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Transparent conductor based on metal ring clusters interface with uniform light transmission for excellent microwave shielding

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ABSTRACT

We present a transparent conductor composed of the flower-shaped multi-angle metal ring clusters (FMMRC) interface structure for simultaneous highly optical transparency with uniform light transmission and microwave shielding performance both theoretically and experimentally. The measured normalized optical transmittance of the FMMRC sample is ~95% covering the visible to near infrared spectra with a sheet resistance of ~5.6 Ω/sq., offering favorable conductivity as a transparent electromagnetic interference (EMI) shielding component. Particularly, the FMMRC structure shows a uniform light transmission with a homogeneous high-order diffraction distribution which introduces negligible impact on optical imaging and observation. In the meantime, both simulations and experimental results demonstrate the shielding effectiveness of the FMMRC structure is > 21 dB from 12 to 18 GHz, obtaining an excellent shielding performance for a single-layer metal structure with high optical transmittance. The proposed FMMRC is insensitive to the polarization direction due to the symmetrical arrangement. These excellent properties of the FMMRC structure represents the highest figure of merit single-layer metallic mesh ever reported, showing great potential in transparent EMI devices as well as transparent electrodes.

1. Introduction

Nowadays, the electromagnetic leakage at radio frequency is a serious problem for our society which affects the utilities and lifetimes of electronic devices as well as the human health [1–5]. In general, transparent conductive films (TCF) are considered as optimum shielding materials for its optical transparency and favorable Electromagnetic Interference (EMI) shielding performance [6]. And materials with a combination of high optical transparency and electrical conductivity have attracted considerable attention in recent years for their applications in optoelectronic devices, including solar cells [7], liquid crystal displays [8], light emitting diodes [9, 10], conductive coatings for windows [11], as well as transparent EMI shielding equipments [12]. Indium tin oxide (ITO) has dominated the TCFs market for its high transparency (85%) and conductivity (10 Ω/sq) [13]. However, better optical and electrical performance are required in increasing applications. And due to low availability of indium resources, recent studies have investigated alternatives to ITO, such as graphene, carbon nanotubes, metallic nanowires (MNWs) and metallic microstructures [14–20]. Generally, carbon-based materials cannot achieve high transparency and strong EMI shielding simultaneously [21–24]. It is reported that MNWs have higher optical haze which goes against the precise detection and observation and large contact resistances between wires [25]. Although metallic microstructures, like periodic metallic meshes, can realize broadband light transmission and strong microwave shielding, stray light caused by diffraction superposition degrades the imaging quality [26–28]. Compared to the traditional metallic mesh, ring-based metallic meshes can achieve uniform diffraction pattern to some extent. However, there is not much work considering the electrical property of the ring-based metallic meshes and to improve its microwave shielding performances without affecting the transmittance. Therefore, it remains a significant technology challenge to develop metallic microstructures that exhibits all of the above-mentioned excellent features simultaneously.

In this paper, we report on a strategy to design high-performance optically transparent conductor which achieve excellent transmittance covering a wide optical region and strong EMI shielding performance. A flower-shaped ring clusters is considered as the basic unit cell which forms the flower-shaped multi-angle metal ring clusters (FMMRC) by a relative multi-angle rotation arrangement around their own centers.

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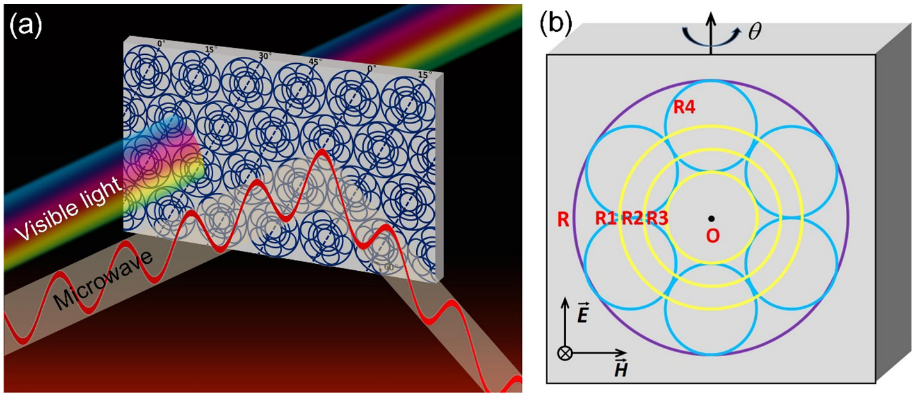

Fig. 1. (a) Schematic diagram of the flower-shaped multi-angle metal ring clusters. (b) Mesh unit cell with different rings, with the polarization direction of TE waves and the incident angle θ illustrated.

