(Dated: January 26, 2022)
Abstract

Millimeter wave (mm-wave) communications and radar receivers capable of processing small signals must be protected from high-power signals, which can damage sensitive receiver components. Many of these systems arguably can be protected by using photonic limiting techniques, in addition to electronic limiting circuits in receiver front-ends. Here we demonstrate, experimentally and numerically, a free-space, reflective mm-wave limiter based on a multilayer structure involving a nanolayer of vanadium dioxide (VO\textsubscript{2}), experiencing a thermal insulator-to-metal transition. The multilayer acts as a variable reflector, controlled by the input power. At low input power levels, VO\textsubscript{2} remains dielectric, and the multilayer exhibits resonant transmittance. When the input power exceeds a threshold level, the emerging metallic phase renders the multilayer highly reflective while dissipating a small portion of the input power without damage to the limiter. In the case of a Gaussian beam, the limiter has a nearly constant output above the limiting threshold input.

Millimeter wave (mm-wave) is a valuable network and sensing technology which utilizes frequency bands in between 30 GHz and 300 GHz \[1\text{–}3\]. Operating in this spectral range has important advantages over lower frequency bands. Not only do mm-waves allow larger bandwidths to transmit data at multi-gigabit speeds \[4\], they also provide higher spatial resolution due to shorter wavelengths, which can be exploited for a variety of accurate sensing applications \[5\]. Another advantage of mm-wavelengths is that the size of system components required to receive and process mm-wave signals is small enough to allow using standard optical techniques \[6\text{–}12\].

Optical limiting is a technique to protect photosensitive devices from damage caused by intense optical radiation \[13\text{–}14\]. Optical limiters are therefore designed to block high-intensity laser radiation while transmitting low-intensity light. Most passive optical limiters utilize materials with nonlinear absorption, which are transparent to low-intensity light but turn opaque if the light intensity exceeds a certain (limiting) threshold level \[15\text{–}17\]. However, a typical passive limiter absorbs a significant portion of high-level radiation, which can cause overheating and damage to the limiter itself \[14\text{–}18\].

To overcome this problem, the concept of a reflective photonic limiter, which reflects rather than absorbs high-intensity radiation, has been introduced \[19\text{–}21\]. A passive reflective photonic limiter involves a photonic bandgap structure, such as a multilayer cavity,
incorporating a nonlinear [21, 22] or a phase-change material (PCM) [23, 24]. At low incident intensities, transmittance of the photonic structure is at its maximum due to resonant transmission via a localized mode in photonic bandgap. High-intensity radiation, however, forces nonlinearity to kick in or phase transition to be induced, producing an impedance mismatch, which reflects most of the incident radiation. The high reflectivity prevents the limiter from overheating, thereby greatly increasing the limiter damage threshold. Other important advantages of the photonic design include orders-of-magnitude larger extinction ratio (the ratio of transmittances below and above the limiting threshold) and the possibility to significantly lower the limiting threshold by adjusting the photonic structure hosting the nonlinear material or PCM. The aforementioned approach thus provides advanced broadband protection from high-level radiation, although low-intensity transmission is essentially narrowband due to its resonant nature. Arguably, mm-wave limiters can be designed in much the same way to protect systems receivers from high-power signals and also to allow the receivers to function normally when these high-power signals are not present.

In this Article, we report for the first time a free-space, reflective photonic limiter for the W band (75-110 GHz), inspired by recent optical designs. First, we design and fabricate a resonant multilayer structure incorporating a nanolayer of vanadium dioxide (VO$_2$), undergoing an insulator-to-metal transition when heated above the critical temperature of $\theta_c \approx 69^\circ$C. Then, we investigate the mm-wave limiting properties of the multilayer by low-power spectral measurements at successively increasing temperatures and by time-resolved continuous-wave (CW) measurements at high input powers. Our experimental findings are then corroborated by 3D multiphysics simulations, which allow us to gain deeper insight into the limiting process by exploring the dynamics of the limiter driven by the VO$_2$ phase transition.

The approach based on the use of insulator-to-metal transition materials is highly scalable and can be replicated in any spectral range, from microwave (MW) to optical (see, for example, [25–28] and references therein). At MW frequencies, however, the insulator-to-metal transition is accompanied by much greater change in the complex permittivity of the phase-change material – orders of magnitude in our case. This provides an unprecedented flexibility in control of the MW radiation flow, unattainable in optics.

**Mm-wave limiter design and low-power measurements at varying temperature.** The reflective mm-wave limiter studied in this work is illustrated in Fig. 1a,b. It involves a
photonic bandgap structure constructed of 76.2-mm-diameter C-cut sapphire (Al₂O₃) wafers, with a 525-µm thick wafer in the middle and four 256-µm thick wafers on the sides, separated by air gaps of a uniform thickness of about 792 µm. The middle sapphire wafer is coated on one side with a polycrystalline VO₂ to a thickness of approximately 150 nm (see Methods and Supplementary Figure 1). Measurements of sheet resistance of the VO₂ coating reveal an abrupt insulator-to-metal transition at ∼ 67°C, with a four orders of magnitude change in the sheet resistance over a temperature range of ∼ 5°C (see Supplementary Figure 2). According to literature [29, 31], in the transition region the electrical and optical properties of thin-film VO₂ are determined by the volume fraction of the thin film transformed into the metallic phase.

