Shorted Micro-Waveguide Array for High Optical Transparency and Superior Electromagnetic Shielding in Ultra-Wideband Frequency Spectrum

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While functional materials with both light transmitting and electromagnetic shielding are highly desirable and have made rapid advancements, only very few of them meet the stringent electromagnetic interference (EMI) shielding criteria for optoelectronic systems. Achieving high optical transparency and superior EMI shielding in a broad frequency spectrum is a remaining challenge in both academic and industrial areas. Herein, a design strategy of shorted micro-waveguides (SMWs) array to decouple the light transmission and EMI shielding is proposed and experimentally demonstrated. The array of SMWs, consisting of cutoff metallic micro-waveguides and shorting indium tin oxide (ITO) continuous conductive film, exhibits high optical transmittance of 90.4% and superior EMI shielding effectiveness of 60.8 dB on average over ultra-wide frequency spectrum (0.2–1.3 GHz & 1.7–18 GHz). Compared to previously reported works, an improvement of 17 dB in average shielding effectiveness is achieved under the same level of light transmission, and the shielding frequency spectrum is significantly expanded. The working principle is explained in depth and factors influencing the performance are investigated for design optimization. These outstanding properties enable the transparent shielding material based on SMWs to excel in future applications of EMI shielding for optoelectronic systems.

1. Introduction

The electromagnetic (EM) environment becomes increasingly complex as wireless technology advances, and severe electromagnetic interference (EMI) risks have arisen to electronic devices as well as human health due to the intensification of electromagnetic radiation and the expansion of the electromagnetic spectrum.[1–5] Especially for most sensitive components in optoelectronic systems, the wideband high-intensity radiated fields (HIRF) can be coupled into electronic equipment through optical windows due to their lack of electromagnetic reinforcement, resulting in detrimental influences on the stability and security of entire systems.[6,7] It is becoming increasingly difficult to ignore the corresponding EMI problem for optoelectronic systems.

Electromagnetic shielding is an effective approach to isolate strong electromagnetic radiation from sensitive devices.[8] Electromagnetic shielding materials applied in optoelectronic systems are required to provide not only high EMI shielding effectiveness (SE) and ultra-wideband shielding characteristics against intense and broadband electromagnetic radiation, but also high optical transparency to ensure sufficient optical transmission for clear visual observation or high-quality imaging. In consideration of the functional requirements for attenuating microwaves and transmitting visible light, the essence of transparent electromagnetic shielding is to provide a frequency-selective filtering function capable of forming a passband for optical signals and a stopband for microwaves. The practice has proved that the requirements for electromagnetic shielding and optical transmittance can be met simultaneously through the rational structure design of various transparent conductive materials.[9–13]

To date, considerable studies have attempted to develop transparent EMI shielding materials based on metals,[9,10] polymers,[9,14] nanomaterials,[15–16] and composites,[9,11,17] which can be categorized into continuous conductive thin films and apertured type conductive materials based on their conductive structures.

However, decoupling the restrictive performance factors of optical transmittance and EMI shielding effectiveness is proving difficult. For continuous (or quasi-continuous) conductive thin films, a higher electrical conductivity improves the EMI SE, while reducing the optical transparency. For example, continuous ITO and ultrathin metal films (typically, thickness
< 20 nm) can achieve transparency and be employed as transparent electromagnetic shields,\[10,18–20\] and the light transmission of ultrathin metal films depends heavily on their thickness due to light absorption or reflection. For example, Wang et al. reported an ultrathin (8 nm) and continuous doped silver film with a high visible transmittance of 96.5%, while the EMI SE is \(\approx 26 \text{ dB} \).\[19\] It follows that achieving superior EMI shielding performance at such thickness is difficult since efficient shielding requires much thicker material than the skin depth. Despite being promising electromagnetic shielding materials, conductive polymers suffer from exponential light transmission decay as their thickness increases, and the overall performance is also limited (EMI SE of 14.72 dB and transmittance of 79.8% for GNR-Fe₃O₄/PEDOT:PSS/PVA composite film).\[9,14\] Due to the limitation of intrinsic conductivity, developing next-generation polymer-based EMI shielding materials relies on rational structural design and new preparation methods.\[21\] The emerging nanomaterials graphene, presents high transparency of 97.8%, while its shielding performance is low (only 2.27 dB in the X band) due to its high sheet resistance,\[11,15,22–24\] and its combination with other shielding materials are proven practical.\[13,23,25\]

With analysis of the above continuous conductive films, the greater the thickness relative to the wavelength, the less EM waves are transmitted. On the other hand, achieving high EMI shielding performance requires lower sheet resistance, i.e., higher carrier concentration or mobility, which enhances the interaction of photons with electrons in the material and decreases light transmission under high photon absorption. Consequently, a trade-off has to be made between the optical transmittance and electrical conductivity in developing high-performance transparent conductive materials, and their applications in EMI shielding are constrained by the inability to concurrently combine high light transmission and high shielding performance.

