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An ultra-broadband flexible polarization-insensitive microwave metamaterial absorber

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Abstract
In this paper, an ultra-broadband flexible polarization-insensitive microwave metamaterial absorber is proposed, characterized, and fabricated. To achieve high broadband absorption, a two-layer periodic indium-tin-oxide (ITO) patches array printed on polyethylene terephthalate (PET) dielectric layers is used to generate high ohmic loss. The simulation results show that the proposed absorber can achieve greater than 90% absorption in the microwave band range of 19.68 to 94.7 GHz. The absorber is polarization-insensitive due to the symmetry of the structure with high absorption over a wide incidence angle of 60°. The mechanism of ultra-broadband absorption is discussed by the impedance matching theory, the surface current distribution, and the electric field distribution. In addition, the equivalent circuit model is utilized to analyze the effect of the structural parameters. Furthermore, the bow-frame method validates that the experimental measurements are consistent with the simulated spectra. With advantages of absorption of ultra-broadband, polarization-insensitivity, and flexibility, the proposed absorber facilitates its use in numerous potential applications for energy harvesting, imaging and sensing, stealth technology, modulating, and so on.

1. Introduction
Since Landy et al first proposed the metamaterial perfect absorber [1], the metamaterial absorber has aroused widespread attention due to its promising applications, such as sensors [2], energy harvesting [3–6], thermal emitters [7], modulators [8]. The sandwich structure, which consists of a periodically arrayed metal pattern layer, a dielectric spacer, and a flat metal plate, is one of the most classic and traditional designs for metamaterial absorbers. Following that, various metamaterial absorbers ranging from microwave [9], terahertz [10], infrared and visible bands [11–13], are proposed and investigated. The absorber can exhibit single band [14], dual band [15, 16], or multi-band characteristics as the structure evolves from three-layer to multi-layer [17–19]. However, the metamaterial absorber’s inherent narrow absorption hampers the practical application. Therefore, broadband absorption is desirable for the scope of applications, such as energy conversion [20–22].

To extend the absorption bandwidth, a variety of strategies have been proposed [23, 24], such as by assembling multi-shaped resonators on the same layer [25, 26], by stacking multiple layers [27–29], or by adding lumped components [30, 31], which would be bulky or relatively complex to fabricate. Furthermore, in recent years, the realization of broadband metamaterial absorbers based on resistive films has also been introduced. The indium tin oxide (ITO) resistive film is used widely as an excellent alternative with the advantage of commercial availability, low cost, mechanical flexibility, optically transparent, and conductive properties. The metamaterial absorber based ITO simultaneously achieved strong microwave absorption and shielding performance over an ultra-wide microwave region with thinner thicknesses, lighter weights, optically transparent, and wider bandwidths. In 2014, Govind Dayal and S. Anantha Ramakrishna proposed a broadband infrared metamaterial absorber using ITO as ground plane [32]. In 2017, Harsh Sheokand et al introduced a
broadband metamaterial absorber based on ITO in the frequency of 6.06–14.66 GHz [33]. In 2020, Rui Liu et al designed a broadband metamaterial absorber based on composite structure in the frequency of 8–30.3 GHz [34]. Besides, several other similar broadband absorbers were proposed based on ITO resistive film [35–41]. However, there have been few reports of ultra-broadband flexible polarization-insensitive microwave metamaterial absorber, which can be used for energy conversion, electromagnetic shielding.

In this paper, we propose a flexible ultra-broadband metamaterial absorber based on multilayer ITO resistive patterns films. By nesting and stacking multilayer ITO patterns, a broadband absorption of more than 90% from 19.68 to 94.7 GHz with a relative absorption bandwidth of 131% can be obtained. The proposed absorber is polarization-insensitive with high absorption of above 90% over a wide incidence angle of 60° in any polarization direction. The effects of parameters such as dielectric thickness and surface resistance of ITO pattern films are discussed. We finally achieved optimized parameters corresponding to high-performance absorption by adjusting the number of layers of the arranged ITO pattern and the integration of multiple resonances. In comparison to previous reports, our structure has superior ultra-broadband, wide incident angle, and polarization-insensitive performance.