FIG. 1. Reflective mm-wave photonic limiter. A picture (a) and schematic (b) of the mm-wave photonic limiter consisting of 256-µm (S) and 525-µm (SS) thick sapphire wafers separated by 792-µm air-gap spacers (PR) and a 150-nm VO₂ layer deposited on the SS sapphire. The layer stack is retained in a plastic holder (PH). c,d, Simulated transmittance T and reflectance R of the photonic structure at normal incidence, at θ > θ_c (c) and θ < θ_c (d). e,f, Simulated internal intensity profiles in the direction of wave propagation of the incident intensity I₀ at the resonance frequency 95 GHz, at θ > θ_c (e) and θ < θ_c (f). Sapphire and air-gap layers are shown in dark and light blue, and the VO₂ layer in green and yellow at the lower and higher temperatures, respectively.

Since design and modeling of the photonic limiter required accurate values of the dielectric properties of the constitutive materials, we performed mm-wave measurements of sapphire and VO₂-on-sapphire wafers at low power (≤ 10 mW) and successively increased temperatures from 27°C to 110°C (see Methods). The (ordinary) relative permittivity of sapphire in the W band, ε_s = 9.32 + i0.009, was determined from measurements of insertion
loss and phase of the sapphire wafer and remained unchanged on heating over the whole temperature range. Fig. 2a shows the transmittance $T$ (blue circles), reflectance $R$ (black circles), and absorptance $A = 1 - T - R$ (red circles) of the VO$_2$-on-sapphire wafer at 95 GHz (in the vicinity of the Fabry-Pérot resonance of the substrate) as a function of increasing temperature. The phase transition in the VO$_2$ layer manifests itself as an abrupt drop in the transmittance accompanied by a steep increase in the reflectance and a sharp peak in the absorptance, due to dramatic change in the permittivity of VO$_2$ during the transition (see Fig. 2b). The relative permittivity, $\epsilon_{\text{VO}_2} = \epsilon'_{\text{VO}_2} + i\epsilon''_{\text{VO}_2}$, was found by fitting the observed insertion loss and phase of the VO$_2$-on-sapphire wafer to those obtained from numerical simulations using $2 \times 2$ transfer-matrix formalism [32]. The real and imaginary parts, $\epsilon'_{\text{VO}_2}$ and $\epsilon''_{\text{VO}_2}$, obtained from the fit at $\theta \geq 69^\circ$C are plotted with the increasing temperature by solid lines (in green and magenta, respectively) in Fig. 2b. Below 69°C, the VO$_2$ contribution to the insertion loss and phase was too small to be observed; it was observed, though, in mm-wave measurements of the photonic limiter which follow. The corresponding $\epsilon'_{\text{VO}_2}$ and $\epsilon''_{\text{VO}_2}$ are shown by the dashed lines in Fig. 2b.

FIG. 2. Mm-wave dielectric properties of the VO$_2$ nanolayer at low input power and increasing temperature. a, Mm-wave transmittance $T$, reflectance $R$, and absorptance $A$ of the VO$_2$-on-sapphire wafer at 95-GHz input power of $< 10$ mW and successively increasing temperature $\theta$. b, Temperature-dependent real ($\epsilon'_{\text{VO}_2}$) and imaginary ($\epsilon''_{\text{VO}_2}$) parts of the relative permittivity of the VO$_2$ layer at 95 GHz, determined from the measurements of the insertion loss and phase of the VO$_2$-on-sapphire wafer (solid lines) and transmittance measurements of the photonic limiter (dashed lines).

According to Fig. 2a, the VO$_2$-on-sapphire wafer can act as a temperature-controlled
mm-wave limiter with an extinction ratio of 20 dB. As for self-induced mm-wave limiting, the threshold level of such a limiter is too high due to very low absorptance and thus weak heating effect at low temperatures. By using the highest (in this study) mm-wave input power (55 W) and by starting at room temperature, we could not heat the wafer up to $\theta_c$.

The resonant setting of the limiter of Fig. 1a,b allows to enhance both absorptance and extinction ratio by orders of magnitude. According to transfer-matrix calculations below $\theta_c$, the multilayer structure exhibits a resonant transmittance (with a resonance $Q$ factor of 260) at a frequency of the (defect-)localized mode close to 95 GHz (see Fig. 1c). Spatial intensity distribution of the electric field component within the multilayer at the resonance frequency is plotted with a red solid line in Fig. 1d. The position of the VO$_2$ layer (shown in green) is seen to coincide with an antinodal plane of the resonant electric field, providing resonance enhancement of the absorptance and thus heating of VO$_2$. Above $\theta_c$, the multilayer turns highly reflective over the entire W band (see Fig. 1e). Moreover, the VO$_2$ layer (shown in orange) is shielded from incident radiation by the multilayer front-end (as seen in Fig. 1f), thus significantly increasing the limiter damage threshold.