The restriction between light transmittance and EMI shielding also exists in apertured-type conductive materials such as metallic nanowires (NWs) and carbon nanotubes (CNTs).\[26–31\] For instance, the Ag NW-based film can achieve a shielding effectiveness of 20.7 dB while maintaining a light transmittance of 92%.\[26\] Although the shielding performance can be further enhanced by increasing the loading amount of Ag NWs, its light transmission will inevitably decrease. Likewise, CNT-based films also require an adjustment to the content of the material to balance light transmission and electrical conductivity. Another aperture type of transparent EMI film is metallic mesh, ranging from simple square grids to complex cracked meshes, as well as grids with stacked structures.\[12–36\] However, conventional mesh-based transparent EMI shielding materials still suffer from the inability of integrating outstanding EMI SE with high optical transmittance. The light transmittance of metallic mesh is linearly related to the aperture area percentages of the whole film. An increase in aperture area results in a higher sheet resistance, which consequently translates into a reduction in shielding effectiveness. Besides, as the operating frequency increases, the shielding effectiveness of the metal grid shielding material diminishes dramatically as a result of filtering characteristics of meshes,\[37,38\] which remains a barrier to the realization of efficient electromagnetic shielding over a broad frequency band.

The difficulty in designing optoelectronic windows with high transmittance and efficient EMI SE across a broad frequency range lies in: i) separating the correlation parameters between optical transmission and EMI shielding via a decoupling design and overcoming the mutual constraints between transmission and shielding efficiency, and ii) constructing a rational structure to reduce the dependence of shielding efficiency and wavelength in order to obtain a high shielding efficiency in the ultra-wide frequency spectrum. So far, to the best of our knowledge, obtaining electromagnetic functional materials integrated with high visible light transmittance with superior EMI shielding properties in an ultra-wide frequency spectrum remains a major challenge.

In this work, we propose a design strategy for shorted micro-waveguides (SMWs) array aimed at decoupling the optical transmittance and EMI SE for electromagnetic shielding windows. In the designed transparent EMI shielding materials, the shielding layer of microstructures has unique features of microscale aperture, thin pore-wall, and large aspect ratio, which enables superior EMI SE while maintaining high optical transmittance. SMWs array obtained by assembling apertured micro-waveguides shielding layer and continuous transparent conductive film further enhances shielding effectiveness and extends the effective shielding frequency spectrum. Through the optimal decoupling design, the mutual suppression indicators of light transmittance and EMI SE, as well as wideband shielding features have been incorporated into the shorted micro-waveguides array, exhibiting a promising design strategy on electromagnetic shielding for optical channels in imaging and detecting applications.

2. Results and Discussion

2.1. Design Strategies of SMWs array

According to the waveguide theory, cutoff waveguides have characteristics that can be described by their cutoff frequencies. Electromagnetic waves with a frequency higher than the cut-off frequency can propagate in the waveguide, otherwise, the waves are cut-off and attenuated.\[39\] As previously stated, the essence of transparent electromagnetic shielding is to provide a passband for light and a stopband for microwaves, which can be realized by waveguides with a micron-sized aperture. The micro-waveguide for transparent EMI shielding can be designed with a cutoff frequency much higher than that of the waves to be shielded while lower than optical frequencies, allowing a substantial attenuation of the EM wave as it passes through it while ensuring the effective transmission of light.

Here, microstructures with large apertures and thin pore-wall are designed in the first place. Considering the obscuration rate and stray light uniformity,\[40\] the efficient geometry of the honeycomb was adopted. Each unit of microstructures in this case can be considered as a micro-scale cutoff waveguide owing to the large aspect ratio feature (Figure 1a). The cutoff effect of micro-waveguides can be understood as follows:\[41\] EM waves propagate in a zigzag pattern along the waveguide and tend to be perpendicular to the wall of the waveguide under waveguide boundary conditions. The lower the frequency, the
larger the angle of reflection. When the frequency reaches the cut-off frequency, EM waves bounce up and down the wall and then stop propagating forward with all energy dissipating in the conductor.

It is feasible to establish a cutoff filtering property for microwaves and efficiently shield against microwaves while providing a passband for light waves and keeping a high optical transmission rate by engineering the structural parameters of the metallic micro-waveguides array. According to the theoretical analysis, micro-waveguides with an aperture side length of 80 µm and pore-wall thickness of 4.3 µm have a cutoff frequency of up to 0.924 THz, which is much higher than those of the microwaves to be shielded. (The estimated calculation of the cut-off frequency can be seen in Note S1 of Supporting Information for details). As illustrated in Figure 1b, effective electromagnetic shielding can be achieved in the cut-off region where the operating frequency band is far from the cut-off frequency. The inset of Figure 1b shows the simulation result of field distribution in the hexagonal micro-waveguide, revealing the effective attenuation of EM waves along the short-circuited waveguides. Simultaneously, the large aperture and thin pore wall provide a high obscuration ratio and ensures a high rate of light transmission. Consequently, the cutoff effect of the micro-waveguide array yields enhanced electromagnetic attenuation without sacrificing optical transmission, allowing for a decoupling of light transmission and EMI shielding property.

