

Formula:

$$A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2 \quad (1)$$

$$A(\omega) \approx 1 - |S_{11}(\omega)|^2 \quad (2)$$

$$\varepsilon(\omega) = \varepsilon_\infty - \omega_p^2(\sigma) / (\omega^2 + i\gamma\omega) \quad (3)$$

$$\omega_p^2(\sigma) = \frac{\sigma}{\sigma_0} \omega_p^2(\sigma_0) \quad (4)$$

$$r \approx R_{12} + \sum (-1)^m T_{12} T_{21} (R_{21} R_{23})^{m-10} R_{23} e^{i2m\beta} \quad (5)$$

$$r = R_{12} + \frac{T_{12} R_{23} T_{21} e^{i\beta}}{1 - R_{21} R_{23} e^{i\beta}} \quad (6)$$

$$\text{RAB} = \frac{2(f_H - f_L)}{f_H + f_L} \times 100\%, \quad (7)$$

$$Z_r = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (8)$$

Chart data:

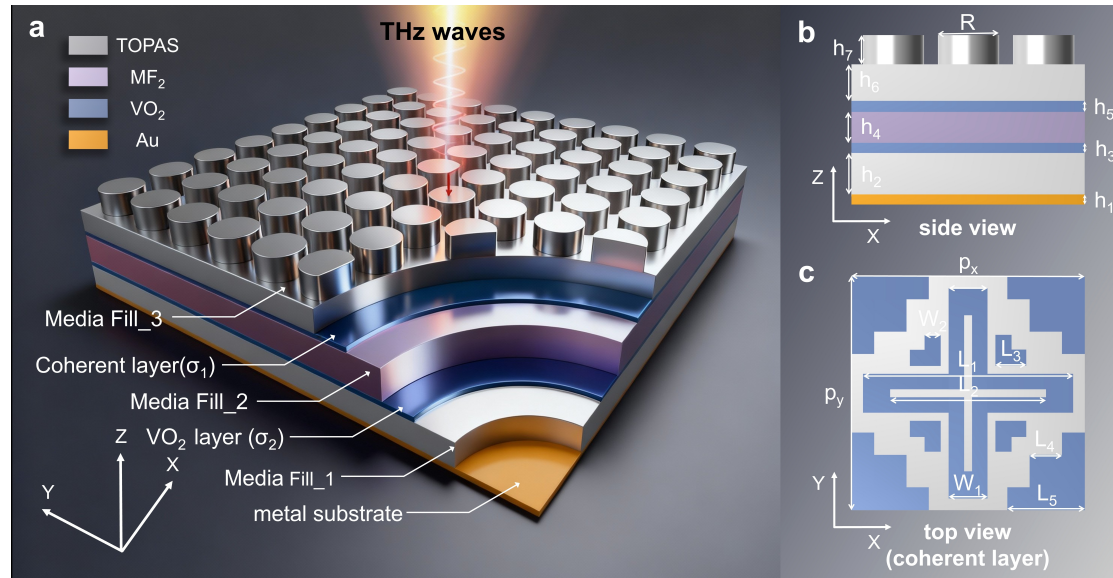


Fig. 1 Schematic of the proposed VO₂-tunable TMA. (a) Three-dimensional view of the multilayer stack composed of the patterned VO₂ coherent layer and dielectric spacers backed by a metallic ground plane. (b) Cross-sectional view (y-z plane) of the unit cell with the layer thicknesses h₁–h₇ and pillar diameter R labelled. (c) Top view of the coherent layer defining the in-plane geometric parameters (period p, feature lengths L₁–L₅, and line widths W₁–W₂).