Mm-wave measurements of the limiter carried out at low power and successively increased temperatures agree well with the transfer-matrix calculations. In Fig. 3a, the resonance transmittance peak is seen to drop by 40 dB within 70°C to 75°C temperature range, to completely disappear by the end of the transition. When this takes place, the limiter becomes totally reflective (see Fig. 3b). Below the transition temperature, the transmittance peak is seen gradually shifting to lower frequencies (see Fig. 3c), indicating an increase in the refractive index of VO$_2$ with the increasing temperature, while its peak value remains unchanged implying negligible VO$_2$ absorption below $\theta_c$. The extracted $\epsilon'_{\text{VO}_2}$ and $\epsilon''_{\text{VO}_2} \approx 0$ are plotted by dashed lines in Fig. 2b. Note that no noticeable change was observed in transmittance spectra of the multilayer without VO$_2$ coating in the same temperature range.

**High-power measurements of the mm-wave limiter.**

To investigate self-induced mm-wave limiting, time-resolved transmission measurements of the limiter have been carried out with the use of a high-power CW source centered on 95 GHz with a FWHM of 300 MHz (see Methods). To prevent adverse effects of back-reflected radiation on the mm-wave source, the reflective limiter was tilted by an angle of 6° from the normal incidence direction, shifting the transmission resonance to a higher frequency than 95 GHz. Fig. 4a shows linear-log plots of the transmitted power $P_T(t)$ for incident Gaussian
FIG. 3. Mm-wave measurements of the photonic limiter at low input power and increasing temperature. a, b, Spectra of transmittance $T$ (a) and reflectance $R$ (b) of the photonic limiter at input power of $\leq 10$ mW over the resonance spectral range and phase-transition temperature interval. c, Transmittance spectra over the wider temperature range from 27°C to 76°C.

beams of input powers $P_0 = 30, 35, 40, 45,$ and 55 W. For each input power, $P_T(t)$ is seen to initially increase and then decrease with time. This is due to the fact that the transmission resonance shifts to lower frequencies with increasing temperature, in accordance with Fig. 3c, crossing the peak frequency of 95 GHz at a time of maximum transmission. In addition, at input powers $P_0 > 30$ W, $P_T(t)$ exhibits a sharp drop associated with the insulator-to-metal transition in the VO$_2$ layer. The corresponding transition or switching time, $t_s$, is plotted versus $P_0$ in the inset; notice that at 30 W input power, the transition is not manifested in $P_T(t)$. The shortest switching time observed in these proof-of-concept measurements was about 7 s at the highest available input power of 55 W. It can be significantly reduced by increasing the input power (see Fig. 5a) or ambient temperature, and by further optimizing the limiter design.

The transition in the VO$_2$ layer was observed with a FLIR thermal camera which could distinguish between the dielectric and metallic phases of VO$_2$ because of their different emissivities in the infrared. Fig. 4b-d display thermal images of the limiter front end at elapsed times indicated by dashed arrows in Fig. 4a for the incident power of 45 W. The first occurrence of the metallic phase in the center of the VO$_2$ layer (red spot in Fig. 4c) coincides with the sharp drop in $P_T(t)$. Then the metallic domain grows in size (see Fig. 4d), accompanied by further decrease in $P_T(t)$, until thermal equilibrium is reached. When high input power is no longer present, the VO$_2$ reverts from the metallic to the dielectric phase after a brief delay.
FIG. 4. High-power mm-wave measurements of the photonic limiter. a, Time-varying transmitted power $P_T(t)$ of the photonic limiter following excitation by a CW 95-GHz Gaussian beam of input powers $P_0 = 30, 35, 40, 45,$ and $55$ W. Inset: switching time $t_s$, corresponding to the onset of the metallic phase in the VO$_2$ layer, versus the input power $P_0$. b-d, Thermal images of the limiter front end at elapsed times indicated by the dashed arrows in a, for $P_0 = 45$ W.

The equilibrium size of the metallic domain and thus the extinction ratio of the limiter increase with the incident power $P_0$. In contrast, the transmitted power $P_T(t)$ in the steady-state regime (i.e., at longer times) is nearly independent of $P_0$, as seen in Fig. 4a. This practically important feature is, in fact, due to the Gaussian intensity distribution of the incident beam, $I(r) = (2P_0/\pi r_0^2) \exp(-2r^2/r_0^2)$. Indeed, if the beam is centered on and blocked by a disk of radius $a$, the transmitted power is $P_T \approx P_0 \exp(-2a^2/r_0^2)$ provided the limiter aperture is considerably larger than the disk. Assuming that the value of $a$ is determined from $I(r = a) = I_t$, where $I_t$ is the intensity threshold value, the transmitted power is $P_T \approx \pi r_0^2 I_t/2$ (i.e., independent of the input power $P_0$).

