RESEARCH ARTICLE

Flexible optically transparent ultra-wideband millimeter-wave metasurface with infrared stealth and polarization insensitivity

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Supporting Information

Supplementary Note 1: Analysis of absorption performance based on equivalent circuit theory

As illustrated in Fig. 2(a), the impedance of free space is Z_0 = 377Ω. For normally incident EM waves, the adjacent ITO patterned films function as resonant elements. The accumulation of charges between them generates capacitor, while the equivalent inductance arises from the changing current. Therefore, ITO patterned films in the IRSL are represented by a series resistor-inductor-capacitor (RLC) circuits of equivalent impedance Z_1, Meanwhile, the resonant ring and a concave equilateral dodecagonal structure in ITO1 film can be modeled as a series RLC circuits with an equivalent impedance of Z_2. It is noted that the above two circuits are connected in parallel. The equivalent circuit impedance of the ITO patterned films is obtained as follows:

$$Z_n = R_n + j(\omega L_n - 1/\omega C_n), n = 1, 2. \tag{1}$$

Since the sheet resistance of ITO2 film is 15 Ω/sq, exhibiting quasi-metallic behavior, it can be represented as a short -circuited transmission line with impedance Z_t [48]. The PET and the PVC dielectric substrate are equivalent to transmission lines with characteristic impedance Z_{PET} and Z_{PVC} respectively. After establishing the ECM of the FOTMA, the ABCD matrix is employed on calculating the absorption under normal incident waves [49]

$$\begin{aligned}\begin{bmatrix} A & B \\ C & D \end{bmatrix} &= \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_1} & 1 \end{bmatrix} \begin{bmatrix} \cos\delta & jZ_0 \sin\delta \\ \dfrac{j\sin\delta}{Z_0} & \cos\delta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_b} & 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos\delta + \dfrac{jZ_0}{Z_b}\sin\delta & jZ_0 \sin\delta \\ \dfrac{(Z_1+Z_b)\cos\delta + jZ_0 \sin\delta}{Z_1 Z_b} + \dfrac{j\sin\delta}{Z_0} & \cos\delta + \dfrac{jZ_0}{Z_b}\sin\delta \end{bmatrix}\end{aligned} \tag{2}$$

$$\delta_{PET} = \beta_{PET} h_{PET} = \frac{2\pi\sqrt{\varepsilon_{PET}}\, h_{PET}}{\lambda} \tag{3}$$

$$\delta_{PVC} = \beta_{PVC} h_{PVC} = \frac{2\pi\sqrt{\varepsilon_{PVC}}\, h_{PVC}}{\lambda} \tag{4}$$

Where ε_{PET} and ε_{PVC} is the dielectric constant of PET and PVC respectively. λ is the wavelength of the incident wave. Furthermore, the S-parameters is described by

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{AZ_d + B - (CZ_d + D)Z_0}{AZ_0 + B + (CZ_d + D)Z_0} & \dfrac{2\sqrt{Z_d Z_0}}{AZ_0 + B + (CZ_d + D)Z_0} \\ \dfrac{2\sqrt{Z_d Z_0}}{AZ_0 + B + (CZ_d + D)Z_0} & \dfrac{-AZ_d + B - (CZ_d + D)Z_0}{AZ_0 + B + (CZ_d + D)Z_0} \end{bmatrix} \tag{5}$$

$$Z_d = \frac{Z_0 Z_t}{Z_0 + Z_t} \tag{6}$$

The term Z_t is the input impendence of ITO2 film, which can be considered as a short-circuited, $Z_t = 0$. The S-parameters can be further calculated and used in the assessment of absorption performance

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{B - DZ_0}{AZ_0 + B + DZ_0} & \mathbf{0} \\ \mathbf{0} & \dfrac{B - DZ_0}{AZ_0 + B + DZ_0} \end{bmatrix} \tag{7}$$

Supplementary Table 1. Equivalent circuit parameters of FOTMS.

Parameter	Value	Parameter	Value
R_1	6Ω	L_2	2.15nH
L_1	0.051nH	C_2	0.08pF
C_1	3.26pF	R_t	15Ω
R_2	321.9Ω		

Supplementary Table 2. Structural parameters of different stages.

Parameter	Value(Stage-1)	Value(Stage-2)	Value(Stage-3)
l_1	/	4.3mm	4mm
l_2	0.65mm	1mm	1mm
w_1	/	/	0.3mm
w_2	/	0.3mm	0.3mm
w_3	/	0.4mm	0.3mm

Supplementary Table 3. Comparison of absolute and fractional bandwidths for the three design stages.

Design Stage	Absorption Bandwidth (GHz)	Absolute Bandwidth (GHz)	Fractional Bandwidth (%)
Stage-1	28.4-38.4	10	29.9
Stage-2(Band I)	17.6-31.5	13.9	56.6
Stage-2(Band II)	40.4-42.2	1.8	4.4
Stage-3	15-38.7	23.7	88.3

Supplementary Table 4. Performance comparison of the proposed metasurface and other designs.

Reference	Infrared Emissivity	Conformal	Optically Transparent (%)	Absorption Bandwidth (GHz)	Unit Size (mm^2)	Thickness (mm)	Relative volume	Cost-efficient absorption Bandwidth (%)
[1]	None	No	No	2.5-14.6	20×20	13.4	0.1241	11.40
[17]	None	Yes	60.5	9.9-27.7	11×11	4	0.1191	7.97
[19]	None	Yes	74	9.85-41.76	15×15	1.85	0.2649	4.68
[22]	None	Yes	85	21.6-39.2	12×12	1.44	0.2158	2.68
[23]	None	No	48	9.44-120.9	9×9	2.78	2.3083	0.74
[34]	0.35	Yes	No	1.96-20.72	12.1×12.1	16.5	0.1305	12.67
[42]	0.30	No	75.02	6-18	18×18	7.525	0.1560	6.41
[48]	None	No	62.05	2.5-21.3	16.6×16.6	12.9	0.2219	7.12
This work	0.47	Yes	85.09	15-38.7	5×5	1.25	0.0224	38.88