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Optical and radio-frequency properties of silver mesh transparent conductor with irregular structure

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Abstract. The article presents the results of studying the optical and radio-frequency properties of silver irregular mesh transparent conductors obtained using an original self-organized template. It is shown that variation in the thickness of the deposited silver allows easy control of the surface resistance, which is the determining factor affecting the transmission in the radio-frequency range. In particular, we have obtained an irregular silver mesh, which has a surface resistance of 1.44 Ω/sq with an optical transparency in the visible range of about ~81%. This combination of optoelectric parameters made it possible to achieve an extremely low transmittance in the range of 0.7–14 GHz, an average of −37.34 dB over the range, which means that this mesh blocks 99.9815% of radiowave.

Keywords: cracked template, transparent conductor, irregular mesh, shielding efficiency

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Оптические и радиочастотные свойства серебряных микросеток с нерегулярной структурой

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Аннотация. Представлены результаты исследования оптических и радиочастотных свойств серебряных нерегулярных микросетчатых прозрачных проводников, полученных при помощи оригинального самоорганизованного шаблона. Показано, что вариация толщины напыляемого серебра позволяет легко управлять поверхностным сопротивлением, что является определяющим фактором, влияющим на пропускание в радиочастотном диапазоне. В частности, нами получена нерегулярная серебряная микросетка, которая имеет поверхностное сопротивление 1,44 Ом/кв при оптической прозрачности в видимом диапазоне, порядка ~81 %. Такое сочетание оптоэлектрических параметров, позволило достичь крайне малого коэффициента пропускания в диапазоне 0,7–14 ГГц в среднем по диапазону равно –37,34 дБ, что означает, что данное покрытие блокирует 99,9815 % излучения радиочастотного диапазона.

Ключевые слова: самоорганизованный шаблон, прозрачное проводящее покрытие, нерегулярная сетка, коэффициент экранирования

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Introduction

Optically transparent conductors are an important class of materials for optoelectronics, automotive, aerospace, and buildings industries. Studying the radio-frequency (RF) characteristics of these materials is crucial for designing optically transparent screens, antennas and metamaterials. Metallic meshes are among the most promising types of transparent conductors, particularly for RF applications [1], due to their combination of high optical transparency and low surface resistance. Typically, metallic micro- and nanomeshes are fabricated using standard methods such as: photolithography [2], imprinting [3], Electrohydrodynamic jet printing [4]. These methods for producing micro- and nanomeshes offer advantages related to excellent performance parameters but also have drawbacks, such as difficulties in scaling or high production costs. In terms of balancing optoelectronic properties, shielding performance, and production costs, some of the most notable examples include cracked template lithography [5] and nanosphere lithography [6]. In this work, we investigate the broadband shielding properties of irregular Ag meshes fabricated using the cracked template method.

Materials and Methods

The method of forming cracked template, based egg white and irregular Ag meshes based him is described in detail in our previous work [5]. The morphology of cracked tenplate and irregular silver meshes was studied by the method of scanning electron microscopy (SEM) using Hitachi TM-4000 Plus (Hitachi, Japan).

Optical Transmittance spectra of irregular Ag meshes were obtained in the range of 400–800 nm on a UV-3600i Plus spectrophotometer (Shimadzu, Japan).

The sheet resistance was measured by the four-probe method using a JG ST2258 four-point probe station (Suzhou Jingge Electronics Co., China) and a JG ST2558-F01 four-probe head (Suzhou Jingge Electronics Co., China).

The transmission (S_{21}) and reflection (S_{11}) coefficients were measured in the range of 0.7–14 GHz. The measurement technique is described in our previous work [7].

Results and Discussion

Fig. 1, *a* shows an SEM image of the cracked template. Statistical analysis of the SEM image revealed an average cell size of 78.9 ± 39.4 μm and an average crack width of 6.5 ± 3.3 μm. Fig. 1, *b* presents an SEM image of the irregular Ag mesh with a deposited silver thickness of 600 nm. According to statistical analysis, the average cell size is 75.3 ± 37.7 μm, and the average track width is 7.2 ± 3.6 μm. The Ag mesh closely replicates the geometry of the original cracked template, demonstrating high fidelity in structural transfer.