Electromagnetic and heat transfer modeling of the mm-wave limiter.

To gain deeper insight into the mm-wave limiting process in the photonic limiter, we have performed time-domain 3D multiphysics simulations of a Gaussian beam propagating through the multilayer of Fig. 1a,b. The electric field component $E$ of the incident Gaussian beam (assuming polarization in the radial direction $\hat{r}$ and propagation in the $+z$ direction) is given by

$$E(z,r) = E_0 \hat{r} \exp \left( -\frac{r^2}{r_0^2} \right) \exp(-ikz),$$  \hspace{1cm} (1)
where \( E_0 \) is the on-axis \((r = 0)\) electric field amplitude, \( E_0 = \sqrt{4\eta_0 P_0/\pi r_0^2} \), \( \eta_0 = 377 \ \Omega \) is the wave impedance of free space, \( k = 2\pi/\lambda \) is the wave number for a free-space wavelength \( \lambda \), and \( r_0 = 16.5 \text{ mm} \) is the beam waist radius at which the field amplitude falls to \( 1/e \) of its axial value.

The mm-wave propagation in the case of temperature-dependent permittivity of the VO\(_2\) layer is described by the following set of coupled electromagnetic and thermal equations:

\[
\nabla \times \mathbf{H} = j + \varepsilon \frac{\partial \mathbf{E}}{\partial t}, \quad \nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}, \quad \rho c \frac{\partial \theta}{\partial t} = \nabla \cdot (\kappa \nabla \theta) + \dot{Q},
\]

where \( \mathbf{H} \) is the magnetic field component, \( j = \sigma \mathbf{E} \) is the current density, \( \sigma(z, \theta) \) is the electrical conductivity, \( \varepsilon(z, \theta) = \varepsilon'(z, \theta) + i\varepsilon''(z, \theta) \) is the permittivity, and \( \mu \) is the permeability. In the second line of equations (2), \( \dot{Q} = \frac{1}{2} (\text{Re}(j \cdot E) + \omega \varepsilon'' |E|^2) \) is the volumetric heat production rate. For computational convenience, we recast the above expression as \( \dot{Q} = \frac{1}{2} \omega \varepsilon_0 \varepsilon'' |E|^2 \), where \( \varepsilon_0 \) is the vacuum permittivity, and \( \varepsilon'' \) is the imaginary part of the effective relative permittivity, which can be directly obtained from our measurements. The other parameters in equations (2) include the specific heat capacity \( c(z) \), the mass density \( \rho(z) \), and the thermal conductivity \( \kappa(z) \). In the modeling, we assume that the multilayer is thermally insulated on the cylindrical surface (due to the plastic holder) and that the heat flux \( q \) across the limiter front and rear ends dissipates by convection, i.e., \( q = h(\theta - \theta_0) \), where \( h = 100 \text{ W/(m}^2\text{K)} \) is the convection heat transfer coefficient [33], and \( \theta_0 = 296 \text{ K} \) is the ambient temperature. Furthermore, we use the experimentally determined relative permittivities of sapphire (\( \varepsilon_s \)) and VO\(_2\) (\( \varepsilon_{\text{VO}_2} \)) and assume \( \mu \) to be the magnetic permeability of free space, \( \mu = \mu_0 \). Finally, the thermal properties of the constitutive materials used in the simulations are listed in Supplementary Table 1.

Equations (2) have been solved simultaneously using the coupled Microwave and Heat Transfer modules of COMSOL Multiphysics software [34]. Fig. 5 shows the computed time-dependent transmitted power \( P_T(t) \), reflected power \( P_R(t) \), and absorptance \( A(t) = (P_0 - P_T(t) - P_R(t))/P_0 \) of the limiter following excitation by a 95-GHz Gaussian beam of input powers \( P_0 = 29, 56, 554, \) and 5540 W. A good agreement between the numerical simulations and the experimental data (see Fig. 4) is evident. Specifically, \( P_T(t) \) exhibits abrupt, steep decrease once VO\(_2\) has reached \( \theta_c \) (see Fig. 5a). Also, in the steady limiting regime (flat portion of the curves at later times) the input power is reflected to a greater extent than
is absorbed (see Fig. 5b,c). We further note in Fig. 5a that the switching time is inversely proportional to the input power, $t_s \propto \frac{1}{P_0}$, and that at $t > t_s$, the transmitted power decreases inversely with time, $P_T(t) \propto \frac{1}{t}$ (shown by a black dotted line).

FIG. 5. Simulated temporal response of the photonic limiter under monochromatic excitation. a-c, Time evolution of the transmitted power $P_T(t)$ (a), reflected power $P_R(t)$ (b), and absorptance $A(t)$ (c) of the limiter following excitation by a 95-GHz Gaussian beam of input powers $P_0 = 29, 56, 554, \text{ and } 5540$ W. The black dashed line in panel a indicates a slope of $P_T(t) \propto t^{-1}$.

