

Design and analysis of multi-band zero-index superstructures based on double-sided metal microstructures

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The zero refractive index metamaterial discussed is a new type of material with a special electromagnetic property of equivalent refractive index of zero, which can provide a material platform for the application of terahertz, and is of great significance in the fields of wireless communication, imaging and security. A two-sided symmetric metal-cut line zero-index metamaterial structure is designed. The equivalent refractive index is zero near the resonant frequency of 0.74THz when terahertz wave is vertically incident on the metamaterial surface, and the zero refractive index characteristic of metamaterial is realized. We further designed a zero-index terahertz metamaterial structure with a cross metal block as the basic unit. When the terahertz wave is vertically incident on the surface of the metamaterial, it is observed that the electromagnetic characteristic of zero refractive index is obtained at the resonant frequency of 0.55THz when the electric field is TE polarization. In the case of TM polarization, zero refractive index electromagnetic properties are also obtained at the resonant frequency of 0.55THz. The metamaterial is polarization-insensitive near the resonant frequency of 0.55THz under optimized geometric parameters. Moreover, polarization-insensitive zero-index metamaterials have a wider application prospect in the terahertz field.

(Received March 2, 2026; accepted August 3, 2026)

Keywords: Metamaterials, Terahertz, Zero-refractive index

1. Introduction

In nature, most known materials have a fixed refractive index. At present, the media involved in electromagnetic wave propagation is still relatively lacking, and the discovery and further research of metamaterials are expected to overcome this problem [1-10]. In the process of studying electromagnetic wave propagation, it is very important to study the refractive index of the transmission medium [11-18]. At the same time, being able to control the propagation of light according to the actual demand is also one of the important goals of optical research. The zero refractive index characteristic of metamaterials has important practical significance, so the zero refractive index metamaterials have been paid more and more attention [19-21].

Zero-index metamaterials have been used in new antennas, stealth technology, quantum computing and other fields because of their special electromagnetic properties. It can be seen that the equivalent refractive index is the product of the relative permittivity and the relative permeability and then the arithmetic square root can be obtained. To achieve the zero refractive index characteristic of metamaterial, we can obtain a metamaterial with zero refractive index by achieving zero dielectric constant or permeability. The research on zero-

index metamaterials includes: theoretical model and realization method of zero-index metamaterials. The study of zero permittivity or zero permeability and the electric field distribution of metamaterial structures are emphasized. The development of zero-index metamaterials is rapid, and the application fields of this material are more and more extensive, and people have achieved good results in this direction. Researchers can adjust or design the geometric structure parameters of metamaterials according to their own reasonable and innovative ways and ideas, which can achieve the electromagnetic characteristics of zero refractive index of metamaterials.

In 2010, Yang et al. analyzed the zero refractive index characteristics of metamaterials based on periodic arrays of metal open ring elements at local waveguide resonant frequencies [22]. In 2013, Moitra et al. designed an all-dielectric zero-index metamaterial and confirmed the existence of zero-index metamaterial [23]. In 2014, Qing et al. designed a fishnet-shaped zero-refractive index terahertz metamaterial, studied and controlled the electromagnetic characteristics of the designed metamaterial, such as dielectric constant and permeability, and realized a zero-refractive index metamaterial [24]. In 2016, Kaipurath et al. investigated the photoinduction of metal-layer to dielectric layer transitions for metamaterials with zero dielectric constant. They designed a layered

metamaterial structure of metals and media to achieve a zero-refractive index metamaterial in the near infrared band [25]. In 2019, Kinsey et al. discussed and studied the latest progress and application fields of near-zero refractive index photonic materials [26]. In the same year, Jiang et al. designed a double-layer metal ring structure to study its characteristics of high refractive index and near zero refractive index [27]. Ma et al. proposed a near-zero refractive index metamaterial with low loss and wide bandwidth in the frequency range of 10.50GHz-11.54GHz, which can be applied to broadband electromagnetic wave switching [28]. In 2020, Takehito et al. designed a non-reflective zero-index metasurface in the terahertz band [29]. In 2021, Horsley et al. studied and discussed the conditions of near-zero refractive index metamaterials and found a method to calculate the refractive index [30].

Zero-index metamaterials are artificial structures whose electromagnetic properties can be studied and analyzed through appropriate unit structural design to achieve special phenomena that cannot be observed in materials in nature. At present, the research and application of zero-refractive index metamaterials have made great progress, and their applications in antenna field, electromagnetic wave control, stealth technology and so on are of great significance. At the same time, zero-refractive index metamaterials have important application value in many fields such as electromagnetic radiation, communication, advanced manufacturing and so on. In the field of antenna application [31], according to Snell's law, when the refractive index of the transmission medium is zero, the incident beam enters the free space through the medium. Since the refractive index of the free space is greater than zero, the exit angle of the beam exiting into the free space will be zero, so as to achieve the purpose of controlling the exit angle and enhance the directionality of the antenna. In addition, the function of zero-index metamaterial beam polymerization polymerizes the radiated electromagnetic energy, which improves the gain characteristics of the antenna. In the field of electromagnetic wave control, people hope to achieve accurate manipulation of light, and design a metamaterial structure that can control the propagation path of light. In the field of invisibility technology, taking invisibility cloak as an example [31-33], it is made of micro and nano materials, which have special refractive index and can achieve abnormal propagation of transmitted light. Based on this phenomenon, zero-index metamaterials with stealth effect are designed.

We have designed a metamaterial structure with zero refractive index of double-sided symmetric metal cutting lines. When the terahertz wave is vertically incident on the surface of metamaterial, the equivalent refractive index is zero at the resonant frequency of 0.74THz, which realizes the zero refractive index characteristic of metamaterial. At a resonant frequency of 0.55THz, an electromagnetic characteristic of zero refractive index is obtained. The metamaterial is polarization-insensitive at a resonant frequency of 0.55THz with optimized geometric parameters. Moreover, polarization-insensitive zero-index metamaterials have a wider application prospect in the

terahertz field. Terahertz (THz) wave has shown wide application potential in many fields due to its unique frequency range (0.1-10THz) [34-45]. In the field of communication, terahertz waves can be used for ultra-high-speed wireless communication, providing bandwidth far beyond existing technologies; in the field of imaging and security inspection, its penetrability is strong and harmless to biological tissues, which is suitable for nondestructive testing, medical imaging and airport security inspection. In materials science, terahertz spectroscopy can be used to analyze the structure and chemical composition of substances. In addition, terahertz technology has important applications in astronomical observation, environmental monitoring, and national defense security [46-59].