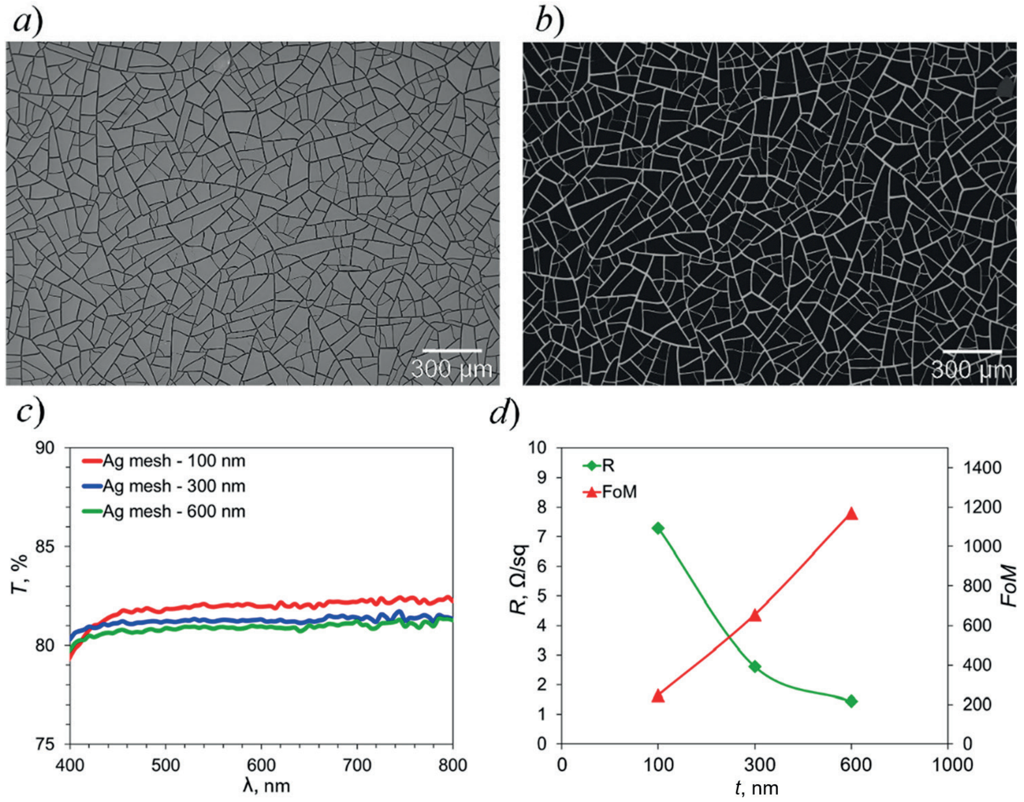

Fig. 1. SEM image cracked template (*a*) and irregular mesh with 600 nm Ag thickness (*b*) Optical transmittance irregular Ag meshes (*c*) and sheet resistance with FoM parameter (*d*)

Visible-range transmittance of irregular Ag meshes with varying thicknesses is presented in Fig. 1, *c*. The data show that increasing the silver thickness leads to only a minor reduction in transmittance. At a wavelength of 550 nm, the transmittance values are 81.94%, 81.25%, and 80.84%, respectively. On the other hand, the sheet resistance decreases significantly with increasing deposited silver thickness (Fig. 1, *d*). The relationship between these two values is characterized by the Figure of Merit (*FoM*) parameter, calculated using the formula:

$$FoM = \frac{Z_0}{2R_\square\left(\frac{1}{\sqrt{T}}-1\right)}. \quad (1)$$

Here, T is the optical transmittance at a wavelength of 550 nm; $R_\square$ is the sheet resistance; Z_0 = 377 Ω is the impedance of free space. Increasing the thickness of the deposited silver leads to a significant decrease in sheer resistance, with a slight decrease in transmission in the visible range, which ultimately leads to an increase in the *FoM* parameter (Fig. 1, *d*).

The spectral transmission (S_{21}) and reflection (S_{11}) coefficients for all fabricated irregular Ag meshes are presented in Fig. 2, *a* and Fig. 2, *b*. The transmission coefficient decreases proportionally with increasing mesh thickness due to the corresponding reduction in sheet resistance. The average transmission coefficients measure −28.15 dB, −34.91 dB, and −37.34 dB, respectively. The frequency dependence of transmission coefficients in the 0.7–14 GHz range results from wave diffraction through the mesh perforated structure. This dependence is well described by the Kontorovich model [8]. Notably, the frequency dependence of S_{21} becomes more pronounced with decreasing sheet resistance of the Ag mesh.

The reflection coefficient (S11) is also quite uniform throughout the studied range; there is a tendency for the reflection coefficient to increase with decreasing sheet resistance of the irregular mesh (Fig. 2, *b*).

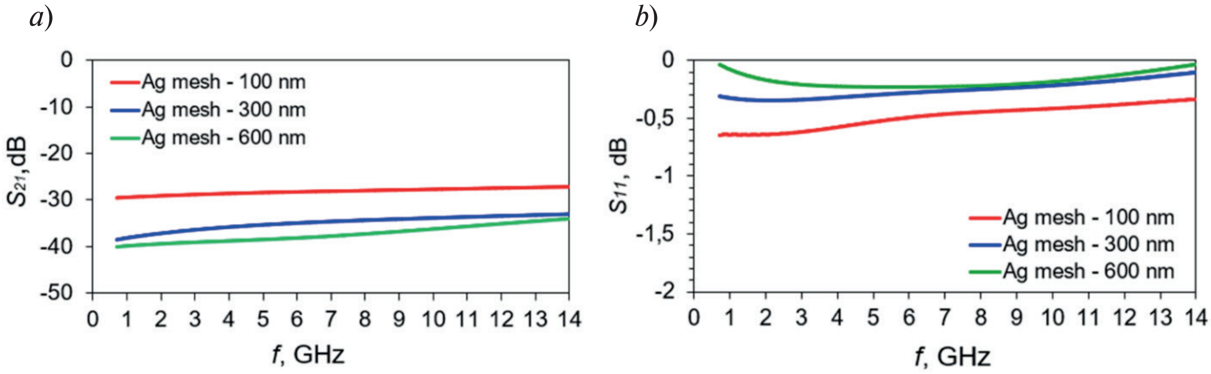

Fig. 2. Transmittance (*a*) and reflectance (*b*) spectra of irregular Ag meshes

Conclusion

We have demonstrated how template structures can be obtained using a self-organized cracking process of egg white. Based on their crack patterns, irregular Ag grids were created with a unique combination of optoelectric and shielding parameters. The properties of the coatings can be easily tuned by varying the thickness of the sputtered metal.

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