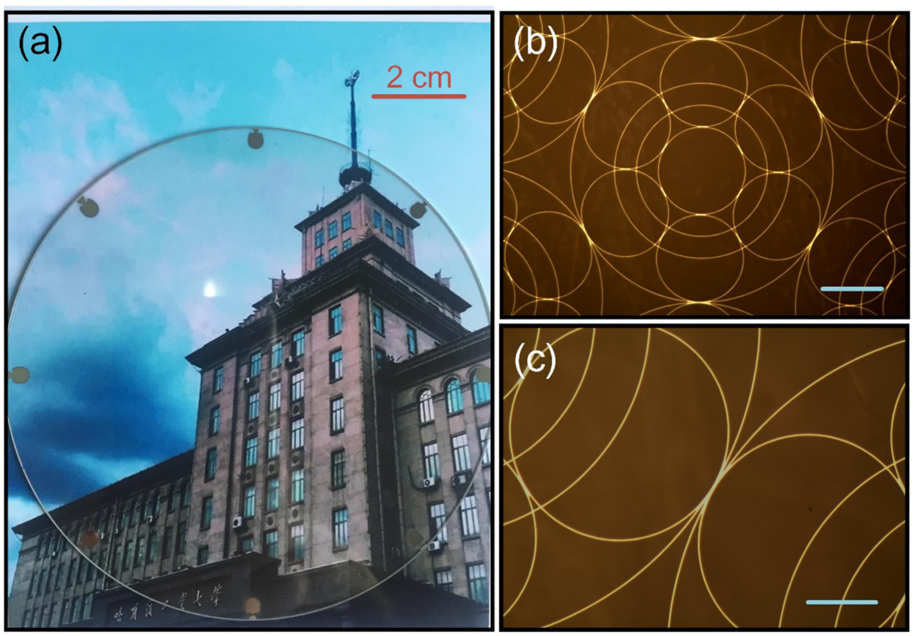

Fig. 2. (a) Photograph of a fabricated FMMRC sample. (b) and (c) Micrographs of the sample with different magnifications, which were taken using Nikon SMZ1500 stereomicroscope. The scale bar in the (b) and (c) represents 100 μm and 50 μm, respectively.

Concentric rings are introduced in the unit cell to improve the electrical conductivity and the shielding performance. The characterized results show that average optical transmittance of the FMMRC film is ~95% over the visible and near infrared spectra with the sheet resistance as low as ~5.6 Ω/sq., which indicates the great potential for practical application as transparent electrodes. More importantly, the shielding effectiveness of the FMMRC film is over 21 dB in the Ku-band, which is among the best shielding performance at high transmittance ever reported, and a homogeneous diffraction pattern has been achieved simultaneously by the FMMRC film.

2. Experimental

2.1. Design of the FMMRC film

Fig. 1a depicts the schematic diagram of the proposed flower-shaped multi-angle metal ring clusters (FMMRC), and the typical unit cell, illustrated in Fig. 1b, consists of flower-shaped element on the quartz-glass substrate. It can be seen from Fig. 1a that the FMMRC is composed of the unit cells with different rotated angles (0°, 15°, 30°, 45°) around their own Centers O. The black dotted lines tilted at 60° in the Fig. 1a show the multi-angle arrangement of the unit cells, which illustrates that unit cells with the same rotated angles distributed along the dotted lines in turn. Ring-shaped elements were used as the unit cell with the advantage of homogenizing the diffraction light, and in this article, we introduce the concentric ring clusters (golden rings in Fig. 1b) in the unit cell, which greatly improve the electrical conductivity of the overall metal structure and enhance the microwave shielding performance further without losing the optical transmittance.

The detailed geometrical parameters for different rings in the unit cell shown in the Fig. 1b are designed to ensure the total optical transmittance of ~ 95%. And the radius of different rings are calculated according to their dimensional relationships at the same ring linewidth (2.5 μm) as follows: $R = 440$ μm, $R1 = 2R/3 = 293.3$ μm, $R2 = R/2 = 220$ μm, $R3 = R4 = R/3 = 146.7$ μm. All the rings maintain good contact with the adjacent rings to guarantee favorable conductivity of the whole metal structure. The electric and magnetic field orientations of the TE mode are shown in Fig. 1b and the θ represents the incident angle of the electromagnetic wave.