2. Principle of S-parameter inversion algorithm for metamaterial equivalent refractive index

According to the equivalent medium theory, we know that when the characteristic size of the designed metamaterial is much smaller than the resonant wavelength, the S-parameter obtained after the incident wave passes through the surface of the metamaterial can be used for inversion, so as to obtain the equivalent refractive index n and impedance z of the metamaterial, and then the equivalent permeability μ and equivalent dielectric constant ε of the metamaterial can be calculated by the formula of $\mu = nz$ and $\varepsilon = n/z$. We can get the S-parameter by numerical calculation. The equivalent refractive index, impedance, equivalent permeability and equivalent dielectric constant can be obtained by inversion calculation of reflection coefficient and transmission coefficient.

According to the relation between S-matrix and transmission coefficient T , the equivalent permittivity and equivalent permeability of metamaterial can be obtained by inversion of S parameter. For a homogeneous structure, the transfer matrix of T can be expressed as [32,33]

$$T = \begin{pmatrix} \cos(nkd) & -\frac{z}{k} \sin(nkd) \\ \frac{k}{z} \sin(nkd) & \cos(nkd) \end{pmatrix} \quad (1)$$

where, n is the effective refractive index, z is the plane wave impedance, d is the effective thickness of the material, and k is the wave number. And n and z are related to permittivity ε and permeability μ . Based on the inversion process of Eq. (1), we can calculate the equivalent refractive index, equivalent impedance, equivalent dielectric constant and equivalent permeability of the metamaterial. They are expressed as [32,33]

$$n_{eff} = \frac{\text{Im}[\ln(e^{jnk_0(d+2h)})] + 2m\pi - j\text{Re}[\ln(e^{jnk_0(d+2h)})]}{k_0(d+2h)} \quad (2)$$

$$e^{jnk_0(d+2h)} = \frac{S_{21}}{1 - S_{11} \frac{Z_r - 1}{Z_r + 1}} \quad (3)$$

$$Z_r = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (4)$$

where k_0 is the wave number in free space, m is an integer, and Z_r is the value of the relative wave impedance divided by the free space wave impedance.

The S-parameter inversion algorithm used to extract equivalent electromagnetic parameters of metamaterials has multiple limiting conditions. This algorithm is built on the homogeneous medium equivalence assumption, which is only valid when the unit cell size is much smaller than the operating wavelength, the array period is uniform, and the incident wave is a standard plane wave. The homogeneous medium hypothesis fails for asymmetric unit cells, abruptly changed periods or unit sizes close to the working wavelength. It can only accurately handle low-loss and weakly dispersive systems, while high-loss and strongly dispersive metallic terahertz metamaterials lead to multiple solutions, parameter jumps and unphysical equivalent refractive indices. Complete measurable transmission and reflection S-parameters are required; sample thickness, substrate loss, substrate interference, edge diffraction and measurement noise will distort S curves and distort inversion results. Furthermore, it cannot distinguish surface modes from bulk equivalent responses and suffers from ambiguity of multiple solutions for equivalent permittivity and permeability. It produces obvious inversion errors for strongly electromagnetically coupled resonant or multi-layer composite meta-structures, and cannot be directly applied to inhomogeneous composite sensing systems covered with adsorbed biomolecular layers.

3. Zero-index metamaterial design

Fig. 1 shows the structure diagram of metamaterial unit with double-sided symmetry of metal cutting lines. We used the optimization method of parameter sweep to optimally obtain the geometric parameters of the cell structure. The unit structure consists of two metal layers and one dielectric layer. The material of the dielectric layer is a cycloolefin polymer, and its thickness is $d = 50 \mu\text{m}$. The metal layer is composed of three metal wires symmetrical on two sides. The material of the metal layer is copper, and its thickness is $h = 0.5 \mu\text{m}$. The distance between the three metal wires of the metal layer is $a = 120 \mu\text{m}$. The other parameters of the unit structure are $s = 361 \mu\text{m}$, $w = 70 \mu\text{m}$, $g = 106 \mu\text{m}$, $l = 202 \mu\text{m}$, and $l_1 = 202 \mu\text{m}$. The conductivity of the metal layer is $\sigma = 5.8 \times 10^7 \text{S/m}$ [2], and the refractive index of dielectric layer material is $n = 1.53 + j0.0012$. This polymer has low loss properties in the terahertz band. It can be seen that the structure appears symmetric along both the X-axis (horizontal direction) and the Y-axis (vertical direction). TE polarization is defined as the

direction of the incident electric field vector perpendicular to the direction of the long edge of the metal strip. TM polarization is defined as the incident electric field vector direction is parallel to the metal strip direction.

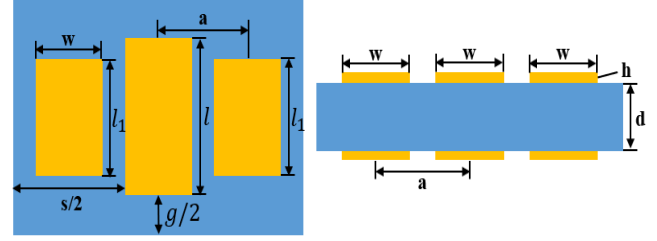


Fig. 1. Schematic diagram of metamaterial unit structure with double-sided symmetrical metal cutting lines, (a) represents the top view of the unit structure; (b) represents a side view of the unit structure (colour online)

To realize polarization-insensitive terahertz metamaterial unit cells, the core principle lies in equipping structures with in-plane geometric isotropy [60-70]. Topologies with central rotational symmetry such as regular polygons, circles, crosses, four-split resonators and snowflake-shaped quad-fold rotationally symmetric layouts are widely adopted, which excite identical resonant modes and localized electric field distributions for linearly polarized electromagnetic waves at any polarization angle along x and y axes. Orthogonally symmetric unit array arrangements are adopted to avoid polarization-dependent loss induced by grating diffraction, and multi-layer stacked symmetric configurations can be used to eliminate interlayer polarization coupling. During simulation, transmission and reflection spectra under polarization angles ranging from 0° to 90° are scanned to verify polarization-independent performance. Parameters including gap width and metal linewidth are optimized to ensure negligible shifts in resonant frequency, sensitivity and Q factor under all polarization states, so as to obtain sensing units with uniform responses to arbitrary linearly and circularly polarized terahertz waves.