The dependence of $t_s$ on $P_0$ can be understood from the solution of a heat balance equation [35] for the VO$_2$ layer in the beam center. Assuming for the time being that the temperature distribution in the VO$_2$-on-sapphire wafer is uniform in the +z direction and neglecting transverse thermal conduction away from the beam center, the heat balance equation is

$$C \frac{d\theta}{dt} = AI_{in} + h'(\theta_0 - \theta),$$  \hspace{1cm} (3)

where $C$ is the heat capacity per unit surface area, $h'$ is the thermal exchange coefficient, $A$ is the absorptance and $I_{in} \sim I_0 \exp(L/2\xi)$ is the internal intensity in the middle of the multilayer length $L$, $\xi$ is the decay length associated with the spatial distribution of the resonant defect mode (see Fig. 1e). Assuming that the initial temperature of the VO$_2$ layer is equal to the ambient temperature, $\theta(t=0) = \theta_0$, and that $C$, $A$, and $h'$ are temperature-independent below $\theta_c$, the solution of equation (3) is

$$\theta(t) = \theta_0 + \frac{AI_{in}}{h'} \left( 1 - \exp \left( -\frac{h'}{C} t \right) \right),$$  \hspace{1cm} (4)
for \( \theta_0 \leq \theta < \theta_c \). At intensities \( I_{in} > \frac{h'}{A}(\theta_c - \theta_0) \), the temperature \( \theta(t) \) grows until it reaches the phase transition value \( \theta_c \) at time,

\[
t_s = -\frac{C}{h'} \ln \left( 1 - \frac{h'}{A I_{in}} (\theta_c - \theta_0) \right) \approx \frac{C(\theta_c - \theta_0)}{A I_{in}} \propto \frac{1}{P_0}.
\]

Note that in the case of the Gaussian beam of equation (1), the larger the radial distance \( r \) is the longer it takes to reach \( \theta_c \). As a result, the radius \( r_m \) of the metallic domain grows with time according to

\[
t = \frac{C(\theta_c - \theta_0)}{A I_{in} \exp(-2r_m^2/r_0^2)},
\]

for \( t \geq t_s \). Since the corresponding transmitted power is

\[
P_T = \left( \pi r_0^2 I_0/2 \right) \exp(-2r_m^2/r_0^2),
\]

it decreases with time as

\[
P_T(t) = \frac{\pi r_0^2 C(\theta_c - \theta_0)}{2 A t \exp(L/2\xi)} \propto t^{-1},
\]

in agreement with Fig. 5a.

According to Fig. 5, it takes \( \sim 10^2 \) s for the limiter to reach the steady state. By then \( P_T(t) \) has dropped substantially compared to its initial level. At the input powers \( P_0 < 60 \) W, the steady-state \( P_T(t) \) is independent of \( P_0 \) in agreement with the experiment (see Fig. 4a). At \( P_0 > 60 \) W, however, \( P_T(t) \) falls further down as the metallic domain becomes comparable to the limiter aperture in size (see Fig. 6b). At \( P_0 = 5540 \) W, \( P_T(t) \) falls by 60 dB, much like in the transmittance measurement of the limiter at spatially uniform, successively increasing temperatures (see Fig. 3a).

As seen from Fig. 5c, the resonant setting of the multilayer enhances the initial (low-temperature) absorptance by two orders of magnitude compared to the stand-alone VO\(_2\)-on-sapphire wafer. In the presence of continuous input power \( P_0 \), \( A(t) \) rises up to a peak of \( \sim 0.32 \) regardless of \( P_0 \) and then falls down to a constant level depending on \( P_0 \). This absorptance behavior, which is characteristic of the entire multilayer rather than the stand-alone VO\(_2\)-on-sapphire wafer (for comparison, see Fig. 2a), is essential to understanding the mm-wave limiting process in the photonic limiter. The increase in absorptance resulting from the heating effect triggers thermal runaway, in which the VO\(_2\) temperature quickly runs up to \( \theta_c \) and higher (see Fig. 6a,b), carrying VO\(_2\) through the phase transition. However, due to rapidly increasing reflectivity with the fraction of VO\(_2\) transformed into the metallic phase, the absorptance changes instantly from rising to falling, and the VO\(_2\) layer from heating to cooling, until equilibrium is reached. The equilibrium sets in at a particular metallic fraction of VO\(_2\), at which the limiter is capable of fully dissipating the absorbed power while reflecting most of the input power. If the input power further increases or decreases, so does the metallic fraction of VO\(_2\) to reset the equilibrium. In contrast, the stand-alone VO\(_2\)-on-sapphire wafer exhibits only thermal runaway and lacks equilibrium at
$\theta > 69^\circ\text{C}$, because its absorbance at $\theta \geq \theta_c$ is higher than that at $\theta < \theta_c$ (see Fig. 2a).

**FIG. 6.** Simulated temperature evolution of the VO$_2$-on-sapphire wafer inside the photonic limiter under monochromatic excitation. a,b, Radial temperature distribution of the VO$_2$ layer as a function of elapsed time $t$ following excitation by a 95-GHz Gaussian beam with the waist radius $r_0 = 16.5$ mm and input powers of 56 W (a) and 554 W (b). c,d, the same for the opposite (uncoated) side of the sapphire wafer. The black dashed lines correspond to $\theta = 69^\circ\text{C}$.