2. Structure and methods

The schematic of the proposed absorber is depicted in figure 1. The metamaterial absorber consists of two-patterned ITO resistive film layers printed on polyethylene terephthalate (PET) film layers arranged in the top and middle layers separated by an air layer, a continuous ITO plate at the bottom backed by PET, and a polydimethylsiloxane (PDMS) film used as the dielectric between the middle layer and bottom. The arrayed ITO patterned resonators are used to generate high ohmic loss. The PET serves as ITO substrate, with a permittivity of 3.2 and a loss tangent 0.003. Because of its low Young’s modulus, PDMS film is selected in many flexible dielectric materials with a permittivity of 2.35 and a loss tangent of 0.06. The bottom continuous ITO plate blocks electromagnetic wave transmission and allows for better absorption characteristics.

The geometry parameters of the unit cell are as follows: $P = 12$ mm, $r_1 = 1.5$ mm, $l_1 = 0.6$ mm, $r_2 = 2$ mm, $l_2 = 2$ mm, $r_3 = 2.8$ mm, $l_3 = 1.5$ mm, $d_{\text{PET}} = 0.175$ mm, $d_1 = 0.4$ mm, $d_2 = 0.6$ mm. The absorber’s total thickness is 1.525 mm (0.1λL, where λL is the maximum working wavelength). Figure 1 (a) demonstrates each layer of the structure from perspective view. The different ITO patterns are carefully arranged along with the horizontal and vertical directions, as seen in the top view of the absorber, and each ITO pattern is labeled with detailed parameters in figure 1 (b). From the bottom layer to the top, the sheet resistance $R_{01}$ of the flat ITO ground is 50 Ω/sq. The resistance $R_{02}$ and $R_{03}$ of the ITO patterned film are 40 and 50 Ω/sq, respectively.

Figure 1. Schematics of a unit cell for the proposed metamaterial absorber. (a) The perspective view, (b) the top view.
CST Microwave Studio is utilized to simulate and optimize the absorption performance of the proposed absorber. In the simulations, the unit cell boundary conditions are applied along with the x and y directions, while the open (add space) boundary condition is utilized in the z direction, with the electric field aligned along the y axis direction in transverse electric mode (TE mode), as shown in figure 1(b).

The absorption $A$ is calculated by using equation (1):

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

where $R(\Omega)$ and $T(\Omega)$ represent the reflectivity and transmittivity, respectively. $S_{11}$ denotes the reflection coefficient, and $S_{21}$ denotes the transmission coefficient, both of which can be acquired through simulation.

The simulated absorption, reflection, and transmission spectrum of the structure are displayed, as illustrated in figure 2. The transmission $S_{21}$ of the proposed absorber is nearly zero because the ITO ground functions as a reflecting plane. Therefore, the above formula can be shortened to $A(\omega) = 1 - R(\omega)$. The proposed absorber can achieve more than 90% broadband absorption from 19.68 to 94.7 GHz. The bandwidth reaches 75 GHz, and the corresponding relative bandwidth can be as high as 131%. The three peak frequencies are depicted with the maximum absorption close to 1, shown in figure 2.

3. Results and discussion

The absorption is derived from the reflection coefficient $S_{11}$, which depends on the impedance matching between the proposed structure and the free space. Therefore, we use impedance-matching theory to describe the absorption mechanism of the absorber. The relative impedance can be extracted from the S-parameters inversion method as follows [42]:

$$ Z = \pm \frac{(1 + S_{11}(\omega))^2 - S_{21}^2(\omega)}{(1 - S_{11}(\omega))^2 - S_{21}^2(\omega)} $$

As illustrated in figure 3(a), the red and blue lines represent the real and imaginary parts of the relative impedance, respectively. The real part of the relative impedance is approximately equal to 1 while the imaginary part approaches 0. The corresponding operating frequency band spans 19.68 to 94.7 GHz, which indicates that the impedance of the proposed absorber matches the impedance of free space in this region. The effective
permittivity $\varepsilon$ and effective permeability $\mu$ are displayed in figure 3(b). The real parts of both effective permittivity and permeability are negative, which is consistent with the nature of metamaterial. The real (imaginary) part of the effective permittivity is close to the real (imaginary) part of effective permeability when the relative impedance is approximately equal to 1. The equation (3) shows that the absorption reaches a maximum of 1.

$$A(\omega) = 1 - R(\omega) = 1 - \frac{Z_{in} - Z_0}{Z_{in} + Z_0}^2$$

For better visualization of the intrinsic absorption principle, the distributions of electric field and surface currents have been obtained by numerical simulations in detail at different absorption peaks. Figure 4 depicts the electric field distribution on the top and middle layer of the ITO pattern at three peak frequencies of 25.3, 55.5, and 85.3 GHz.