The unit structure of the above metamaterials is optimized by scanning parameters using the finite integration method to adjust the structural parameters [71-75]. These unit structures can also be designed using artificial intelligence methods. Intelligent design of terahertz metamaterial unit cells centers on the combined workflow of forward spectral prediction networks and inverse generative networks. First, full-wave simulation tools such as CST and COMSOL are adopted to generate batch datasets consisting of paired geometric parameters and terahertz transmission/absorption spectra of classic unit structures including split-ring resonators, EIT architectures and BIC cavities. Forward neural networks like ResNet and Transformer are trained to instantly output terahertz resonant spectra by inputting structural dimensions, which replaces massive repetitive electromagnetic simulations. Then inverse neural networks are constructed or coupled with genetic algorithms and

multi-objective particle swarm optimization algorithms. Constrained by performance metrics such as sensing sensitivity, quality factor and resonant frequency, the system automatically reversely deduces optimal geometric dimensions including unit period, gap width and metal linewidth by feeding target ideal spectra. Generative adversarial networks and diffusion models can autonomously generate novel asymmetric meta-units. Finally, candidate parameters output by artificial intelligence are imported into simulation software to verify local electric field intensity and refractive index sensing response. Active learning is applied to iteratively expand datasets and improve model generalization, drastically cutting the research cycle of traditional trial-and-error unit cell design.

By changing the geometric parameters of the metamaterial structure, the relative permittivity and relative permeability of the metamaterial can be affected, so the terahertz metamaterial with zero refractive index can be designed according to this characteristic. We mainly discuss the effect of length l_1 and width w on the zero refractive index properties of the designed metamaterial structure. With other parameters unchanged, the optimized geometrical structure can be obtained by changing the length l_1 and width w of the metal wire respectively, and the real and imaginary parts of the optimized metamaterial's relative permittivity, relative permeability, impedance and equivalent refractive index can be numerically simulated. During the computational simulation of the element structure, we used periodic boundary conditions to model the element structure.

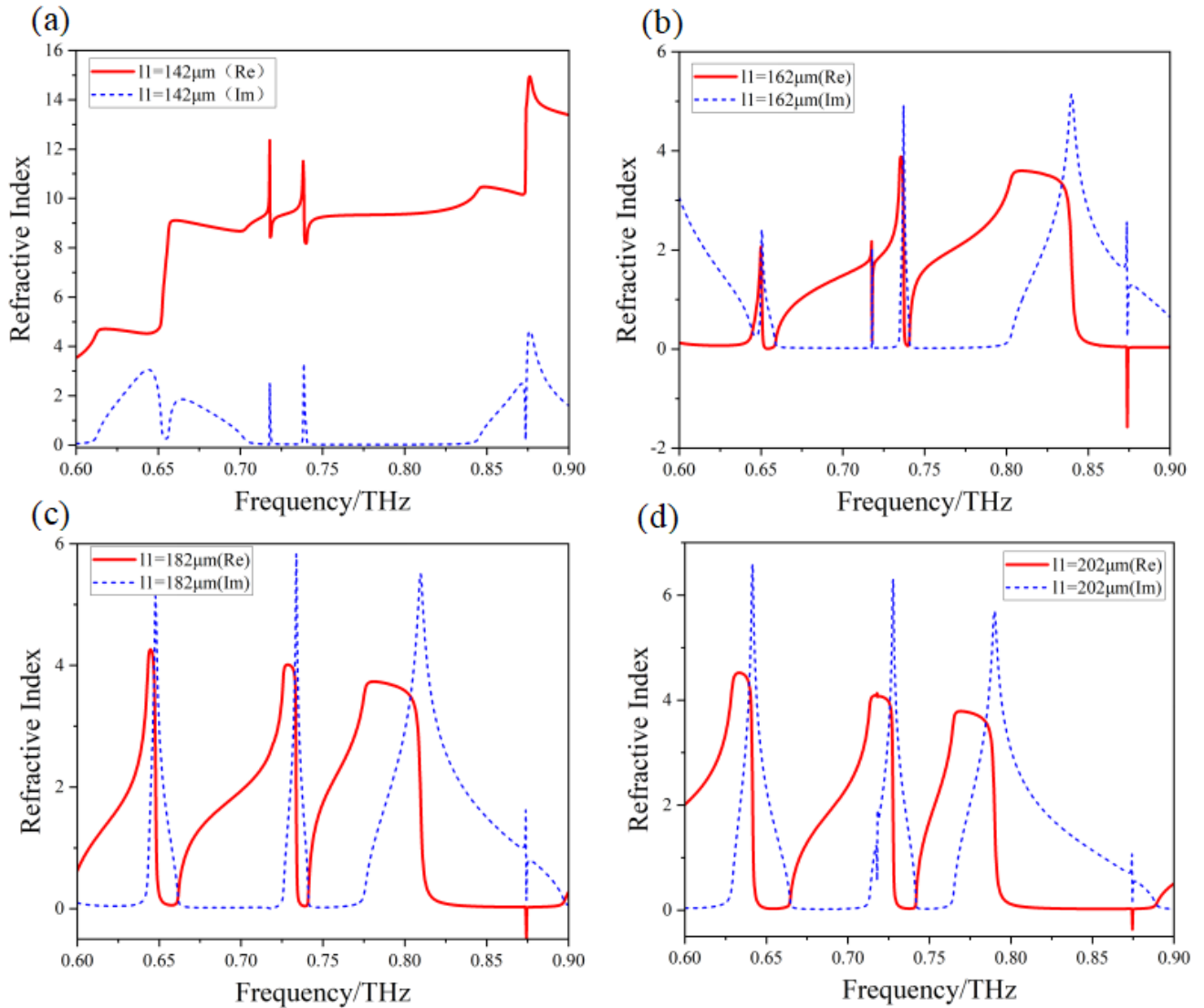


Fig. 2. Variation of equivalent refractive index with length l_1 in metamaterial structures with double-sided symmetry of metal cut lines. (a) is the equivalent refractive index diagram when $l_1 = 142 \mu\text{m}$; (b) is the equivalent refractive index diagram when $l_1 = 162 \mu\text{m}$; (c) is the equivalent refractive index diagram when $l_1 = 182 \mu\text{m}$; (d) is the equivalent refractive index plot at $l_1 = 202 \mu\text{m}$ (colour online)

For two-sided symmetric metal-cut wire zero-index metamaterial structures, we first investigate their zero-index properties in the frequency range of 0.60–0.90 THz. Based on the S-parameter inversion algorithm, we analyze the effect of metal length l_1 on the equivalent parameters of the designed metamaterial structure. We used a finite integration approach to compute the S-parameters and near-field distribution properties of the element structure. In Fig. 2(a), we know that there is no equivalent refractive index of zero when $l_1=142\text{ }\mu\text{m}$ of this structure. In the process of gradually increasing l_1 , we can see that in Fig. 2(b), there are frequency points with an equivalent refractive index of zero, but it can also be observed that there are some miscellaneous peaks in the equivalent refractive index when $l_1=162\text{ }\mu\text{m}$, which obviously does not achieve the optimal result in this case. In Fig. 2(c) and Fig. 2(d), that is, when l_1 is $182\text{ }\mu\text{m}$ and $202\text{ }\mu\text{m}$ respectively, we can find that the zero refractive index characteristics of the designed metamaterial structure are obtained at the frequencies of 0.66 THz and 0.74 THz.