As shown in Figure 1b, EM attenuation of the micro-waveguides decreases in higher frequency bands, revealing the difficulty in getting high SE over broadband frequencies. To address this problem, a continuous transparent conductive layer (ITO) is incorporated into the metallic apertured microstructures to constitute a shorted micro-waveguides array, in which the ITO film serves as the short-circuited terminal (Figure 1a). For a perfect shorted waveguide in electromagnetic theory, its short-circuited load allows all electromagnetic waves to be reflected back. ITO films with low sheet resistance can provide efficient EMI shielding as well as high transparency, which are suitable as proper short-circuited terminals for SMWs array. The selection of short-circuited film for SMWs array can be found in Note S2 of Supporting Information. The shorted micro-waveguide configuration can generate effective EM reflection and attenuation, and compensates for the shielding attenuation of the separate micro-waveguide in higher frequencies through multiple reflection loss excited between the two conducting layers. The synergistic attenuating effect of the shorted micro-waveguides is expected to produce enhanced and balanced shielding over an ultra-wide frequency band. Additionally, to further reduce the optical loss of the shorted micro-waveguide array, anti-reflective (AR) layers for visible light could be introduced, which serve the purpose of regulating the optical transmission characteristics of the combined shielding structure and increasing the light transmission rate without lowering the shielding efficiency.

Motivated by the design concept above, as in Figure 1c, the highly transparent EMI shielding material based on SMWs array consists primarily of a combined shielding structure of hexagonal metallic micro-waveguides and ITO continuous film, separated by thin quartz glass, and the ITO glass is covered with AR coatings. Figure 1d schematically illustrates the
electromagnetic shielding mechanism of the shorted micro-waveguides. When EM waves incident on the shorted micro-waveguides array, a reflection loss occurs on the surface of the metallic apertures due to impedance mismatching. After further attenuating in the cavity of the micro apertures, multiple reflections will be established in the shorted micro-waveguides array between the apertured layer and the continuous conductive layer, contributing to the enhancement of EMI shielding. It follows that the synergy attenuating effect of the shorted micro-waveguide configuration endows the material superior EMI shielding properties over an ultra-wide frequency spectrum.

2.2. Performance of SMWs Array

The shielding effectiveness quantifies the degree to which electromagnetic fields or electromagnetic waves are attenuated by shielding materials. It is defined by the logarithmic ratio of the incident power to the transmitted power,[13,42] and the larger the SE value, the smaller the amount of electromagnetic radiation passes through the material. Generally, the EM shielding effect can be produced by electromagnetic waves being reflected at the surface of shielding materials, being absorbed, or by multiple reflection losses occurring within the shielding material itself. The total EMI shielding effectiveness of the transparent EMI shielding material is the sum of EM reflection, absorption, and multiple internal reflections, and can be obtained by transmission coefficient (T) or the scattering parameters:[42]:

\[
SE = 10 \log \left( \frac{1}{T} \right) = 10 \log \left( \frac{1}{|S_{11}|^2} \right) \tag{1}
\]

Figure 2a presents the EMI shielding performance of the designed transparent shield based on the array of SMWs. For comparison, EMI SE values of freestanding micro-waveguides layer and ITO shorting film are plotted as well. The freestanding micro-waveguides (\(l = 80 \, \mu m, w = 4.3 \, \mu m, t = 14 \, \mu m\)) has an average SE of \(\approx 40.7 \, dB\) in a broad frequency range. Especially in the frequency range from 1.7 to 4 GHz, more efficient EMI shielding with exceptional SE exceeding 40 dB is obtained owing to the cut-off effect of micro-waveguides. It should be noted that the freestanding micro-waveguide layer demonstrates a downward trend in EMI shielding effectiveness as the frequency goes higher, exhibiting an over 30 dB reduction in SE from 1.7 to 18 GHz (59.4 dB to 29.1 dB). Likewise, a steep decline in EMI SE is also observed with the frequency decreasing to the megahertz spectrum.

![Figure 2](image-url)

**Figure 2.** Performance of SMW array. a) EMI shielding performance of the freestanding micro-waveguides layer (\(l = 80 \, \mu m, w = 4.3 \, \mu m, t = 14 \, \mu m\)), ITO shorting film with AR coatings, and the shorted micro-waveguides array. b) Optical transmittance of the shorted waveguide array and its components in the visible range. c) Visible observation through the transparent EMI shielding material based on SMWs array.
It is associated with two factors of the frequency dependence on the sheet resistance and the perforated structure of the micro-waveguide that leads to the reduction in EMI SE with increasing frequency. The frequency dependence on sheet resistance of the micro-waveguide layer can be described by the following equation\textsuperscript{[34,43]}:

\[
R = \frac{1}{\sigma \delta (1 - e^{-\delta l})} \frac{l}{2a}
\]  

(2)

