Simulation of transparent electromagnetic interference shielding materials based on periodic conductive networks

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Abstract. This paper is a preliminary report on a theoretical study of transparent shielding materials with potentially very high shielding efficiency based on quasi-periodic conductive networks. An empirical model for rapid calculation of shielding efficiency vs frequency and mesh geometrical parameters is suggested based on numerical simulation results.

1. Introduction
Development of electromagnetic interference (EMI) shielding materials is a topical task for electronic device industry. Continuous growth of electronic devices in all spheres of life led to a new type of pollution known as electromagnetic interference that can harmfully affect both the device performance and human beings [1]. The usage of metal sheets and cases as the original EMI shielding method has been the most widespread technique over the years. Unfortunately, they are not suitable for producing optically transparent materials. This problem is partially solved by using transparent conducting oxides (TCOs), such as indium-tin oxide (ITO) [2], but they can only provide limited shielding without losing transparency and are prone to degradation due to cracking. Potentially superior alternatives, which receive much attention lately, include silver nanowire (AgNW) coatings [3] and graphene sheets, but their shielding efficiency (SE) is also limited by the requirement of transparency.

Higher SE values can be achieved by using highly conductive meshes. Unlike continuous thin conducting layers, they exhibit a strong frequency dependence of SE. Obviously, their SE also strongly depends on their geometry and electrical properties of the material they are comprised of. Due to the overall complexity of the system, analytical solutions are only possible for very special cases. However, structure optimization based solely on numerical solutions can be computationally expensive, so there is a need for simple empirical models.

In this paper we suggest an empirical model for the frequency dependence of shielding efficiency (SE) parametrized by geometrical parameters of a quasi-periodic conducting hexagonal mesh.

2. Simulation
The investigated conductive mesh is inspired by Shen S. et al. research [4] who proposed a material which has both good SE and transparency. The active layer of the material consists of a 2D network of straight metallic conductors. The network geometry is based on a periodic (constructed on a flat torus) Voronoi diagram of a uniformly distributed set of points which was subject to multiple iterations of Lloyd’s algorithm in order to equalize cell sizes (Fig. 1a). Such design provides highly uniform surface resistance and transparency over the entire material surface and prevents the appearance of a moiré pattern if the mesh is applied onto a highly periodic structure, such as the display surface. If the
number of polygons per periodic cell is sufficiently high, they tend to form a quasi-crystalline close-packed hexagonal structure, akin to that observed for a number of self-organized systems, such as porous anodic oxides or breath figures, which makes this kind of material possible to produce via self-organization. This also allows approximating the layer by a periodic hexagonal mesh (Fig. 1b), with properties averaged for all orientations, which simplifies the numerical simulations.

Figure 1(a, b). (a) Transparent network formed by opaque conductor wires; (b) single unit cell of the simplified model used in this study for numerical simulations.

In this study we calculate SE based on power transmission coefficient with respect to a normal-incidence plane wave, $|S_{21}|^2$, as follows:

$$SE = -20 \log |S_{21}|.$$  \hspace{1cm} (1)

The simulation is performed using the finite element method (FEM) in frequency domain. The unit cell model with boundary conditions is presented in figure 2. Simulations are performed for both the perfect electric conductor (PEC) and simple conducting media with $\varepsilon = 1 - \sigma i / \omega \varepsilon_0$ and no spatial dispersion.

Figure 2. Unit-cell model with boundary conditions.
During the simulations, all the geometrical parameters \((l, w, h)\) are varied independently. In our study, the length of the hexagon side is varied from 10 \(\mu\)m to 70 \(\mu\)m. Side width \(w\) and height \(h\) are varied in a range which allows to meet the conditions of optical transparency \((T = 90-98\%)\), which is calculated as the area ratio of opaque conductor wires to the entire area (Fig. 3a), and field of view \((FOV = 2\theta = 90-175^\circ)\) (Fig. 3b), respectively. Here, we define field of view as the maximum angle at which light can pass through the cell holes (in the geometrical optics approximation).

![Figure 3(a, b). (a) Areas used in optical transparency calculation; (b) angle used in field of view (FOV) calculation.](image)

In this study, we focus on shielding properties of the structure at frequencies much smaller than those of visible light. Figure 4 shows an example of a SE versus frequency curve for a specific combination of geometry parameters in case when conductor wires are made of a lossy conductor with \(\sigma = 63\) MS/m.

![Figure 4(a, b). (a) SE versus frequency; (b) SE versus log-frequency. Geometrical parameters: \(l = 10\) \(\mu\)m, \(w = 0.17\) \(\mu\)m, \(h = 10\) \(\mu\)m.](image)

In case of finite conductivity materials, the SE curves asymptotically approach the SE value of a thin uniform layer with the same static effective sheet conductivity at lower frequencies (see fig. 3b). As frequency gets higher, the frequency dependence of \(|S_{21}|^2\) becomes exactly quadratic, which is also observed for all frequencies in case of PEC:

\[
|S_{21}|^2 = k \cdot f^2,
\]  

\((2)\)
where $f$ is frequency and $k$ is a geometry- and material-dependent parameter. Further frequency increase must lead to an asymptotic approach to the transparency value predicted by geometrical optics, but this frequency region is out of scope of our research.

Depending on geometry of the structure, the transition between the aforementioned lower- and higher-frequency regions can be either monotonic or resulting in a single bump in the curve (see fig. 3a,b). The latter can be explained by a locally more prominent effect of the decrease in skin layer thickness than of the increase in hole transparency.

It appears that coefficient $k$ in equation (2) can be adequately described by an 8-parametric empirical model derived as follows. First, in order to reduce the number of free variables, we define dimensionless parameters $\alpha$ (relative area of the conductor’s normal projection) and $\beta$ (structure thickness relative to average hole size):

$$\alpha = r \cdot \left(2 / \sqrt{3} - r / 3\right),$$

$$\beta = \frac{h}{3\sqrt{3}/2 \cdot (l - w / \sqrt{3})},$$

where $r = w / l$. The model equation is then built based on the LSE function:

$$\ln k = \ln \left(e^{k_1 \alpha + k_2 \beta + k_3 \alpha \beta} + e^{k_4 \alpha + k_5 \beta + k_6 \alpha \beta}\right),$$

where $k_{1,6}$ are empirically found coefficients.

The empirical coefficients were calculated by fitting results of numerical simulations in a few stages by using the equally-weighted least squares method. The discrepancy between the model predictions and numerical simulation results does not exceed 1.5 dB within the studied parameter range. SE values calculated both using (2) and using the proposed FEM model for several random geometries are shown in Figure 5.

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**Figure 5.** Empirical model verification.
3. Conclusions
Irrespective of material and geometrical parameters, the frequency dependence of SE in the frequency range where the mesh can no longer be considered a uniform sheet but the average cell size is still small compared to wave length is exactly quadratic, and the single coefficient of this dependence can be adequately modeled by an 8-parametric empirical model. Depending on mesh geometry and composition, the transition between the lower-frequency “plateau” and higher-frequency quadratic regions can either be monotonic or have a single bump in SE value, the latter being its global maximum.

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