Next, the zero refractive index properties in the frequency range 0.60 THz–0.90 THz are investigated. With $l_1=182\text{ }\mu\text{m}$ and other parameters unchanged, we discuss the effect of changing the width w of the metal layer on the refractive index of the designed metamaterial structure. As shown in Fig. 3, we calculated the refractive index change with the width w from small to large. The width is set to $50\text{ }\mu\text{m}$, $70\text{ }\mu\text{m}$, $90\text{ }\mu\text{m}$, and $110\text{ }\mu\text{m}$, respectively. In Fig. 3(a) and Fig. 3(b), it is found that the designed metamaterial structure has zero refractive index at the frequencies of 0.66 THz and 0.74 THz. Carefully observing the two data curves in Fig. 3(a) and Fig. 3(b), it can be known that the metamaterial structure has a superior zero refractive index property when $w=70\text{ }\mu\text{m}$. When w is further increased, as shown in Fig. 3(c) and Fig. 3(d), it can be found that the equivalent refractive index of the designed metamaterial structure does not exist a zero value point.

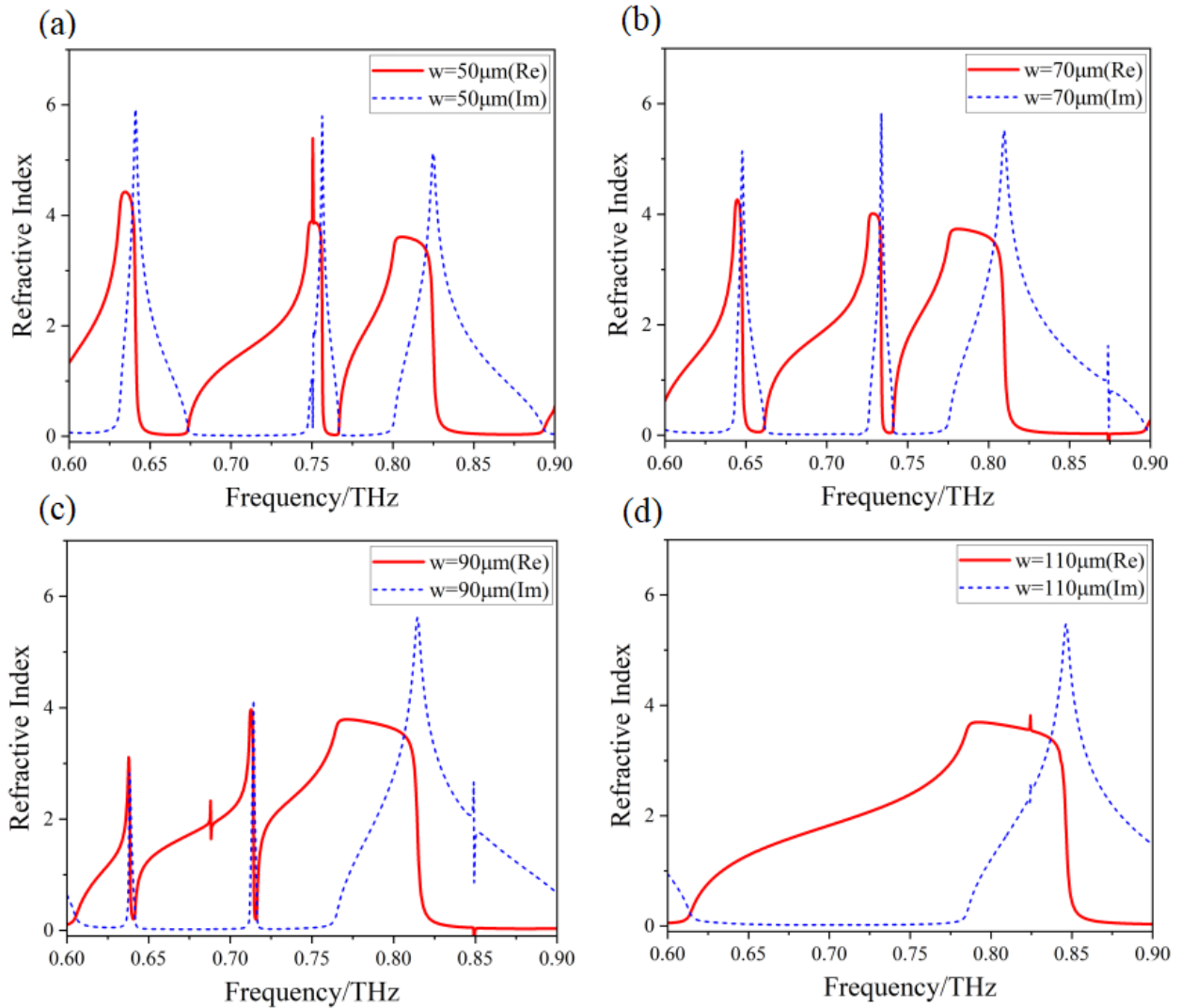


Fig. 3. The variation of the equivalent refractive index with width w for a metamaterial structure with double-sided symmetry. (a) is the equivalent refractive index when $w=50\text{ }\mu\text{m}$; (b) is the equivalent refractive index when $w=70\text{ }\mu\text{m}$; (c) is the equivalent refractive index when $w=90\text{ }\mu\text{m}$; (d) is the equivalent refractive index for $w=110\text{ }\mu\text{m}$ (colour online)