As shown in figures 4(a), (b), at the peak frequency of 25.5 GHz, the electric field is mainly concentrated on the tip of the top layer of ITO pattern film, while the electric field distribution on the middle ITO pattern is smaller. And at the peak frequency of 55.5 GHz, the electric field on the middle ITO layer is more intense, illustrated in figures 4(c), (d). At 85.3 GHz, the electric field is spreading on the top and middle ITO structure, especially at the edges of the structures, which means that they both play a crucial role in the absorption at this frequency, depicted in figures 4(e), (f).

Similarly, the surface current distributions on different ITO layers at three peak frequencies are also arranged in figure 5. As shown in figures 5(a)–(c), the surface current is concentrated on the top layer at 25.3 GHz. In addition, the direction of the surface current flow in the ground layer is downward opposite to the direction of...
flow in the top layer, thus forming a loop that excites the additional magnetic dipole resonance and leads to strong absorption [38]. Figures 5(d), (e) illustrate that the surface currents are more intense in the middle layer of the ITO structure at 55.5 GHz. Therefore, the power loss in the middle layer is the reason for the strong absorption. Figures 5(g)–(i) depict that the surface currents are distributed in the top and middle layers, both of which cause power loss and thus have an important effect on the absorption of 85.3 GHz. The direction of the surface currents in the top layer is opposite to that bottom layer, resulting in strong absorption at 85.3 GHz. The surface current distribution is consistent with the electric field distribution. Therefore, broadband absorption can be achieved by different coupling of ITO resistive pattern layers.

The effect of structural parameters on the absorption performance is also demonstrated, including the dielectric thickness and the ITO resistance. The simulated absorption of dielectrics with different thicknesses is characterized in figure 6. When the thickness $d_1$ of PDMS decreases from 0.8 to 0.4 mm, the absorption bandwidth exceeding 90% is broadened. The first absorption peak is enhanced, due to the reduction of the thickness leading to the enhancement of magnetic resonance coupling between the top and bottom layer, accompanied by a blue shift in resonance frequency. The second absorption peak is mainly dependent on the middle resistive film, which is less affected by the change of the thickness $d_1$. The third absorption peak is related to the structure of both two layers, and the decrease of the distance leads to enhancement of the coupling with the bottom as well as a blue shift of frequency, as depicted in figure 6(a).

In the same way, we analyze the effect of the air layer thickness $d_2$ on the absorption performance. As the $d_2$ decreases, it can be found that the decrease of air layer thickness will also lead to the decrease of the distance between the top layer and the bottom layer. However, the air layer can easily match the input impedance, achieving good absorption. Thus the decrease of air layer thickness has no obvious effect on the first absorption peak. The second absorption peak has a certain frequency shift, and the third absorption peak is enhanced with a blue shift of the resonance frequency, thus expanding the absorption, as demonstrated in figure 6(b). The thicknesses $d_1$ and $d_2$ are optimized to obtain high absorption performance.

In addition to the parameters of the thickness, another influential factor to be considered is the surface resistance of the ITO film. Figure 7(a) shows that increasing the surface resistance $R_{01}$ of ITO ground leads to absorption increasing, especially a great effect on absorption at the first and third peak, both of which are associated with the magnetic resonance formed by the ITO ground and top structure, while the second peak remains essentially constant. When the sheet resistance $R_{02}$ of the middle ITO layer varies from 10 to 50 $\Omega$/sq, the absorption at the second peak improves significantly, further indicating that the absorption at this frequency is mainly attributed to the middle ITO resistive film structure, as demonstrated in figure 7(b). The increase in the
surface resistance $R_{03}$ of the top ITO pattern layer could enhance its energy loss and change the coupling strength with the bottom layer, which in turn affects the absorption depicted in figure 7(c). According to the above explanation, surface resistance has a significant influence on absorption performance.

The effect of structural parameters on the absorption performance can be analyzed by the equivalent circuit model, which is derived from the interaction between the structure and the incident wave, further explaining the working mechanism, as illustrated in figure 8(a).