Where \(\delta\) is the skin depth and \(\delta = \sqrt{\frac{l/\pi}{\mu \sigma}}\), \(\mu\) and \(\sigma\) are the permeability and conductivity of the micro-waveguide layer. The active part of their sheet resistance increases with increasing frequency in proportion to the square root of the frequency.\textsuperscript{[43]} The increased sheet resistance of the micro-waveguides layer partly influences on the attenuating EMI shielding behavior. Additionally, the cut-off effect of micro-waveguides also contributes to the degradation of EMI SE at higher frequencies. Besides, apertures in metallic micro-waveguides cause radiation leakage due to the diffraction relationship between wavelength and aperture size. According to the study carried out by Lee et al., it is not the number of waveguides that determines the shielding effectiveness of the hexagonal micro-waveguide array, but rather the geometrical parameters of the unit waveguide. And the shielding effectiveness of the micro-waveguides array can be described by the following equation\textsuperscript{[44]}:

\[
SE = 17.5 \frac{l}{\sqrt{1 - \left(\frac{lf}{96659}\right)^2}} - 20 \log \frac{2kl}{\pi} \cos \phi
\]  

(3)

where \(k\) is the wavenumber, \(l\) is the transverse dimension of the waveguide, and \(\phi\) is the angle of incident waves. It indicates that the shielding effectiveness of micro-waveguides gets weaker with increasing frequencies. Not surprisingly, strong evidence of shielding performance degradation of the freestanding micro-waveguides was found as frequency goes higher, which is consistent with the reported shielding properties of apertured-type shielding materials.\textsuperscript{[36–38,45]} At frequencies of the megahertz spectrum, the wavelength of the incident electromagnetic wave is much larger than the section size of the micro-waveguide. As the frequency decreases, the influence of the cutoff waveguide effect on the shielding characteristics is gradually weakened. And the micro-waveguide layer behaves as a thick continuous conductive film when EM waves incident. At the low frequency limit of the measured frequency band (200 MHz), the calculated SE is \(\approx 29\) dB (according to Equation S4 of Supporting Information), which is close to the measured result (30.7 dB). It confirms that the cut-off effect of the microwave guide has little contribution to the shielding performance at megahertz frequency spectrum.

To achieve both higher level of light transmission and EMI shielding performance in the broadband frequency spectrum, we fabricated shorted micro-waveguides array by assembling the metallic micro-waveguides and ITO film. What is striking about the results is that the EMI SE of the SMWs array is measured to be 60.8 dB on average in a wide frequency range (0.2–1.3 GHz & 1.7–18 GHz) while keeping an outstanding optical transmittance of 90.4% at 550 nm. More importantly, there was no significant shielding degradation as the frequency changes, demonstrating the indiscriminate shielding property over a broad frequency range. The remarkable EMI shielding performance of SMWs array originates from the enhanced attenuation by the waveguide effect and multiple internal reflections from the layered structures.

In comparison to the pristine micro-waveguide layer, the SMW-based structures are more effective at attenuating microwaves owing to the introduced ITO film. As shown in Figure 2a, the ITO shorting film exhibits a stable EMI SE of \(\approx 30\) dB over the entire frequency. The ITO continuous film with high electrical conductivity functions as the short-circuited terminal for the micro-waveguides, which can reflect EM waves back to the micro-waveguides and arive additional reflection loss on the interior interfaces for further attenuation (Figure 1d). The incident microwaves can be adequately shielded in the low-frequency region due to the reflection from the surface of the micro-waveguides and the further attenuation of the apertured microstructure by waveguide effects. The microwave energy contained within the micro-waveguide is converted to heat and dissipated. Microwave energy transmitted through apertures stimulates multiple reflections between the micro-waveguides and the ITO shorting film, hence increasing the shielding effectiveness. The shielding enhancement effect is restricted in lower frequencies due to the dominant shielding property of the micro-waveguide. In the high-frequency range, the shielding efficacy of freestanding micro-waveguides drops, and more microwaves enter the layered structure, resulting in constructive interference and effective multiple reflection loss, thereby exhibiting extremely high overall EMI SE as well. As a result of the synergistic effect of the assembled shielding materials in the SMWs array, the EMI attenuating effect of the freestanding micro-waveguide in the higher frequency band is enhanced and strong and balanced microwave shielding performance in the wide frequency band is achieved.

Optical transmittance is a fundamental and essential performance indicator of transparent electromagnetic shielding material to ensure that the shielding material does not impair the signal transmission of the optoelectronic system itself. The optical transmittance curves of freestanding micro-waveguides, short-circuited terminal (glass with ITO and AR coatings), and the SMW array are shown in Figure 2b. By depositing properly designed AR layers onto the ITO glass (see Figure S1 of Supporting Information for details), the optimized ITO shorting film exhibits an average transmittance of 91.0% in the wavelength range of visible light (400–800 nm) and an exceptional transmittance of 96.1% at 550 nm. The optical AR layers modulate the transmission properties of visible light and further reduced the optical loss, especially around 550 nm, thereby contributing to the high transparency of ITO shorting films. Apertured materials have total transmittance equal to each diffracted order’s transmittance, and can be expressed as the obscuration ratio.\textsuperscript{[38]} That is, the total optical transmittance of the freestanding micro-waveguides layer is approximately equal to the ratio of the area covered by non-metallic material to the entire area. The large opening fraction of the micro-waveguide layer (large side length of 80 \(\mu\)m and fine pore-wall thickness of 4.3 \(\mu\)m) allows more light transmitting through the material to achieve a high transmittance. Consequently, the average transmittance of the freestanding micro-waveguides was measured to
be 93.1%. Remarkably, a high transmittance of 90.43% at 550 nm is maintained by the SMW array owing to the high transparency of its two functional components. Figure 2c shows the digital photograph of the fabricated shorted micro-waveguide array. High optical transmission ensures a good visual effect, allowing clear observation of the scene behind the shielding materials.