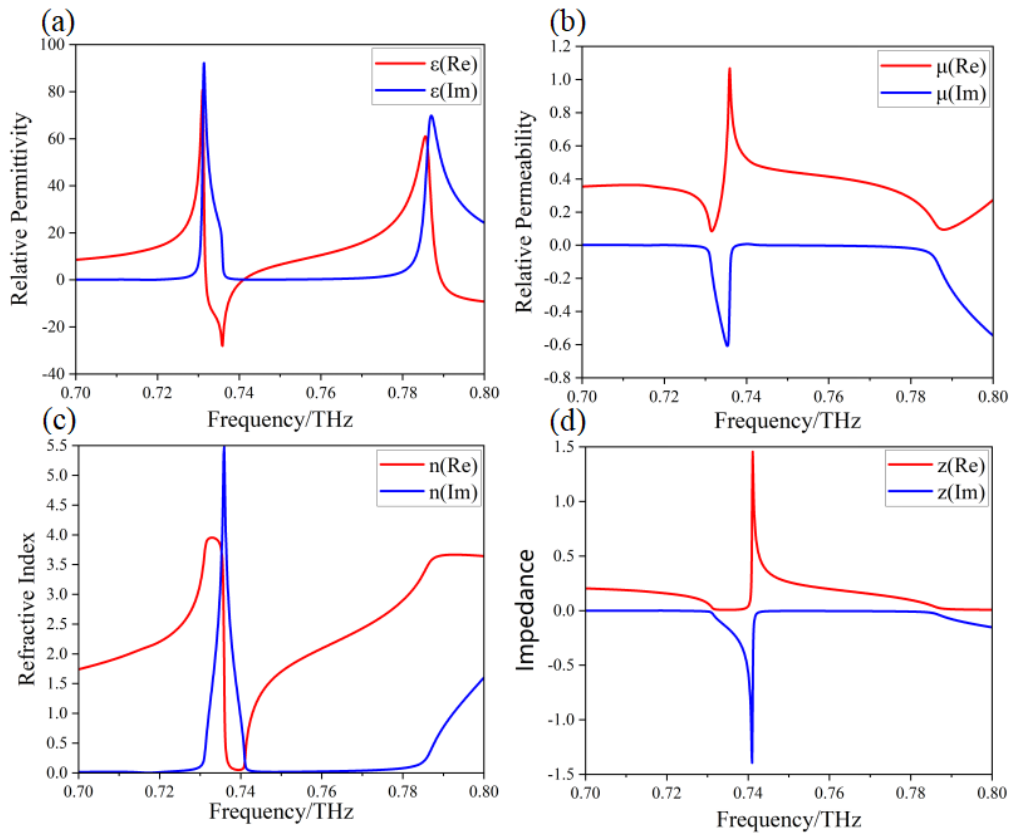


Fig. 4. Electromagnetic parameters of TE polarization incident, (a) relative dielectric constant of the structure; (b) the relative permeability of the structure; (c) the equivalent refractive index of the structure; (d) impedance of the structure; (The red line indicates the real part of the parameter, and the blue line indicates the imaginary part of the parameter) (colour online)

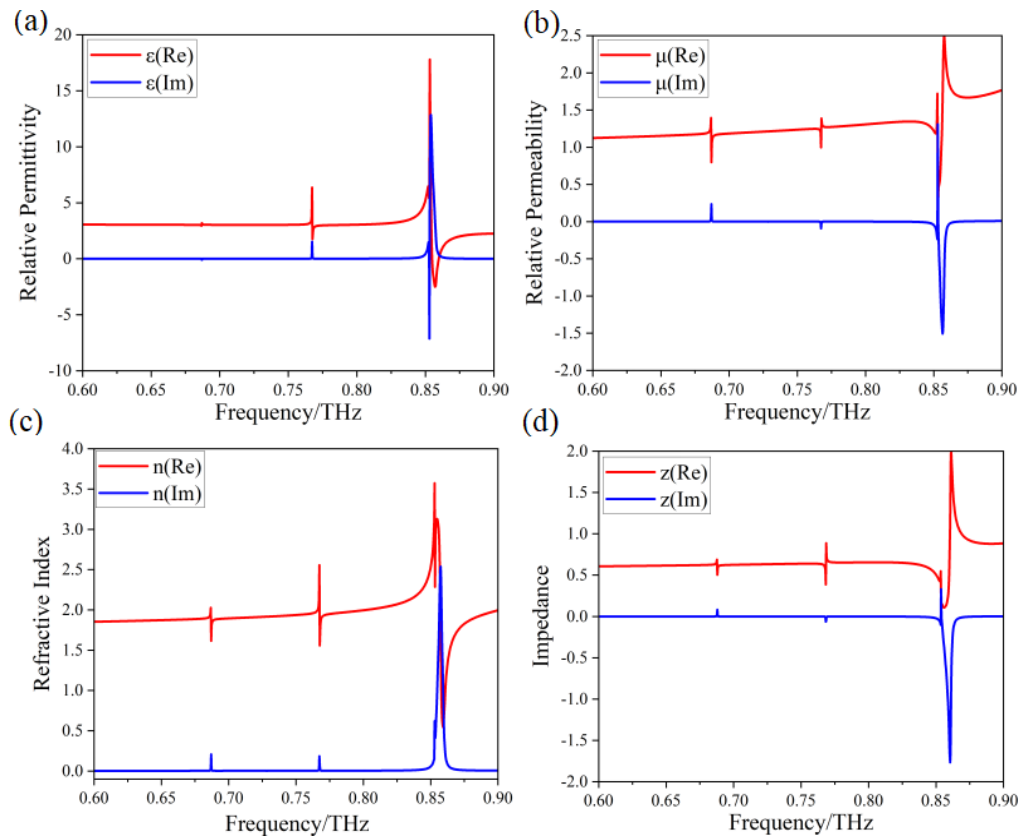


Fig. 5. The electromagnetic parameters of the TM polarization incidence, (a) the relative dielectric constant of the structure; (b) the relative permeability of the structure; (c) the equivalent refractive index of the structure; (d) impedance of the structure; (The red line indicates the real part of the parameter, and the blue line indicates the imaginary part of the parameter) (colour online)

In Fig. 4, we show the electromagnetic parameters of a double-sided symmetrical metal-cut line metamaterial structure with TE polarization incidence. As shown in Fig. 4 (c), the absolute value of the real part of the equivalent refractive index of the metamaterial structure at the frequency of 0.741 THz is zero. In addition, as can be seen in Fig. 4 (a), 4 (b) and 4 (d), the equivalent relative dielectric constant is zero at this frequency, the equivalent permeability is positive, and the real part of the equivalent impedance is zero.

In Fig. 5, we show the electromagnetic parameters of a two-sided symmetric metal-cut line metamaterial structure at TM polarization incidence. As shown in Fig. 5(c), the equivalent refractive index is not zero. In the 0.60-0.85 THz band, the equivalent refractive index is about 2. However, when we compared the metamaterial structure at different polarizations of TE and TM, we found that the equivalent refractive index of the metamaterial structure at different polarizations was quite different. To solve this problem, we then tried to study a polarization-insensitive terahertz zero-refractive index metamaterial structure.