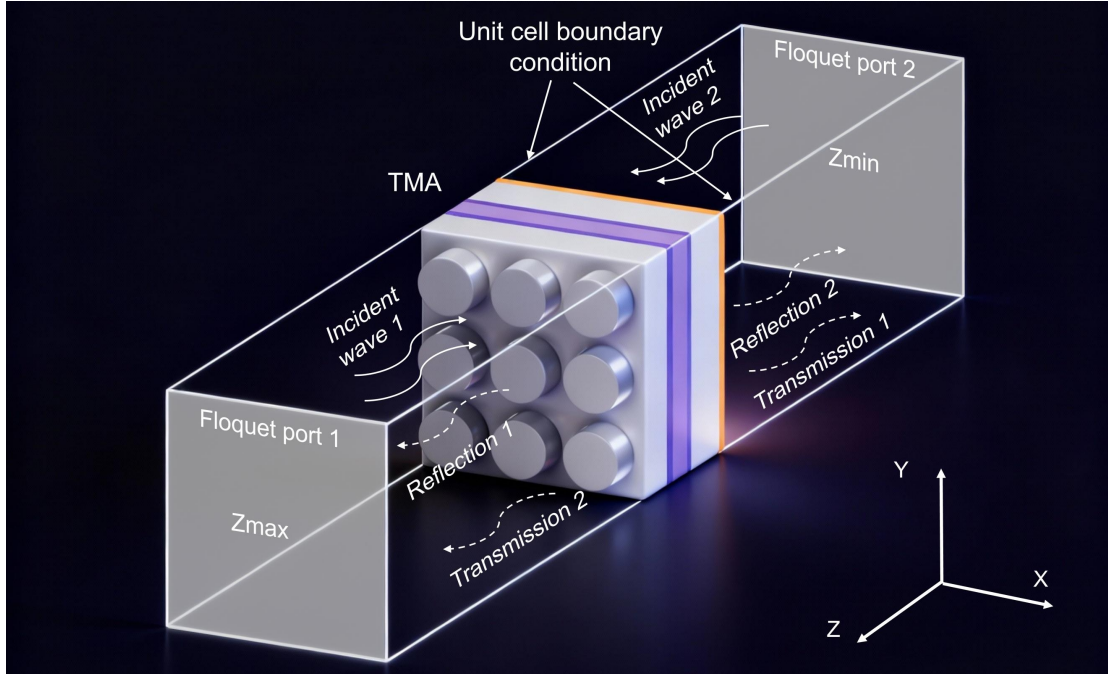


Fig. 2 Numerical model and boundary conditions used for the electromagnetic simulations. The periodic unit cell is excited by a normally incident plane wave using Floquet ports, with periodic boundaries applied along the x and y directions and open boundaries along z; the reflected and transmitted waves are monitored at the ports

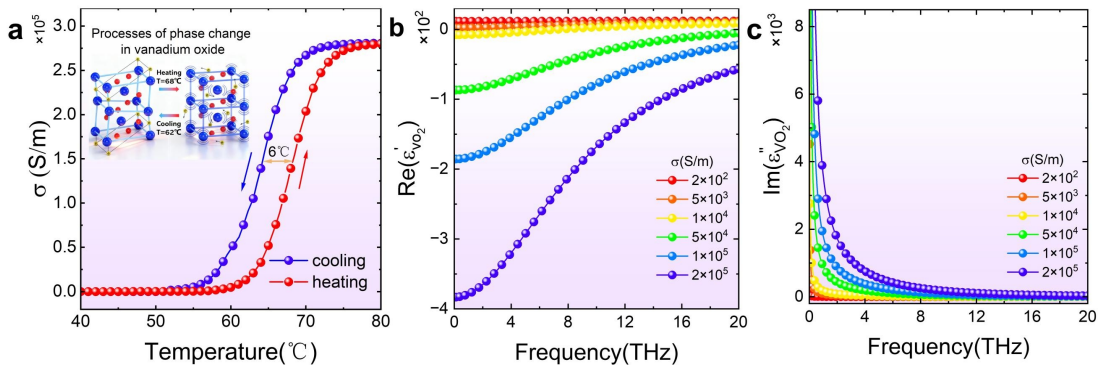


Fig. 3 Electrical response of VO₂ employed in the simulations. (a) Temperature-dependent conductivity σ of VO₂ illustrating the hysteretic phase transition behaviour (heating and cooling). (b) Real part and (c) imaginary part of the effective relative permittivity $\epsilon_r(\omega)$ of VO₂ over 0.1–20 THz for different conductivities σ .