To simplify the equivalent circuit model, we consider that the intermediate dielectric layer is lossless and that the ITO resonant structure is the primary reason for the energy dissipation. The transmission line $Z_\text{0} = 377 \Omega$ is the characteristic impedance of free space. The bottom continuous ITO ground plane is equivalent to a short circuit. The surface of the resistance thin film $Z_{RLC}$ with ITO pattern resonant structure can be regarded as the series of cascade inductor $L$, capacitor $C$ and resistor $R$, which can be represented as:

$$Z_{RLC} = R + j \left( \frac{\omega L}{\omega C} - \frac{1}{\omega C} \right), i = 1, 2, 3$$

The intermediate different dielectric layers can be regarded as characteristic impedances:

$$Z_p = \frac{Z_0}{\sqrt{\varepsilon_p}}, Z_1 = \frac{Z_0}{\sqrt{\varepsilon_1}}, Z_2 = \frac{Z_0}{\sqrt{\varepsilon_2}}$$

where $\varepsilon_p$, $\varepsilon_1$, and $\varepsilon_2$ are the relative permittivity of PET, PDMS, and air, respectively.

The input impedance of each part could be derived according to transmission line theory, just as follows:

$$Z_a = jZ_0 / \sqrt{\varepsilon_p} \tan(\beta d)$$

$$Z_b = Z_1 \frac{Z_a \cos(\beta_1 d_1) + jZ_1 \sin(\beta_1 d_1)}{jZ_a \sin(\beta_1 d_1) + Z_1 \cos(\beta_1 d_1)}$$

**Figure 8.** (a) Equivalent circuit model of the proposed absorber. (b) The comparison results between the ADS calculation of the equivalent circuit model and the CST simulation.
Where the $\beta$, $\beta_1$, $\beta_2$ are the propagation constant of incident electromagnetic waves of PET, PDMS, and air, with the corresponding thicknesses of $d$, $d_1$, and $d_2$, respectively.

According to the above equations of the equivalent circuit model, the input impedance $Z_{in}$ has a certain relationship to the thickness of the dielectric and the resistance of ITO. In order to verify the reliability of the analysis, we provide the comparison results between the calculation of the equivalent circuit model and the CST simulation, as illustrated in figure 8(b). The optimized equivalent circuit parameters are obtained as follows: $L_1 = 1.376 \, \text{nH}$, $R_1 = 267.68 \, \Omega$, $C_1 = 0.7836 \, \text{pF}$, $L_2 = 0.3588 \, \text{nH}$, $R_2 = 240.92 \, \Omega$, $C_2 = 0.6214 \, \text{pF}$, $L_3 = 0.342 \, \text{nH}$, $R_3 = 290.85 \, \Omega$, $C_3 = 0.708 \, \text{pF}$. The simulation results are in accordance with Advanced Design System (ADS) calculations.

Subsequently, the effects of incident angle and polarization angle on the absorption performance are analyzed. Figure 9(a) demonstrates that broadband absorption is still maintained as the incident angle increases to $60^\circ$ in the transverse electric mode (TE mode) owing to the the symmetric structure and the coupled resonances with multi-layer structure [43]. As the angle continues to increase, the low-frequency absorption is significantly weakened. Similarly, the absorber still maintains broadband absorption in transverse magnetic mode (TM mode), where the incidence angle increases up to $60^\circ$. With the angle further increasing, the high-frequency absorption decreases and the bandwidth shrinks significantly, as represented in figures 9(b), (c) demonstrates the polarization-insensitive characteristics, when the polarization angle varies from 0 to 90, i.e., from TE to TM mode, the absorption remains the same, which is attributed to the symmetry of the structure. Thus, the designed structure is ultra-broadband absorption with wide-angle incidence and polarization-independent characteristics.

Furthermore, the combination of nesting and stacking is adopted to broaden the absorption band. The absorption characteristics of various components are presented separately for comparison. The absorption bandwidth can be broadened from structure I to structure II by adding resonance units of different sizes on the same layer, as shown in figures 10(a), (b). Moreover, the different shapes of ITO resonators are stacked on multiple dielectric layers, from structure II to III, leading to a broadband absorption expansion, as presented in figures 10(b), (c). The design not only enhances absorption resulting from the coupling between different layers but also adds extra absorption peaks, thus effectively expanding the bandwidth at the same time.

Compared to several other similar broadband absorbers to quantify performance, the designed absorber achieves more than 90% broadband absorption from 19.68 to 94.7 GHz via a combination of nesting and stacking, with the benefits of thin thickness, flexibility, and polarization insensitivity as shown in table 1.

Figure 11(a) depicts the measurement of reflection of metamaterial absorber samples using the bow frame method to verify the proposed absorber’s broad absorption. The measurement system consists primarily of a standard fully automatic bow frame, an 18–40 GHz horn antenna, a spread spectrum module and antenna with
frequencies of 50–75 GHz and 75–110 GHz, a standard test board, a low loss cable assembly, and a vector network analyzer. A low-loss cable connects a pair of standard wideband horn antennas, one transmitting and the other receiving, to the vector network analyzer. By switching the antennas in different frequency bands, the

Figure 10. The absorption characteristics of different structures of (a) I, (b) II; (c) III.