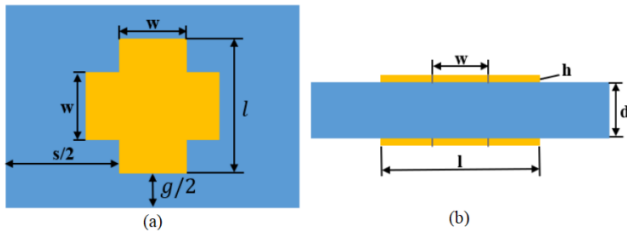


Fig. 6. Cross metal block unit structure diagram, (a) represents the top view of the unit structure; (b) represents a side view of the unit structure (colour online)

We further design a polarization insensitive terahertz zero-index metamaterial structure based on a cross metal block element structure. The unit structure of the metamaterial is composed of a metal layer and a medium layer. The metal layer is composed of a cross structure as shown in Fig. 6. The material of the medium layer is a cycloolefin polymer and its thickness is $d = 50 \mu\text{m}$. The material of the metal layer is copper, and its thickness is $h = 0.5 \mu\text{m}$. The optimization design of other parameters of the unit structure is as follows: $s = 361 \mu\text{m}$, $w = 120 \mu\text{m}$, $g = 106 \mu\text{m}$, and $l = 202 \mu\text{m}$. In addition, the conductivity of the metal layer is $\sigma = 5.8 \times 10^7 \text{ S/m}$. The refractive index of dielectric layer material is $n = 1.53 + j0.0012$. For the designed double-sided symmetric metal-cut line metamaterial structure, we studied its equivalent refractive index variation when TE polarization incident in the frequency range of 0.50 THz-0.60 THz, as shown in Fig. 7. First, we studied the influence of the change of metal layer length l on the zero refractive index characteristic of the designed metamaterial structure. It can be seen from Fig. 7 that when the length l increases from $162 \mu\text{m}$ to $202 \mu\text{m}$, it can be clearly seen that when $l = 202 \mu\text{m}$, the designed metamaterial structure meets the zero refractive index characteristic at 0.55 THz.

For the designed double-sided symmetric metal-cutting wire metamaterial structure, we studied its equivalent refractive index in the frequency range of 0.50 THz-0.60 THz, as shown in Fig. 8. We studied the effect of the change of the length l of the metal layer on the zero refractive index characteristic of the designed metamaterial structure during TM polarization. It can be seen from Fig. 8 that when the length l increases from $162 \mu\text{m}$ to $202 \mu\text{m}$, the frequency meeting the zero refractive index characteristic has an obvious redshift, and it can be found that with the increase of the length l , the designed metamaterial structure has a better zero refractive index effect.

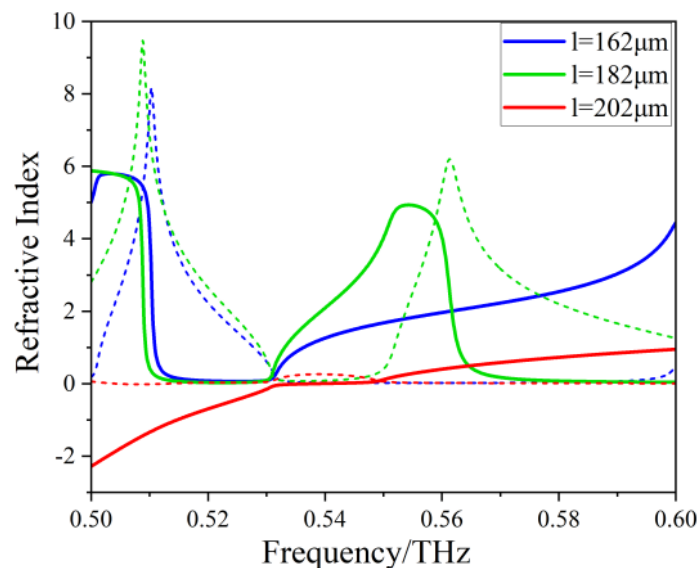


Fig. 7. Variation of equivalent refractive index with length l when TE polarization incident (colour online)

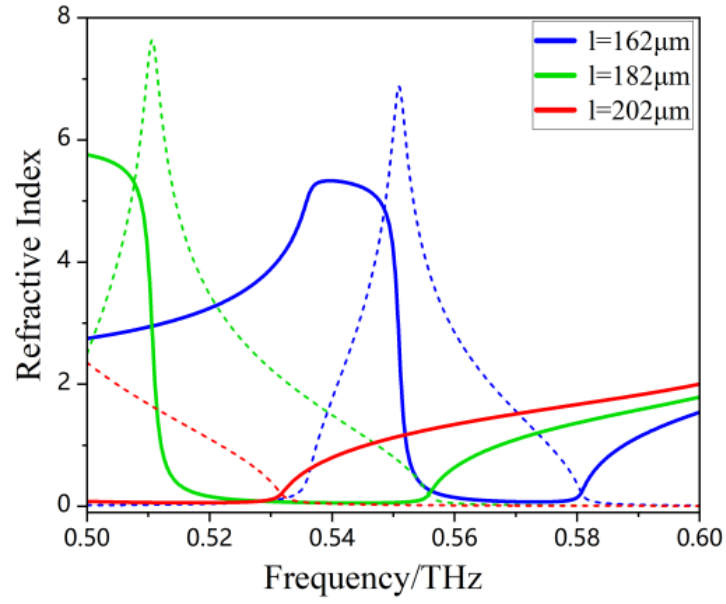


Fig. 8. Variation of equivalent refractive index with length l when TM polarization incident (colour online)