The picture of a self-regulating limiting process in the photonic limiter is further supported by the computed temperature time evolution of the VO$_2$-on-sapphire wafer inside the photonic limiter at input powers of 56 W and 554 W shown in Fig. 6. Due to the limiter’s axial symmetry, we have plotted time-varying radial temperature distributions at the two $z$-positions: in the VO$_2$ layer (see Fig. 6a,b) and on the opposite side of the sapphire wafer (see Fig. 6c,d). Below 69$^\circ\text{C}$ (shown by a black dashed line), the temperature distributions at these two positions are nearly the same, indicating that the VO$_2$ layer (assumed to be lossless) is efficiently heated by the absorbing sapphire wafer. At $\theta > 69^\circ\text{C}$, the VO$_2$ temper-
ature rises faster and higher than in sapphire, particularly at the beam center \((r = 0)\) and the higher power of 554 W. The two temperatures peak and fall at the same time despite a temperature gradient across the sapphire wafer, indicating that sapphire is shielded by VO\(_2\) from the incident beam as the latter is being transformed into the metallic phase. Next, the two temperatures quickly level off, eventually reaching equilibrium temperatures of 75°C and 80°C for input powers of 56W and 554W, respectively, in accordance with Fig. 5 and the subsequent discussion.

**Conclusion**

We have designed and demonstrated a free-space, reflective photonic limiter for the \(W\) band as an alternative or a complement to electronic limiting circuits used in mm-wave receivers. The proposed photonic limiter is a resonant air/sapphire multilayer structure, a few mm thick, incorporating a 150-nm VO\(_2\) layer undergoing an insulator-to-metal transition when heated above the critical temperature, \(\theta_c \approx 69\)°C. The limiter acts as a variable reflector, controlled by the input power \(P_0\). If \(P_0\) is below a certain threshold level \(P_t\), the VO\(_2\) layer remains in the dielectric state, and the multilayer exhibits high transmittance in a finite frequency band, despite the fact that a portion of \(P_0\) is absorbed by the multilayer, leading to some heating of VO\(_2\). When \(P_0\) exceeds \(P_t\), a fraction of the VO\(_2\) layer transitions into the metallic phase with sharply increased electrical conductivity, rendering the entire multilayer highly reflective. The time \(t_s\) before the transition starts is inversely proportional to the input power, \(t_s \propto \frac{1}{P_0}\), after which the multilayer is brought to equilibrium by a combination of positive and negative feedbacks between mm-wave absorption and heating of VO\(_2\). For a given input power \(P_0 \geq P_t\), the equilibrium is determined by the fraction of the VO\(_2\) layer transformed into the metallic phase. At that point, the limiter is capable of safely dissipating a small portion of the incident power while reflecting the rest of the energy back to space. The high reflectivity (as opposed to absorptance) prevents the limiter from overheating. Moreover, a combination of the resonant conditions and the high contrast in electrical conductivity between the two phases of VO\(_2\) results in a significant enhancement of the limiter extinction ratio and allows drastic reduction in the limiting threshold — both highly desirable features in limiting applications.

The limiter properties, such as operating frequency, bandwidth, threshold level and switching time, are determined by the limiter design, ambient conditions, as well as spatial and temporal characteristics of the incident radiation. In particular, in the case of CW
Gaussian beam, the output power of the limiter operating above the threshold appears finite and virtually independent of the input power due to non-uniform heating of the VO$_2$ layer.

**Acknowledgement**

This research has been supported by the Air Force Office of Scientific Research (FA9550-19-1-0359, LRIR 18RYCOR013, LRIR 20RDCOR022), Office of Naval Research (N00014-19-1-2480), and DARPA (HR00111820042). We thank K. Leedy and E. Shin for technical help with the PLD system and helpful discussions.

**Methods**

**Thin-film deposition and structural analysis.** The VO$_2$ thin film was deposited in a Neocera Pioneer 180 Pulse Laser Deposition system with a KrF excimer laser (Coherent COMPexPro 110, $\lambda = 248$ nm, 10-ns pulse duration, 10-Hz repetition rate) applied for the ablation of a high-purity vanadium disk. The chamber base pressure of a 5%-O$_2$/95%-Ar gas mixture was maintained at 25 mTorr during the deposition. The 76.2-mm double-side-polished C-cut (006) sapphire substrate was held at 600$^\circ$C. X-ray diffraction (XRD) analysis of the VO$_2$ films was carried out using a PANalytical X-Pert diffractometer with a hybrid monochromator for Cu K$\alpha_1$ radiation ($\lambda = 1.54056$ Å) at room temperature. The presence of highly oriented monoclinic VO$_2$ crystalline phase is indicated by the characteristic XRD peaks (020) and (040) at 39.87° and 85.97°, respectively [36] (see Supplementary Figure 1). The average VO$_2$ crystalline grain size about 110 nm was found from the Scherrer equation for the FWHM ($\beta$) of the (020) peak [37]. A VO$_2$ film thickness of approximately 150 nm was measured with SEM.