Figure 11. (a) The experimental setup for reflection measurement. Inset: different type of antenna. The fabricated ITO pattern of (b) top layer; (c) middle layer. (d) The fabricated sample. (e) The bendable sample. (f) The measured and simulated reflection spectra and absorption for normal incidence. (g) The measured absorption spectra for oblique incidence.

Table 1. Performance comparison of wideband absorbers, where $\lambda_L$ is the maximum working wavelength.

| Absorber       | Thickness (mm)/$\lambda_L$ | More than 90% absorption bandwidth (GHz) | Fractional Bandwidth (%) | Pattern layer | Polarization insensitivity | flexible |
|----------------|-----------------------------|-----------------------------------------|--------------------------|---------------|---------------------------|----------|
| Reference [34] | 3.35 / 0.09$\lambda_L$     | 8–30.3                                  | 116                      | 1             | Yes                       | Yes      |
| Reference [36] | 4.62 / 0.12$\lambda_L$     | 8–18                                    | 76.92                    | 1             | Yes                       | Yes      |
| Reference [38] | 3.85 / 0.1$\lambda_L$      | 8.3–17.4                                | 70.8                     | 1             | Yes                       | Yes      |
| Reference [39] | 3.1 / 0.07$\lambda_L$      | 6.8–18.0                                | 90                       | 1             | No                        | No       |
| Reference [40] | 3.62 / 0.075$\lambda_L$    | 6.2–19.3                                | 102.7                    | 1             | Yes                       | No       |
| Reference [41] | 5 / 0.13$\lambda_L$        | 8–20                                    | 85.7                     | 1             | Yes                       | No       |
| This work      | 1.52 / 0.1$\lambda_L$      | 19.68–94.7                              | 131.17                   | 2             | Yes                       | Yes      |
system can measure sample reflection in different microwave bands. Figures 11(b), (c) show the top and middle layers of the prepared ITO pattern array. The prepared sample with bendability and optically transparent is demonstrated in figures 11(d), (e). Figure 11(f) depicts the simulated and measured reflection spectra for normal incidence, as well as the calculated simulated and measured absorption spectra. The measured absorption is slightly lower than the simulated results, as presented in which may be caused by manufacturing defects of the sample and deviations from the ideal value of the resistive film. Figure 11(g) displays the measured absorption spectra for oblique incidence, demonstrating the wide-angle characteristics. Nevertheless, the experiment results are following the simulation results.