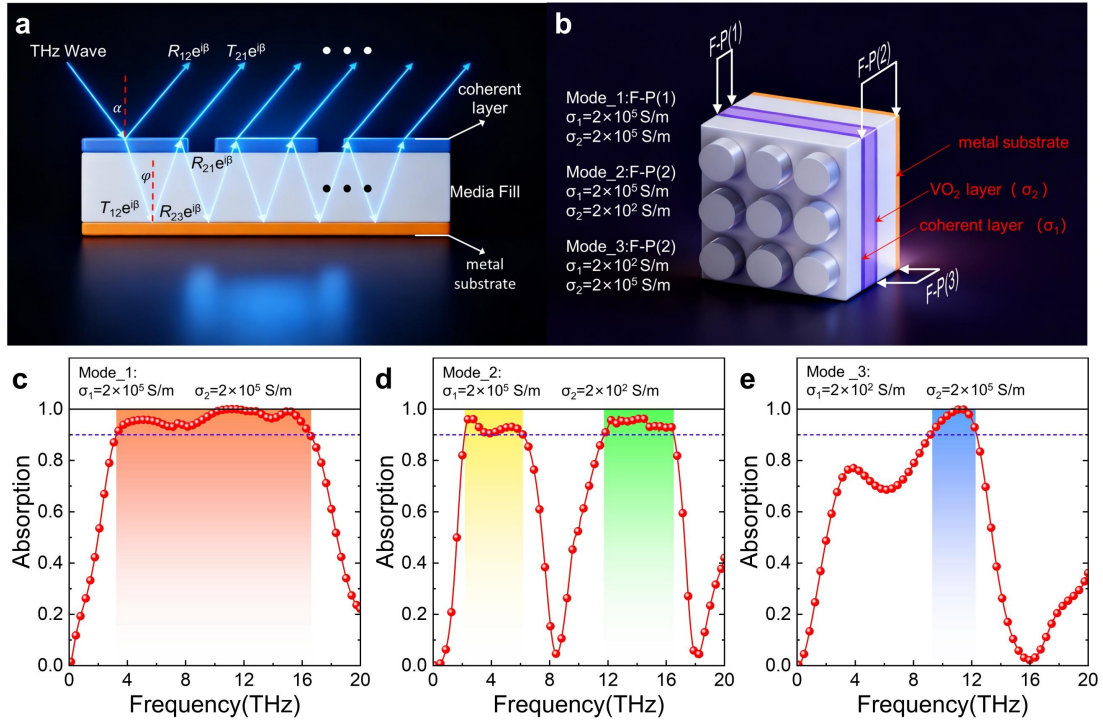


Fig. 4 Multi-mode absorption concept enabled by the VO₂-tunable cavity configuration. (a) Schematic illustration of the multiple-reflection (F–P-like) interference picture in the metal–dielectric–metal stack. (b) Unit-cell configurations corresponding to different operating modes controlled by the VO₂ states in the coherent layer and the continuous VO₂ film. (c–e) Absorption spectra $A(f)$ of Mode 1–Mode 3, showing the reconfigurable broadband/dualband/narrowband responses.