It is worth noting that the insulation distance \(d\) of SMW is a contributing factor in determining the constructive interference degree of multiple interspace reflection, and the intensity is greatest when \(d\) equals to the quarter-wave. We evaluated the shielding enhancement effect of different insulation distances on the performance of the shorted micro-waveguide array, as shown in Figure 3. The shielding performance has been improved by increasing insulation distance, however, the degree of enhancement varies between the high and low-frequency bands. In the lower frequency band (1.7–4 GHz, Figure 3a), the shielding effectiveness increases by 14.3% with \(d\) changing from 0.2 mm to 1 mm, exhibiting a limited enhancement effect. Satisfyingly, the average shielding effectiveness can be effectively enhanced by 18.6 dB under the same setting in X- and Ku-band (Figure 3b), thereby providing a comparable shielding property in higher frequencies. In addition, the trend of improvement in SE becomes slowing down with the further increase of \(d\), which is caused by the fact that the equivalent reflectivity of dielectric substrates increases gradually as the equivalent optical thickness of the substrate increases from zero to quarter-wave. The result verifies the critical influence of the insulation thickness between the metallic micro-waveguides and the ITO continuous conductive layer on the shielding performance, and obtained the shielding performance that can be comparable in the high and low-frequency bands under the 1-mm thickness insulation condition.

In addition, we investigated the performance of SMWs arrays with different structural parameters \((l = 60 \, \mu m, 65 \, \mu m, 75 \, \mu m,\) and \(t = 14\) of micro-waveguides, as shown in Figures 4a-f. One can see that the shielding effectiveness of SMWs slightly increases with smaller micro-waveguide apertures but is accompanied by a slight decrease in transmittance (as seen in Figure S2, Supporting Information). The enhanced shielding performance of SMWs array with decreased side length can be understood from the following two aspects: a) The effective electromagnetic shielding band is moving away from the cut-off frequency as the side length of the micro-waveguide aperture decreases. According to the electromagnetic transmission characteristic of micro-waveguides (Figure 1b), the transmission coefficient gets smaller, which leads to a higher shielding effectiveness. b) The sheet resistance of SMWs array is decreased as the side length gets smaller, which can reflect the microwave more effectively. The specific performance parameters are summarized in Table 1. It demonstrates that the proposed shorted micro-waveguide array exhibit excellent overall performance, i.e. both high transparency and strong broadband EMI shielding. On the other hand, variations in structural parameters in this range produce insignificant changes in performance, providing a high degree of tolerance for material design and implementation.

To highlight the merits of this work, we have conducted a comprehensive literature review and compared the optical transmittance and EMI SE of the major transparent electromagnetic shielding materials currently available, including ultrathin metal films, metallic mesh films, various transparent conductive composite films based on graphene, transparent conductive polymers, carbon nanotubes, and silver nanowires. Although EMI SE exceeding 20 dB in a wide frequency band can meet commercial application standards, effective EMI shielding for optoelectronic systems needs strengthened shielding performance. As depicted in Figure 5, while some of the state-of-the-art works achieve extremely high transmittance (≈90%), the associated shielding performance is limited, typically below 40 dB, making it hard to meet the requirements for high-level shielding application scenarios. By comparison, our study reveals the capacity to achieve exceptional shielding performance (average SE of 60.8 dB) while maintaining high optical transparency, providing an outstanding comprehensive performance, and meeting the demand for EMI shielding of optoelectronic equipment. It should be noted that the proposed SMWs array outperforms previously reported highly transparent EMI shielding materials with transmittance higher than 90% in shielding effectiveness and shielding frequency band. More specific performance comparisons of these transparent EMI shielding materials can be found in Table S1 (Supporting Information).

2.3. Comparative Study on Micro-Waveguides Array with Varying Structural parameters

Due to the limit of the existing lithography process, preparing apertured microstructures with a high aspect ratio is
We adopted a hybrid manufacturing process that combines nanoimprinting and electroplating to fabricate the micro-waveguide array, as described in Figure 6a. It has an overwhelming advantage over other micro and nano fabricating methods such as lithography, screen-printing, and inkjet printing. The high precision of nanoimprinting technology allows for ultra-narrow notches, which ensures the high-resolution characteristics of apertured metal microstructures. Compared to the lithography process, the electroplating process makes the fabrication of high-aspect-ratio metal microstructures highly efficient. Besides, the processing method used in this paper enables large-area processing of metal microstructures with a high aspect ratio. The specific fabrication of freestanding micro-waveguides and SMWs array is given in the Experimental Section. After being peeled from the PET substrate, the freestanding micro-waveguides were achieved. The micrograph of apertures under different magnifications are shown in Figure S3 (Supporting Information).