4. Conclusions

In conclusion, we have proposed an ultra-band flexible metamaterial absorber composed of nesting and stacking ITO resistance film. The proposed absorber can achieve more than 90% absorption range of 19.68 to 94.7 GHz, covering multiple microwave bands. The absorber is polarization-insensitive and exhibits high absorption over a wide incidence angle of 60° in both TE and TM polarization. The physics mechanism of absorption is discussed by analyzing the impedance-matching theory, the surface current distribution, and the electric field distribution. The equivalent circuit of the proposed absorber is derived from the interaction between the incident microwaves and its unit cells and thus provides a guide to obtaining broadband absorption. The experimental measurements obtained with the bow-frame method agree with the simulated spectra. This work provides a general way to achieve a wide-band flexible metamaterial absorber which opens up new possibilities in fields such as electromagnetic shielding and smart materials.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Landy N I, Sajuuyibge S, Mock J J, Smith D R and Padilla W J 2008 Phys. Rev. Lett. 100 207402
[2] Hu X, Xu G, Wen L, Wang H, Zhao Y, Zhang Y, Cuming D and Chen Q 2016 Laser Photonics Rev. 10 962–9
[3] Zhong H T, Yang X X, Tan C and Yu K 2016 Appl. Phys. Lett. 109 253904
[4] Sekhi S Z, Shokooh-Saremi M and Miresmailli MM 2020 J. Nanophotonics. 14 046014
[5] Alam A, Islam S S, Islam M H, Almutairi A F and Islam M T 2020 Materials 13 2560
[6] Wang H, Sivan V P, Mitchell A, Rosengarten G, Phelan P and Wang L P 2015 Sol. Energy. Mat. Sol. C. 137 235–42
[7] Dien M, Koschyn T and Soukoulis C M 2009 Phys. Rev. B. 79 0353101
[8] Li D, Huang H, Xia H, Zeng J, Li H and Xie D 2018 Results Phys. 11 659–64
[9] Zhi Cheng Y, Wang Y, Nie Y, Zhou Gong R, Xiong X and Wang X 2012 J. Appl. Phys. 111 044902
[10] Wang B X, Wang L L, Wang G Z, Huang W Q and Zhai X 2014 Phys Scripta. 89 113501
[11] Mason J A, Allen G, Podolskiy V A and Wasserman D 2012 IEEE Photonic Tech. L. 24 31–3
[12] Lee S and Kim S 2013 IEEE Photonics J. 5 4880610
[13] Mahmoud S, Islam S S, Mat K, Chowdhury M E H, Rmili H and Islam M T 2020 Results Phys. 18 103259
[14] Hu C G, Zhao Z Y, Chen X N and Luo X G 2009 Opt. Express 17 11039–44
[15] Su Z X, Yin J B and Zhao X P 2015 Opt. Express. 23 1679–90
[16] Feng S J, Zhao Y and Luo Y L 2020 Results Phys. 18 103272
[17] Jia W, Bai J, Roberts K, Le K Q and Zhou D 2020 Microw Opt Techn Lett. 62 2649–55
[18] Park J W et al 2013 Opt. Express 21 9691–702
[19] Bhattacharyya S, Ghosh S and Vaibhav Srivastava K 2013 J. Appl. Phys. 114 094514
[20] Zhang M, Cao M S, Shu J C, Cao W Q, Li L and Yuan J 2021 Mater. Sci. Eng. R: Reports. 145 100627
[21] He P, Cao M S, Cao W Q and Yuan J 2021 Nanomicro Lett. 13 115
Balci O et al 2018 Science Advances. 4 eaao1749
Cao M S, Wang X X, Zhang M, Cao W Q, Fang X Y and Yuan J 2020 Adv. Mater. 32 1907156
Cao M S et al 2019 Adv. Funct. Mater. 29 1807398
Lu Y, Li J, Zhang S, Sun J and Yao J Q 2018 Appl. Opt. 57 6269–75
Ma W, Wen Y and Yu X 2013 Opt. Express 21 30724–30
Deng H, Stan L, Czaplewski D A, Gao J and Yang X 2017 Opt. Express 25 28295–304
He X, Yan S, Ma Q, Zhang Q, Jia P and Wu F 2015 Opt. Commun. 340 44–9
Zhang H F, Liu J X, Yang J, Zhang H and Li H M 2018 Results Phys. 11 1064–74
Deng F, Cui Y X, Ge X C, Jin Y and He S L 2012 Appl. Phys. Lett. 100 103506
Luo M, Shen S, Zhou L, Wu S, Zhou Y and Chen L 2017 Opt. Express. 25 16715–24
Dayal G and Ramakrishna S A 2014 Opt. Express 22 15104–10
Sheokhand H, Ghosh S, Singh G, Saikia M, Srivastava K V, Ramkumar J and Anantha R S 2017 J. Appl. Phys. 122 105105
Liu R, Zhang B, Duan J, Dong L, Yu J and Zhang Z 2020 Mater. Res. Express. 7 045803
Deng G, Lv K, Sun H, Yang J, Yin Z, Chi B and Li X X 2021 J. Phys. D: Appl. Phys. 54 165301
Zhou Q, Yin X, Ye F, Mo R, Tang Z, Fan X, Cheng L F and Zhang L T 2019 Appl. Phys. A-Mater. 125 131
Li L, Xi R, Liu H and Lv Z 2018 Appl. Phys. Express 11 052001
Zhang C, Cheng Q, Yang J, Zhao J and Cui T 2017 Appl. Phys. Lett. 110 143511
Zhang X K, Jiang S L, Kong L Q, Wang Q, Hu H B, Zhang X and Zhao X 2020 Iet. Microw. Antenna. P. 14 1580–6
Zheng Y, Chen K, Jiang T, Zhao J and Feng Y 2019 J. Phys. D: Appl. Phys. 52 335101
Xu J, Fan Y, Su X, Guo J, Zhu J, Fu Q and Zhang F L 2021 Opt. Mater. 113 110852
Smith D R, Vier D C, Koschny T and Soukoulis C M 2005 Phys. Rev. E. 71 036617
Wang B X, Wang L, Wang G, Huang W, Li X and Zhai X 2014 IEEE Photonic. Tech. L. 26 111–4