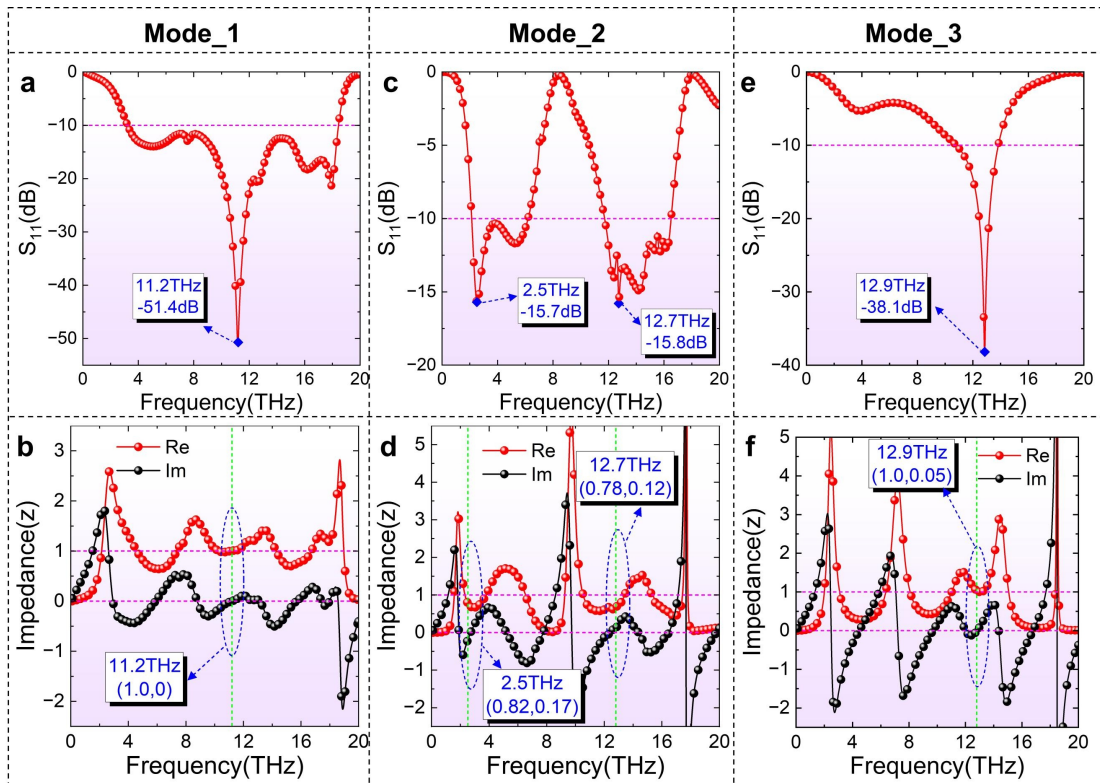


Fig. 5 Reflection and impedance characteristics for the three operating modes. (a), (c), (e) Simulated reflection coefficient $|S_{11}|$ (in dB) for Mode 1– Mode 3. (b), (d), (f) Corresponding normalized effective impedance Z (real and imaginary parts) retrieved from the scattering parameters, evidencing impedance matching at the representative resonance frequencies.