Optimizing the geometric parameters of the micro-waveguide is crucial for the construction of a high-performance shorted micro-waveguide array. For a hexagonal micro-waveguide, the side length is a primary indicator of its aperture, which determines the conductivity and shielding ability of the micro-waveguides. Meanwhile, the variation of the aperture also directly affects the light transmission rate. In Figure 6b,c, the shielding characteristics of four samples with different side lengths of 60 µm, 65 µm, 75 µm, 80 µm, and 85 µm are compared to investigate the specific influence of different periods on the shielding performance of the metallic apertured materials (waveguide length = 14 µm). As the side length increases from 60 µm to 85 µm, there is a 12.5-dB reduction and a 6.5-dB reduction in shielding effectiveness in the frequency ranges of 1.7–2.6 GHz and 8–12 GHz, respectively. Correspondingly, the visible light transmittance increased from 90.8% to 93.2% (at 550 nm, see Figure 6d).

### Table 1. Summary of optical and EMI shielding performance of SMWs arrays with varying geometric dimensions.

| SMWs arrays<sup>a</sup> | Sheet resistance [Ω sq<sup>−1</sup>] | EMI SE<sup>b</sup> [dB] | Transmittance<sup>c</sup> [%] | Frequency range [GHz] |
|--------------------------|-----------------------------------|----------------------|----------------------------|----------------------|
| SMWs (l = 60 µm)         | 0.044                             | 65.7                 | 87.7                       | 1.7–18               |
| SMWs (l = 65 µm)         | 0.056                             | 64.7                 | 88.8                       | 1.7–18               |
| SMWs (l = 75 µm)         | 0.083                             | 63.3                 | 89.5                       | 1.7–18               |
| SMWs (l = 80 µm)         | 0.101                             | 60.8                 | 90.4                       | 0.2–1.3, 1.7–18      |

<sup>a</sup>The insulation distances of SMWs arrays were 1 mm; <sup>b</sup>The values were average shielding effectiveness obtained in the measured frequency range; <sup>c</sup>Optical transmittances were obtained at 550 nm.
The proposed micro-waveguide shielding layer is distinguished by its high-aspect-ratio feature in comparison to conventional metallic meshes. For micro-waveguides arrays with limited thickness and large aperture, the shielding efficiency can be improved by increasing the waveguide length. Longer pore walls can enhance the cutoff effect of micro-waveguides and consume the EM wave to the greatest extent. Here, we studied the shielding performance of the freestanding micro-waveguide with different waveguide lengths to verify the enhanced effect of the waveguide effect on shielding effectiveness. Figure 6e compares the EMI SE obtained from the prepared micro-waveguide layers with varying thicknesses (i.e., micro-waveguide length) in a lower frequency range (1.7–2.6 GHz). For these measured samples with thicknesses of 2.5 µm, 8 µm, 11 µm, and 14 µm, the side lengths and the linewidths of hexagonal apertures were fixed at 80 µm and 4.3 µm, respectively, meaning they possess the same light transmittance. The corresponding aspect ratios of the samples are 0.58, 1.86, 2.56, and 3.25, respectively. One can see that the metallic apertures with microscale waveguide features exhibit enhanced effects on EMI shielding performance as the length of the metallic micro-waveguide increases at lower frequencies. Close inspection of the figure shows that the sample with a waveguide length of 8 µm has an average SE value of 49.9 dB, which is 15 dB higher than that of conventional thin metal mesh film (2.5 µm in thickness). When the thickness of the aperture increases from 8 µm to 11 µm, the average SE increases by 2.9 dB over the tested frequency range and reaches 57.4 dB when the thickness further rises to 14 µm. In contrast with the micro-waveguides (t = 14 µm), the thin mesh layer shows a much lower SE value of 34.1 dB, which drops nearly 12.5 dB in shielding performance.

This result demonstrates the advantages of micro-waveguide results in terms of enhanced EMI SE due to its cutoff effect, especially at lower frequencies. The observed increase in shielding effectiveness could be attributed to the fact that more EM waves are reflected back into the surrounding space due to the reduced sheet resistance of the apertured layer. Besides, the feature of a large aspect ratio enhances the cut-off effect of waveguides and significantly attenuates the EM wave. However, there is no obvious waveguide effect in higher frequency band (Figure S4, Supporting Information). The optical transmittance appeared to be unaffected by the increase in the length of the separate micro-waveguides (Figure S5, Supporting Information), which is due to the unchanged ratio of the non-metal covered area to the total area. This result demonstrates that it is an effective way to enhance the shielding effectiveness by increasing the aspect ratio of the separate micro-waveguide layer in lower frequencies while maintaining a high light transmittance. More importantly, it also implies that a certain degree of decoupling between optical transmittance and shielding effectiveness has been accomplished.