**Mm-wave spectral measurements.** Mm-wave field spectra of the photonic limiter and complex permittivities of its constitutive components were obtained using a W-band, high-temperature, free-space measurement apparatus [38]. The measurement system consisted of an Agilent 5222A performance network analyzer (PNA), N5261A millimeter head controller, and a set of OML V10VNA-T/R frequency extender heads (one for each port) serving to boost the output of the PNA base unit to W-band frequencies (75–110 GHz). A matched set of custom-designed, lensed horn antennas was used for launching and receiving a Gaussian mm-wave beam (waist radius of 16.5 mm) transmitted via and reflected from the sample. The sample was located in the center of a Mellen tube furnace with an overall length and diameter of 31.75 and 15.24 cm, respectively, and a 15.24-cm-long, uniform heating region centered along the axial length of the furnace. A silicon carbide composite sample holder was
used for the measurements. The temperature was controlled with a E-type thermocouple embedded in the sample holder immediately adjacent to the outer radius of the sample. In the temperature range from 27°C to 110°C, the thermocouple had an accuracy of 1.0°C.

**High-power mm-wave measurements.** For higher-power free-space measurements, a CPI VKB2463L2 Extended Interaction Klystron (EIK) power amplifier was used to provide a CW 95-GHz signal. EIK input and output mm-wave power was sampled utilizing calibrated directional couplers, and then measured using diode-based detectors. The input mm-wave drive signal was controlled with a LabView-based feedback circuit to maintain a consistent mm-wave power output over extended periods of time, which could otherwise drop due to heating of components. The EIK mm-wave output was coupled into the same lensed antenna that was utilized with the network analyzer measurement setup, to form a Gaussian beam directed into a shielded anechoic chamber and focused at the center of the sample being interrogated. At a peak power gain, the maximum incident power of the Gaussian mm-wave beam was 55 W.

**Multiphysics simulations.** Equations (2) were solved numerically, using the coupled Microwave and Heat transfer modules of a finite-element software package from COMSOL MULTIPHYSICS [31] and a 2D axisymmetric model, capturing all the features of the 3D problem with axial (cylindrical) symmetry. In the simulations, we used a varying mesh density (see Supplementary Figure 3). The thin sapphire and air-gap layers were partitioned with the mesh density increased towards the center of the limiter, while the center sapphire and air-gap layers towards the VO$_2$ layer. The convergence of the results has been evaluated with a tolerance factor of 0.1%. We then repeated the calculations by doubling the number of mesh points in order to guarantee the accuracy of the converged numerical solutions. The mm-wave source was modeled with a surface current density line producing the Gaussian beam, which was located 1.5 mm away from the front end of the multilayer inside the far-field air domain. The wave propagation was modeled using PML boundary conditions to avoid the back reflections from the boundaries of the geometry.

[1] Rappaport, T. S. *et al.* Millimeter wave mobile communications for 5G cellular: It will work! *IEEE Access* **1**, 335–349 (2013).
[2] Andrews, J. G. et al. What will 5G be? *IEEE J. Sel. Areas Commun.* **32**, 1065–1082 (2014).

[3] Yujiri, L., Shoucri, M. & Moffa, P. Passive millimeter wave imaging. *IEEE Microw. Mag.* **4**, 39–50 (2003).

[4] Wells, J. C. K. *Multigigabit Microwave and Millimeter-Wave Wireless Communications* (Artech House Publishers, 2010).

[5] Iovescu, C. & Rao, S. The fundamentals of millimeter-wave sensors. [http://www.ti.com/lit/wp/spyy005/spyy005.pdf](http://www.ti.com/lit/wp/spyy005/spyy005.pdf) (2017).

[6] Heath, R. W., Gonzalez-Prelcic, N., Rangan, S., Roh, W. & Sayeed, A. M. An overview of signal processing techniques for millimeter wave MIMO systems. *IEEE J. Sel. Top. Signal Process.* **10**, 436–453 (2016).

[7] Hirata, A., Harada, H. & Nagatsuma, T. 120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals. *J. Light. Technol.* **21**, 2145–2153 (2003).

[8] McKinney, J. Photonics illuminates the future of radar. *Nature* **507**, 310–312 (2014).

[9] Ghelfi, P. et al. A fully photonics-based coherent radar system. *Nature* **507**, 341–345 (2014).

[10] Zou, X., Lu, B., Pan, W., Yan, L., Stöhr, A. & Yao, J. Photonics for microwave measurements. *Laser Photonics Rev.* **10**, 711–734 (2016).

[11] Xie, X. et al. Photonic microwave signals with zeptosecond-level absolute timing noise. *Nat. Photonics* **11**, 44–47 (2017).

[12] Georgiadou, D.G. et al. 100 GHz zinc oxide Schottky diodes processed from solution on a wafer scale. *Nat. Electron.* (2020).