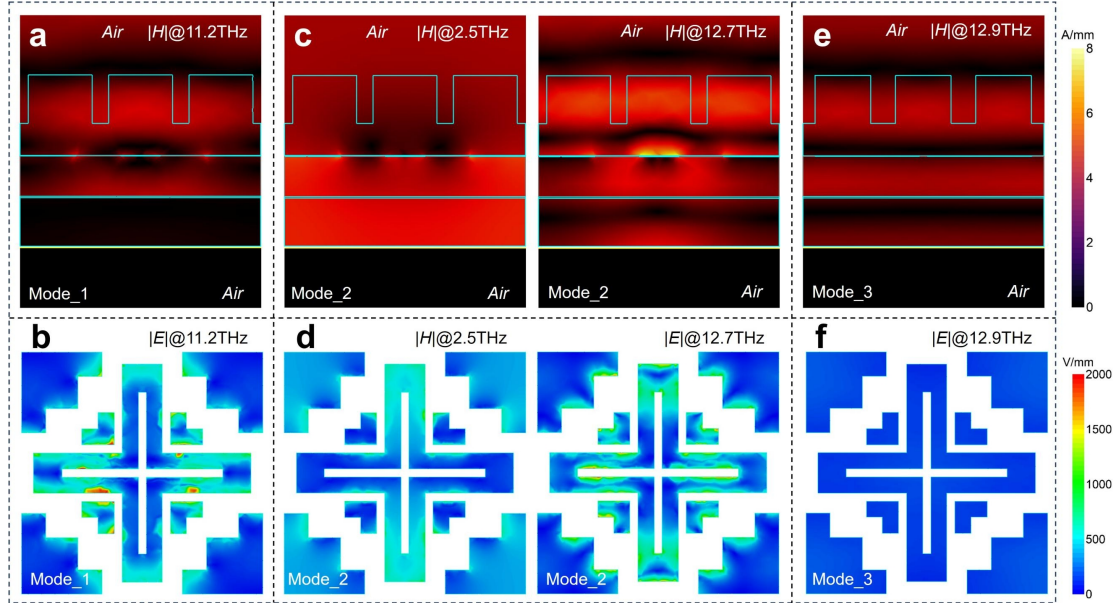


Fig. 6 Electromagnetic-field distributions revealing the physical origin of absorption in different modes. (a–c) Magnetic-field energy-density distributions $|H|$ in the x – z cross-section at representative frequencies f_1, f_2, f_3 , and f_4 for Mode 1–Mode 3. (d–f) Electric-field energy-density distributions $|E|$ on the coherent-layer plane at the same frequencies, illustrating mode-dependent localization and dominant loss channels.

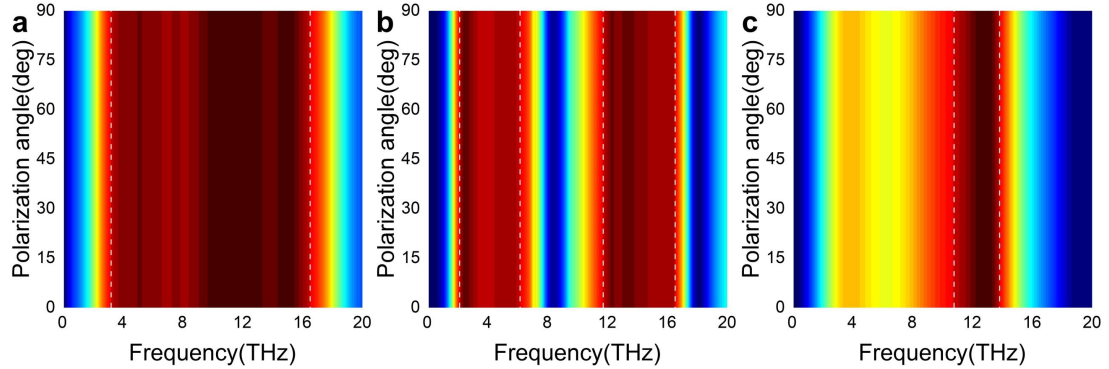


Fig. 7 Polarization robustness of the proposed TMA under normal incidence. Absorbance maps as a function of frequency and polarization angle (0° – 90°) for (a) Mode 1, (b) Mode 2, and (c) Mode 3, demonstrating polarization-insensitive performance over the main absorption bands.