3. Conclusion

In summary, transparent EMI shielding materials featuring high visible transmittance, strong electromagnetic shielding effectiveness, and wide shielding frequency band have been developed in the proposed shorted micro-waveguides array configuration. The design strategy implemented in this scheme decouples the light transmission and EMI shielding, enabling both high optical transmittance of 90.4% and superior EMI SE of 60.8 dB over an ultra-wide frequency spectrum. The improved EMI shielding performance of apertured shielding materials with high aspect ratio at lower frequencies are also demonstrated, verifying the efficient attenuation of EM waves by micro-waveguides. The superiority of our transparent EMI shielding material based on shorted micro-waveguides array against its counterparts lies in the significantly enhanced shielding efficiency, high optical transparency, and the ultra-wide shielding frequency spectrum. We believe that the proposed design concept of the short-circuited micro-waveguides array and the structure optimization strategy would open a new avenue toward higher-level electromagnetic shielding applications in various optoelectronic systems.
4. Experimental Section

Preparation of ITO Shorting Film with AR Coatings: ITO thin film (350 nm in thickness), as the short-circuited load for SMWs, was prepared by an electron beam evaporation system in the presence of oxygen with a base pressure of $2.0 \times 10^{-4}$ Pa, an accelerating voltage of $\approx 7$ kV, and electron beam current of 30 mA. The material used in this study was ITO pellets with nominal 99.9% purity In$_2$O$_3$:SnO$_2$ (95 wt.% and 5 wt.%, respectively). The deposition rate was $\approx 0.10$ nm s$^{-1}$ and the thickness of the deposited films was controlled using a quartz crystal thickness monitor. To reduce light reflection, a silicon dioxide (SiO$_2$) layer was prepared on the ITO thin film. At the same time, tantalum pentoxide (Ta$_2$O$_5$) and SiO$_2$ as the high and low refractive index for the multilayer anti-reflection films were deposited on the back of the substrate by electron-beam evaporator with ion-beam assisted deposition (IAD). The deposition rates were $\approx 0.15$ nm s$^{-1}$ and $0.4$ nm s$^{-1}$, respectively. The substrate temperature during the deposition process was kept at $250 \, ^\circ C$. The specific film structure can be found in Section 2 of Supporting Information.

Fabrication of Freestanding Micro-Waveguides: First, the nickel master plates with designed geometrical dimensions were obtained by direct writing and electroforming. Combined with the nickel master plate, the hexagonal trenches of different depths were formed on the UV-curing adhesive layer after the imprinting process. The optimized process parameters of UV curing energy is 20–30 mJ cm$^{-2}$, while post-curing energy is between 360 and 380 mJ cm$^{-2}$. The silver nanoparticles were filled into the embossed groove structure by blading and sintered afterward. The following step was to electroplate Cu on top of the conductive Ag lines inside the trenches. With this method, metallic apertured microstructures with a high aspect ratio greater than 3 (line width of 4.3 $\mu$m, thickness of 14 $\mu$m) were prepared. The freestanding micro-waveguides can be obtained by removing the UV photoresist. It should be noted that the edges of the freestanding layer are particularly vulnerable to warping due to the inherent mechanical stress. To
facilitate performance testing, they were fixed to the PET frame with copper tape.

Fabrication of SMWs: We obtained the SMWs array by peeling the metallic apertured micro-waveguide film from the PET substrate and transferring it to the ITO glass with AR coatings. First, the micro-waveguide film prepared on PET substrates was immersed in 4 wt.% NaOH solution for 1 min. After that, the sample was placed in a sink with the photoresist stripping solution for 1.5 h, and was rinsed with deionized water to remove the residue of the solution. After debonding, the metal microstructure protrudes from the PET substrate, which is easy to strip off from the PET substrate. Then, place the prepared ITO glass on a flat surface and tape the outside of the ITO glass with double-sided tape. Next, the degummed metallic apertured micro-waveguides sample (larger than the ITO glass in size) was covered over the ITO glass. It should be pressed firmly against the surrounding region where the adhesive tape has adhered. The metallic apertured layer stays on the table due to the adhesive force of the adhesive tape when gently stripping off the PET substrate. This step concurrently completes the process of stripping off the micro-waveguides layer from PET substrate and transferring it onto the ITO glass. Finally, copper foil tape was used to seal the ITO glass and micro-waveguides layer together at all edges. The aforementioned preparing procedures can guarantee the non-destructive transfer of the layer of the micro-waveguides array in a large area to ITO glass. All of the prepared samples are 150 mm × 150 mm in size.

Characterization and Measurements: Optical transmittance of transparent EMI shielding materials in the visible wavelength range was measured using a UV-visible-near-infrared (UV-vis-NIR) spectrophotometer (U-4100, HITACHI) in ambient conditions. The sheet resistance of the SMWs array was measured using a four-point probe resistance tester (DC. FP-001, Kaivo).