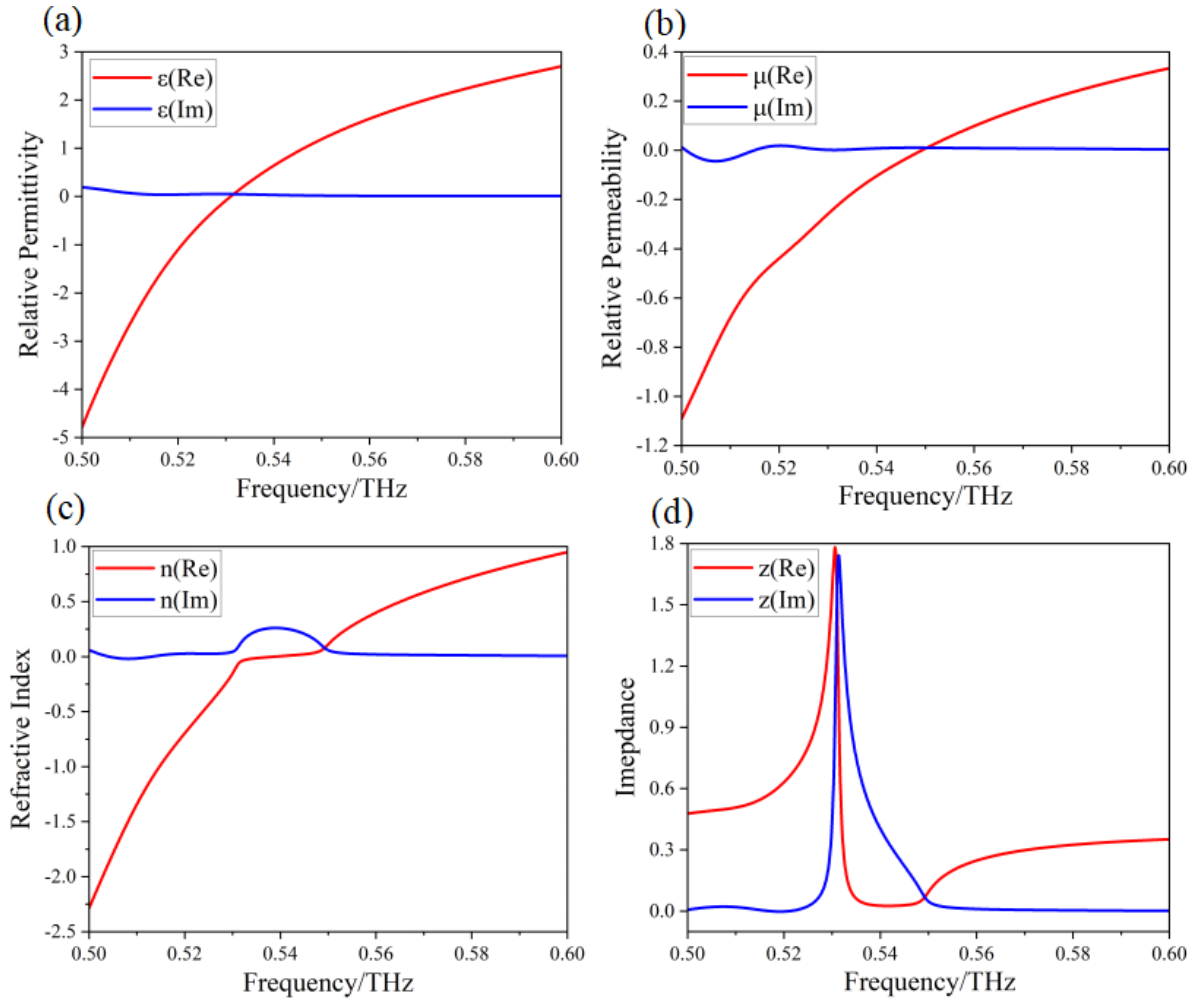


Fig. 9. Electromagnetic parameters of TE polarization extracted from metamaterial structure of cross metal block, (a) equivalent dielectric constant curve; (b) equivalent permeability curve; (c) equivalent refractive index curve; (d) impedance curve; (The red line indicates the real part of the parameter, and the blue line indicates the imaginary part of the parameter) (colour online)

In Fig. 9, we show the electromagnetic parameters of a terahertz wave zero-index metamaterial based on a cross metal block during TE polarization. As shown in Fig. 9 (c), the absolute value of the real part of the equivalent refractive index of the metamaterial structure at the frequency of 0.55 THz is zero. In addition, as shown in Fig. 9 (a), Fig. 9 (b) and Fig. 9 (d), the equivalent relative permeability is zero and the equivalent relative permittivity is positive at the frequency of 0.55 THz, but the effective relative permittivity is zero near 0.53 THz, and the real part of the equivalent impedance is zero.

The method that we use the electromagnetic resonance characteristic obtained by the metamaterial structure unit to achieve zero refractive index is to obtain zero dielectric constant and zero permeability. Using this method, we need to obtain the electric and magnetic resonance characteristics of the designed structure first,

and then we can obtain zero dielectric constant and zero permeability in other regions far from the resonant region. Due to the different strength of the electric resonance and magnetic resonance of the designed structures, the zero crossing frequency of the equivalent permittivity and equivalent permeability in other regions away from the resonant region is also different.

It is precisely because of the different zero crossing frequencies of the equivalent permittivity and the equivalent permeability that the dislocation phenomenon occurs, leading to a frequency range (0.531 THz-0.550 THz) in front of the frequency of 0.55 THz that the equivalent permittivity and the equivalent permeability have different signs, thus causing the real part of the equivalent refractive index to approach 0 in this frequency band. The phenomenon that the value of the imaginary part of the equivalent refractive index increases.