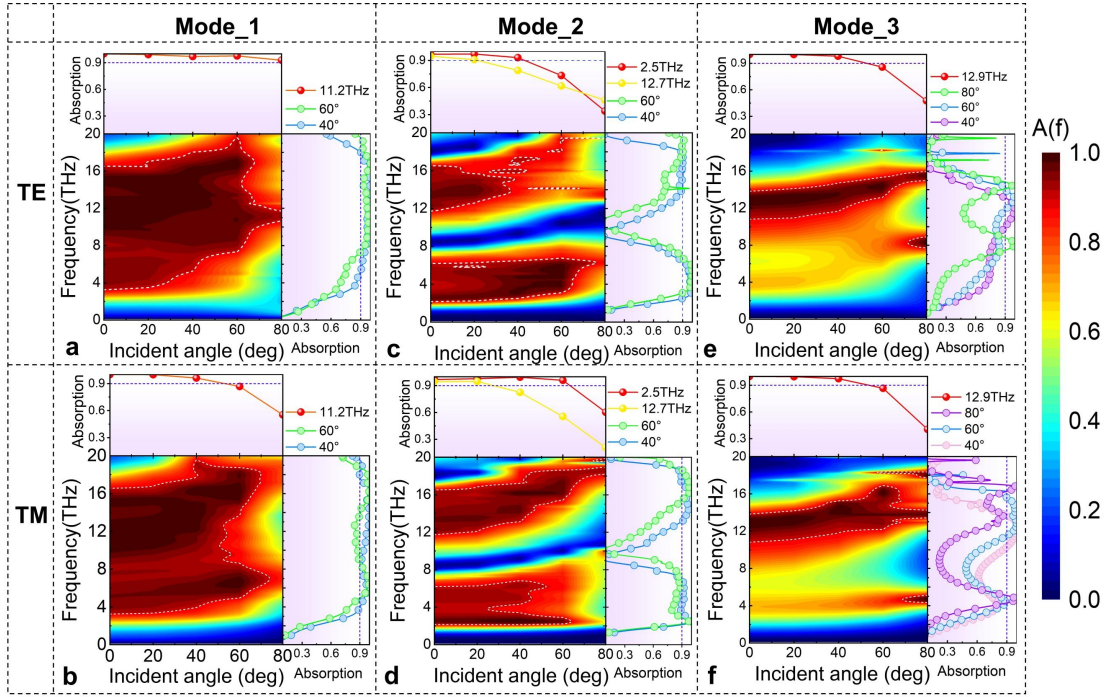


Fig. 8 Wide-angle absorption performance under oblique incidence. Angle-resolved absorptance maps for (a, b) Mode 1, (c, d) Mode 2, and (e, f) Mode 3 under TE and TM polarizations, respectively, with the incident angle varied from 0° to 80° . Insets indicate the absorptance evolution at selected representative frequencies.

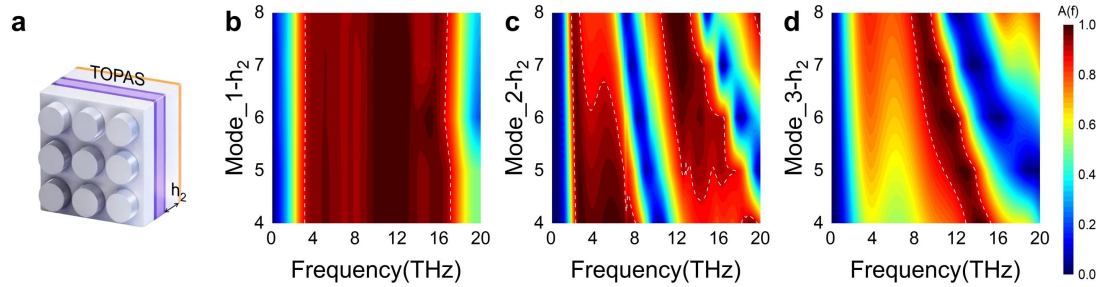


Fig. 9 Effect of the Media Fill_1 (TOPAS) thickness h_2 on the absorption performance. (a) Schematic indicating the parameter h_2 . (b–d) Absorptance maps versus frequency as h_2 varies for Mode 1–Mode 3, respectively, showing the sensitivity of the resonance condition to the cavity thickness.