To obtain the EMI shielding effectiveness over an ultrawide frequency spectrum, we utilized two methods for the EMI shielding measurement according to the measuring frequency range. The measured limits of low and high frequency were 200 MHz and 18 GHz, respectively. In the frequency range of 0.2–1.3 GHz, the flange coaxial method was adopted. The measurement system was connected as shown in Figure S7a (Supporting Information), the input of the network analyzer (VNA, ZVRE, Rohde & Schwarz) is connected to one end of the flanged coaxial unit and the output is connected to the other end of the flanged coaxial unit. After calibrating the measurement system, the measuring specimen was fixed in the flanged coaxial device and the shielding effectiveness of the loaded specimen can be obtained. For the EMI shielding performance in the frequency range of 1.7–18 GHz, the waveguide measuring method was employed. As shown in Figure S7b (Supporting Information), a VNA (AV3672B, Ceyear) which connected to waveguides operated in various frequency bands (1.7–2.6 GHz, 2.6–4 GHz, 4–6 GHz, 6–8 GHz, 8–12 GHz, and 12–18 GHz). The port power of the vector network analyzer was set to -3 dBm, and the dynamic range of the vector network analyzer exceeds 110 dB. The measurement system was calibrated with Transmission-Reflection-Load (TRL) technique at both ends of the waveguides. The two terminals of the vector network analyzer are connected to the waveguide via the coaxial cable, where as-prepared samples are clamped tightly between the commissure of waveguides. Total EMI SE values can be obtained via S-parameters collected by VNA.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
electromagnetic interference shielding, transparency, shorted micro-waveguide, ultra-wide frequency spectrum

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[1] C. Jiang, D. Tan, Q. Li, J. Huang, J. Bu, L. Zang, R. Ji, S. Bi, Q. Guo, ACS Appl. Mater. Interfaces 2021, 13, 15525.
[2] Y. Chen, L. Pang, Y. Li, H. Luo, G. Duan, C. Mei, W. Xu, W. Zhou, K. Liu, S. Jiang, Composites, Part A 2020, 135, 105960.
[3] J. H. Zhang, M. T. Lin, Z. F. Wu, L. Ding, L. B. Aian, P. G. Liu, IEEE Trans. Antennas Propag. 2019, 67, 2494.
[4] Z. Wang, B. Jiao, Y. Qing, H. Nan, L. Huang, W. Wei, Y. Peng, F. Yuan, H. Dong, X. Hou, Z. Wu, ACS Appl. Mater. Interfaces 2020, 12, 2826.
[5] A. Iqbal, P. Sambyal, C. M. Koo, Adv. Funct. Mater. 2020, 30, 2000883.
[6] H. Wang, Z. Lu, Y. Liu, J. Tan, L. Ma, S. Lin, Opt. Lett. 2017, 42, 1620.
[7] A. Schroder, G. A. Rasek, H.-D. Bruns, Z. Reznicek, J. Kucera, S. E. Loos, C. Schuster, IEEE Trans. Electromagn. Compat. 2014, 56, 113.
[8] J. Lin, H. Zhang, P. Li, X. Yin, G. Zeng, IEEE Trans. Electromagn. Compat. 2014, 56, 328.
[9] E. Hosseini, M. Arjmand, U. Sundararaj, K. Karan, ACS Appl. Mater. Interfaces 2020, 12, 28596.
[10] C. Yuan, J. Huang, Y. Dong, X. Huang, Y. Lu, J. Li, T. Tian, W. Liu, W. Song, ACS Appl. Mater. Interfaces 2020, 12, 26659.
[11] G.-M. Weng, J. Li, M. Alhabeb, C. Karpovich, H. Wang, J. Lipton, K. Maleski, J. Kong, E. Shaulsky, M. Elimelech, Y. Gogotsi, A. D. Taylor, Adv. Funct. Mater. 2018, 28, 1803360.
[12] X. Liang, J. Lu, T. Zhao, X. Yu, Q. Jiang, Y. Hu, P. Zhu, R. Sun, C.-P. Wong, Adv. Mater. Interfaces 2019, 6, 1801635.
[13] Y. Han, Y. Liu, L. Han, J. Lin, P. Jin, Carbon 2017, 115, 34.
[14] B. Ray, S. Parmar, K. Date, S. Datar, J. Appl. Polym. Sci. 2021, 138, 50255.
[15] S. K. Hong, K. Y. Kim, T. Y. Kim, J. H. Kim, S. W. Park, J. H. Kim, B. J. Cho, Nanotechnology 2012, 23, 455704.
[16] L. Valentini, S. B. Bon, J. M. Kenny, Carbon 2007, 45, 2685.
[17] B. Ray, S. Parmar, K. Date, S. Datar, 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC). IEEE, New Delhi, India, 2019, p. 1.
[18] R. A. Maniyyara, V. K. Mkhityaryan, T. L. Chen, D. S. Ghosh, V. Pruner, Nat. Commun. 2016, 7, 13771.
[19] H. Wang, C. Ji, C. Zhang, Y. Zhang, Z. Zhang, Z. Lu, J. Tan, L. J. Guo, ACS Appl. Mater. Interfaces 2019, 11, 11782.