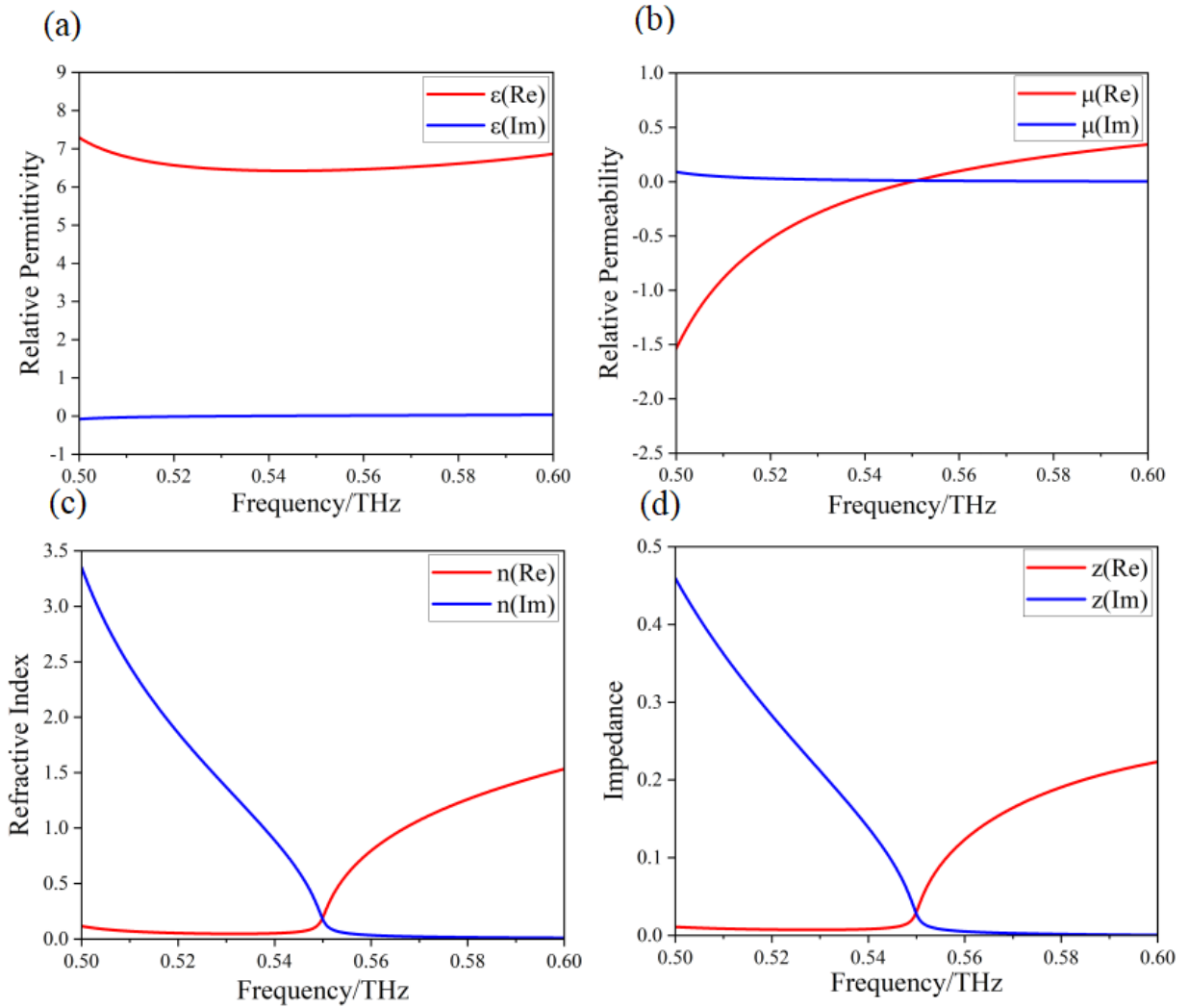


Fig. 10. Electromagnetic parameters of TM polarization extracted from metamaterial structure of cross metal block, (a) equivalent dielectric constant curve; (b) equivalent permeability curve; (c) equivalent refractive index curve; (d) Impedance curve; (The red line indicates the real part of the parameter, and the blue line indicates the imaginary part of the parameter) (colour online)

In Fig. 10, we show the electromagnetic parameters of a terahertz wave zero-index metamaterial based on a cross metal block when the wave is incident with the TM polarization. As shown in Fig. 10(c), the metamaterial structure also has an absolute value of zero for the real part of the equivalent refractive index at the frequency of 0.55 THz. By comparison, as shown in Fig. 9, we can see that the designed metamaterial structure obtains the equivalent refractive index of zero at 0.55 THz, both in TE polarization and in TM polarization. Therefore, it is verified that the metamaterial structure is polarization-insensitive to its zero refractive index property.

In addition, as shown in Fig. 10 (a), 10 (b) and 10 (d), at 0.55 THz frequency, the equivalent relative permeability is zero, the equivalent relative dielectric constant is positive and relatively large, and the real part of the equivalent impedance is zero. Except that the equivalent refractive index is zero at the frequency of 0.55 THz, the variation of the equivalent refractive index in a frequency range near it is relatively large, because the equivalent relative dielectric constant is relatively large.

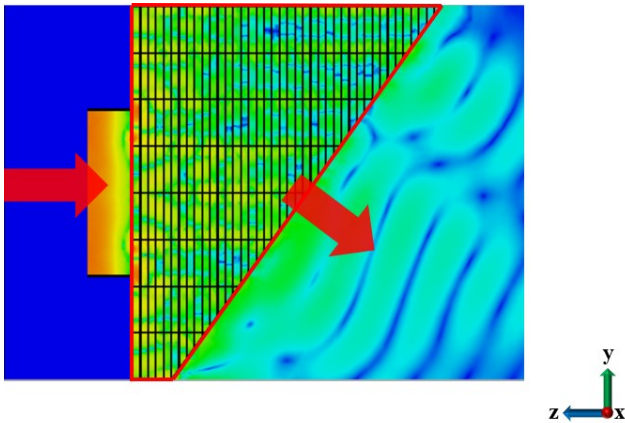


Fig. 11. The electric field diagram obtained after the metamaterial structure of cross metal blocks is arranged (colour online)

In Fig. 11, we show the electric field distribution obtained after stacking the cross metal block structure. The shape of the metamaterial after stacking is a trapezoidal structure, and the overall shape is displayed as the structure inside the red line frame. Electromagnetic waves enter the stacked metamaterial through a notch on the left and exit from the long hypotenuse of the trapezoidal structure. At the same time, in order to prevent the electromagnetic wave from spilling around, we wrapped a layer of PEC material on the three right angle sides of the trapezoidal structure, so as not to affect the electric field distribution effect. We can see that when the electromagnetic wave is emitted from the long hypotenuse, its electric field direction is perpendicular to the hypotenuse, indicating that the wave vector of the electromagnetic wave is propagated along the hypotenuse. According to Snell's law, it can be verified that the zero-refractive index property of metamaterials can be observed by their electric field distribution.

Metal metamaterial structures in the terahertz band are usually fabricated by micro-nano fabrication techniques. First, a metal film (such as gold, silver or aluminum) is deposited on a substrate material (such as silicon, quartz or polymer), and then the designed micro-nano structural patterns such as open rings, cruciforms or periodic arrays are etched on the metal film using precision machining techniques such as lithography, electron beam etching or laser direct writing. The size of these structures is typically in the range of tens to hundreds of microns to match the wavelength of THz waves. Finally, the integrity and performance of the structure are ensured by cleaning and surface treatment, so as to realize the regulation and enhancement of THz waves.

With the development of artificial intelligence technology, this technology has also been applied in the design process of metamaterials. The artificial intelligence-based design of terahertz metamaterial structures consists of four procedures: dataset construction, forward predictive modeling, inverse optimization generation and simulation verification iteration. Firstly, full-wave electromagnetic simulation tools such as CST and COMSOL are used to batch-generate S-parameters and resonant spectra corresponding to diverse unit sizes and materials, establishing labeled datasets linking geometric parameters to spectral responses [76-84]. Next, forward surrogate models including convolutional neural networks and Transformers are trained to rapidly predict the terahertz response of arbitrary structures, eliminating massive repetitive simulations. Afterwards, generative adversarial networks, diffusion models or multi-objective optimizers such as particle swarm optimization and genetic algorithms are adopted for inverse design constrained by target resonant frequency, refractive index sensitivity and quality factor. The system can automatically output optimal geometric dimensions of meta-units and even novel topological configurations hardly conceived via manual design. Ultimately, candidate structures provided by AI are imported into electromagnetic simulations to verify localized electric field distribution and sensing performance. Active learning is employed to supplement hard sample data for continuous model accuracy improvement, which drastically shortens the traditional trial-and-error development cycle and satisfies the development requirements of various terahertz devices including biomolecular sensors and absorbers.

4. Conclusions

A polarization-insensitive zero-refractive index terahertz metamaterial is designed, and a zero-refractive index metamaterial structure based on a cross metal block is proposed. Similarly, the vertical incidence of terahertz waves in the designed metamaterial structure is studied, and the simulation results are analyzed by S-parameter inversion method. The effect on zero index polarization

insensitivity of metamaterials is analyzed by changing the parameter structure of the metal layer.

Disclosures

The authors declare no conflicts of interest.

Data availability

No data were generated or analyzed in the presented research.

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