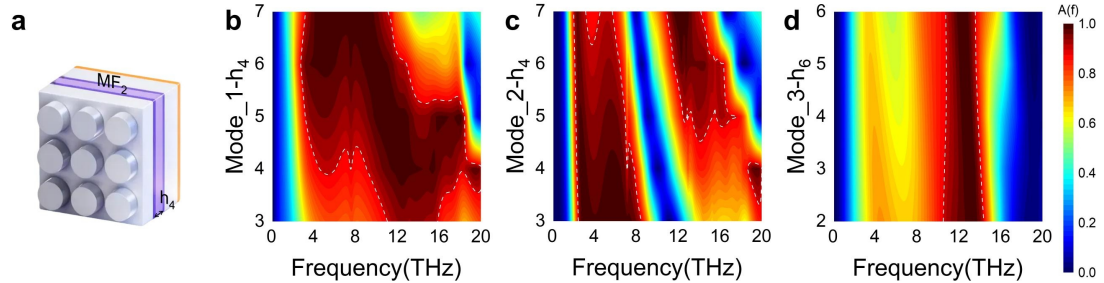


Fig. 10 Effect of the MF2 dielectric thickness on the absorption performance. (a) Schematic of the MF2 layers adjacent to VO₂. (b–d) Absorptance maps versus frequency for Mode 1–Mode 3 as the MF2 thickness (e.g., the upper-side spacer h_4) is varied, illustrating mode-dependent tuning of resonance position and spectral shape.

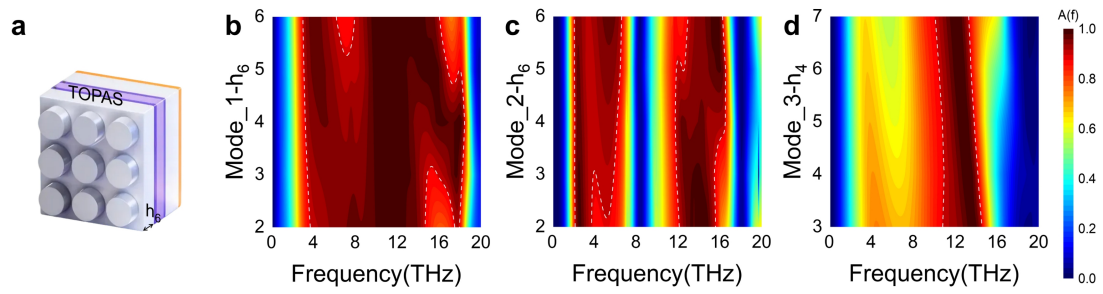


Fig. 11 Influence of the substrate thickness in Media Fill_3 on the absorption response. (a) Schematic indicating the substrate-thickness parameter h_6 . (b–d) Absorptance maps versus frequency for Mode 1–Mode 3 as h_6 varies, demonstrating that this parameter primarily introduces auxiliary dielectric loading with limited resonance shifting.

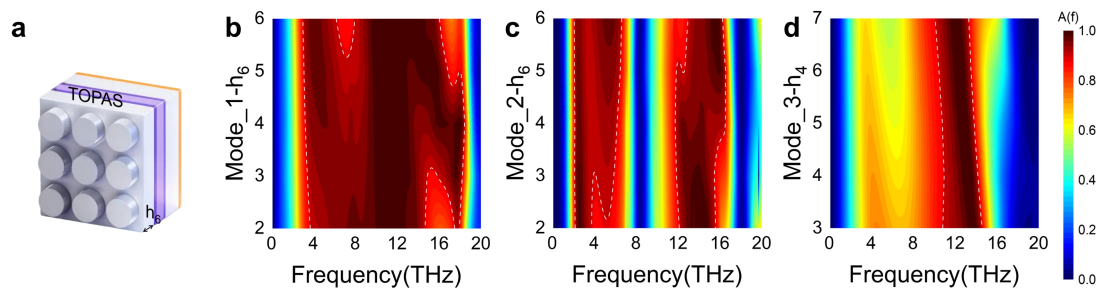


Fig. 12 Influence of the pillar height in Media Fill_3 on the absorption response. (a) Schematic indicating the pillar-height parameter h_7 . (b–d) Absorptance maps versus frequency for Mode 1–Mode 3 as h_7 varies, showing the robustness of the absorption bands against moderate geometric perturbations.