[13] Tutt, L. W. & Boggess, T. F. A review of optical limiting mechanisms and devices using organics, fullerenes, semiconductors and other materials. *Prog. Quantum. Electron.* **17**, 299–338 (1993).

[14] Miller, M. J., Mott, A. G. & Ketchel, B. P. General optical limiting requirements. *Proc. SPIE* **3472**, 24–29 (1998).

[15] Van Stryland, E. W., Wu, Y. Y., Hagan, D. J., Soileau, M. J. & Mansour, K. Optical limiting with semiconductors. *J. Opt. Soc. Am. B* **5**, 1980–1988 (1988).

[16] Tutt, L. W. & Kost, A. Optical limiting performance of C$_60$ and C$_{70}$ solutions. *Nature* **356**, 225–226 (1992).

[17] Chen, P. et al. Electronic structure and optical limiting behavior of carbon nanotubes. *Phys.*
Rev. Lett. 82, 2548 (1999).

[18] Boggess, T., Smirl, A., Moss, S., Boyd, I. & Van Stryland, E. Optical limiting in GaAs. IEEE J. Quantum Electron. 21, 488–494 (1985).

[19] Makri, E., Ramezani, H., Kottos, T. & Vitebskiy, I. Concept of a reflective power limiter based on nonlinear localized modes. Phys. Rev. A 89, 031802 (2014).

[20] Makri, E., Kottos, T. & Vitebskiy, I. Reflective optical limiter based on resonant transmission. Phys. Rev. A 91, 043838 (2015).

[21] Vella, J. H. et al. Experimental realization of a reflective optical limiter. Phys. Rev. Applied 5, 064010 (2016).

[22] Makri, E., Smith, K., Chabanov, A. A., Vitebskiy, I. & Kottos, T. Hypersensitive transport in photonic crystals with accidental spatial degeneracies. Sci. Rep. 6, 22169 (2016).

[23] Thomas, R., Chabanov, A. A., Vitebskiy, I. & Kottos, T. Light-induced optical switching in an asymmetric metal-dielectric microcavity with phase-change material. EPL 126, 64003 (2019).

[24] Antonellis, N., Thomas, R., Kats M. A., Vitebskiy, I. & Kottos, T. Nonreciprocity in photonic structures with phase-change components. Phys. Rev. Applied 11, 024046 (2019).

[25] Ha, S. D., Zhou, Y., Duwel, A. E., White, D. W. & Ramanathan, S. Quick switch: Strongly correlated electronic phase transition systems for cutting-edge microwave devices. IEEE Microw. Mag. 15, 32–44 (2014).

[26] Givernaud, J. et al. Microwave power limiting devices based on the semiconductor-metal transition in vanadium-dioxide thin films. IEEE Trans. Microw. Theory Tech. 58, 2352–2361 (2010).

[27] Chettiar, U. K. & Engheta, N. Modeling vanadium dioxide phase transition due to continuous-wave optical signals. Opt. Express 23, 445–451 (2015).

[28] Wan, C. et al. Limiting optical diodes enabled by the phase transition of vanadium dioxide. ACS Photonics 5, 2688–2692 (2018).

[29] Rozen, J., Lopez, R., Haglund, R. F. & Feldman, L. C. Two-dimensional current percolation in nanocrystalline vanadium dioxide films. Appl. Phys. Lett. 88, 081902 (2006).

[30] Qazilbash, M. M. et al. Mott transition in VO₂ revealed by infrared spectroscopy and nano-Imaging. Science 318, 1750–1753 (2007).

[31] Hood, P. J. & DeNatale, J. F. Millimeter-wave dielectric properties of epitaxial vanadium
dioxide thin films. *J. Appl. Phys.* **70**, 376–381 (1991).

[32] Yeh, P. *Optical Waves in Layered Media* Ch. 5 (Wiley, 1988).

[33] [http://thermopedia.com/content/660/](http://thermopedia.com/content/660/).

[34] COMSOL Multiphysics Model Library, v.5.2 (COMSOL AB, 2015).

[35] Bergman, T. L., Lavine, A. S., Incropera, F. P. & Dewitt, D. P. *Fundamentals of Heat and Mass Transfer*, 7th Ed. (John Wiley, 2011).

[36] Kim, H., Charipar, N., Osofsky, M., Qadri, S. B. & Piqué A. Optimization of the semiconductor-metal transition in VO$_2$ epitaxial thin films as a function of oxygen growth pressure. *Appl. Phys. Lett.* **104**, 081913 (2014).

[37] Littlejohn, A. J. *et al.* Naturally formed ultrathin V$_2$O$_5$ heteroepitaxial layer on VO$_2$/sapphire (001) film. *Appl. Surf. Sci.* **419**, 365–372 (2017).

[38] Hilario, M. S. *et al.* W-band complex permittivity measurements at high temperature using free-space methods. *IEEE Trans. Compon. Packaging Manuf. Technol.* **9**, 1011–1019 (2019).