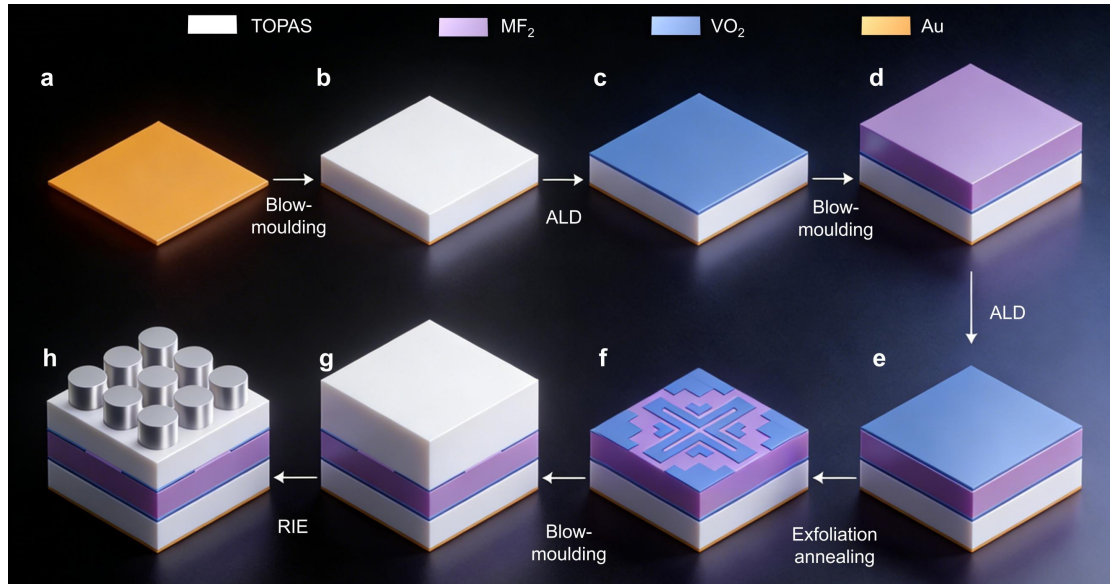


Fig. 13 Schematic illustration of a representative fabrication route for the proposed multilayer VO₂-enabled terahertz absorber

Table 1 Structural parameters of the designed absorber (unit: μm)

Parameter	Value	Parameter	Value
p	30	R	4
h1	0.2	L1	27
h2	6	L2	20
h3	0.07	L3	4
h4	5	L4	4
h5	0.07	L5	10
h6	4	W1	5
h7	6	W2	2

Table 2 Comparison of the performance of the TMA proposed in this paper with other metamaterial absorbers operating in the same frequency spectrum.

References	Broadband bandwidth(RBW(%))	incident angles(deg) TE/TM	Absorption mode	Tunable material
[59]	3.85-7.10(59.4)	60/70:>80%	1	Black phosphorus & VO ₂
[60]	3.77 -9.5(86.36)	45/60:>80%	2	VO ₂
[61]	1.11-6.13(138.7)	30/30:>90%	2	VO ₂
[62]	0.86-3.54(121.8)	60/50:>90%	2	VO ₂ & graphene
[63]	2.6-6.28(82.9)	45/65:>80%	1	graphene
[64]	0.98-1.63(49.8)	60/40:>80%	2	VO ₂ & graphene
[65]	3-12.4(122.08)	50/50:>80%	1	VO ₂ & graphene
[66]	6-24 (120)	30/30:>90%	2	VO ₂
[67]	3.02-7.22(82.03)	30/30:>90%	2	VO ₂
[68]	3.36-6.98(71.85)	50/50:>80%	2	VO ₂ & Si
[69]	4.00-10.08(86.36)	60/50:>80%	1	VO ₂
This paper	3.25–16.56(124.4)	60/60:>90%	3	VO ₂

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