Resonance-induced wave penetration through electromagnetic opaque object

He Wen\textsuperscript{a,c),} Bo Hou\textsuperscript{b),} Yang Leng\textsuperscript{a),} Weijia Wen\textsuperscript{b,d)}

\textsuperscript{a)} Department of Mechanical Engineering, the Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
\textsuperscript{b)} Department of Physics, the Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
\textsuperscript{c)} Department of Electrical and Computer Engineering, the University of British Columbia, Vancouver, Canada
\texttt{phwen@ust.hk}

Abstract: The enhanced transmission of electromagnetic waves through an opaque object is reported in this paper. The samples are constructed as two different configurations: a subwavelength metallic mesh sandwiched either between two metallic plates with periodic fractal slots (ABA for short) or between two plastic plates with periodic metallic fractals (CBC for short). Such ABA or CBC configuration exhibits multiple transmission peaks, indicating the wave penetrations through the opaque metallic mesh. The experimental observations and theoretical simulations demonstrate that the transmission enhancements for two configurations are induced by local resonances in the sandwiching layers.

©2005 Optical Society of America

OCIS codes: (260.5740) Resonance; (160.4670) Optical materials; (350.4010) Microwaves; (160.3900) Metals

References and links

1. Introduction

The phenomenon of resonant transmissions of electromagnetic (EM) waves through structured materials has attracted much attention in recent years. Several kinds of extraordinary transmissions, each associated with the excitation of different kinds of resonances, have been discovered. For instance, the composite medium combining both thin metallic wires and split ring resonators (SRRs) exhibits a transmission band because the simultaneous occurrence of electric resonances in metallic wires and magnetic resonances in SRRs gives rise to a negative refractive index \( n \) [1-7]. By tailoring the surface of a material, Ebbesen et al. reported the enhanced transmission of light through an optically thick metal film perforated with subwavelength holes, where the resonance of surface plasmons is involved [8-11]. Furthermore, high transmissions through metal films with thin slits can be induced by Fabry-Perot-like resonance of propagating waves inside the slits [12, 13]. Very recently, another mechanism was proposed that enabled perfect transmission of a classically opaque flat slab (negative permittivity \( \varepsilon \)) by attaching two identical slabs of high \( \varepsilon \) on both sides to stimulate an enhancement of magnetic fields at the interfaces [14]. This paper will present the observation of the enhanced transmissions of microwave for a subwavelength metallic mesh sandwiched either between two metallic plates with periodic fractal slots (\( ABA \) for short) or between two plastic plates with periodic metallic fractals (\( CBC \) for short), and that the formations and positions of the transmission peaks are closely associated with local resonances of layer \( A \) and \( C \) [15-17].

2. Samples and measurements

The sample was constructed as a three-layered structure \( ABA \) or \( CBC \), where the sandwiching layer \( A \) or \( C \) was fabricated using a shadow-masking/etching process on a 31 cm × 31 cm × 0.5mm PCB sheet. The unit cell of layer \( A \) is intrinsically a 10-level fractal structure [15], wherein the slot etched on the copper plate has a width of 0.2 mm and the first level length of 10 mm, as illustrated on the right side in Fig. 1. On the metallic plate there are 196 replicas of 2 cm × 2 cm squares of fractal-slit arranged periodically. Layer \( C \) is actually an inverted version of layer \( A \), i.e. the metallic fractal strips were constructed instead of fractal slits. Layer \( B \) is a metallic mesh with grid squares of 0.5 mm in width and 1.3 mm in thickness, and a spacing of 3.5 mm between squares in both the \( x \) and \( y \) directions. Two identical layers \( A \) or \( C \) were attached to both sides of the layer \( B \) with a separation of distance 3 mm to form the \( ABA \) or \( CBC \) structures showing in Fig. 1 for the sample configuration. The microwave spectra were measured by an Agilent 8720ES Network Analyzer connected to two double-ridged waveguide horn antennas (HP1196E), separated by a distance of 120 cm. One acts as the microwave generator and the other as a receiver. The sample was placed on a stage 25 cm from the receiving horn. The microwave polarization was identified when the incident electric field was along the \( x \) or \( y \) direction.
3. Results and discussions

Figure 2(a) shows the normal transmittances of EM waves through layers A and B respectively. It is observed that the metallic mesh B is able to block the EM wave in the frequency range measured from 1 to 14 GHz, while layer A reflects the wave at most frequencies except at some pass-bands, 1.8, 4.0, and 10.2 GHz, where almost 100% transmittances could be obtained. It should be noted from Fig. 2(a) that two pass-bands appear at the very low frequencies (long wavelengths) of 1.8 and 4.0 GHz, respectively, indicating the unusual subwavelength transmission since the wavelength (~167 mm) of EM wave penetrated through layer A was more than one order of magnitude greater than the length of the longest slit (10 mm). This transmission can be attributed to local resonance occurring on the metallic plate wherein the subwavelength fractal slits are located periodically.

When combining layers A and B together, the ABA structure exhibits multiple transmission peaks which are located at right hand of the pass-bands of layer A, as shown in Fig. 2(a). The same phenomena occur for another polarization in Fig. 2(b). Actually, incident EM field excites currents in the metal lines of the fractal and the induced current flows toward higher levels of the fractal, therefore the amplitude reaches its maxima at those resonances for a certain line length. Since lengths of fractal with x and y polarization are different and thus results in the different frequencies of stop or pass-bands [16]. For both polarizations shown in Figs. 2(a) and 2(b), it can be observed that the transmission peaks for the ABA structure become broader but weaker with increasing frequency. Since layer C is an inverted version of layer A, it consequentially allows the microwave to pass through at most frequencies except for 1.3, 2.7, and 7.1GHz, showing three stop-bands in the measured frequency range. However, the structured CBC layers give rise to a transmission peak (~80%) at 2.5 GHz and a peak (~60%) around 5.0 GHz, respectively located at left hand of its corresponding stop-band of the bare layer C, as shown in Fig. 3(a). Accordingly, compared to the layer B alone, the introduction of either A or C layer significantly enhances the transmission of the opaque layer B at certain frequencies. It should be emphasized here is that ABA and CBC structures show
different transmission characteristics. For the former, the transmission peaks are located to the right of layer A’s *pass-bands*; while for the latter, the peaks are located to the left of layer C’s *stop-bands*.

Fig. 2. The normal transmission spectra of the layer A and B and the combining layer ABA measured under two polarizations ((a) for y-polarization and (b) for x-polarization). The vertical dot lines denote the corresponding of the transmission peaks of ABA to the pass bands of layer A.

Fig. 3. The normal transmission spectra of the layer C and B and the combining layer CBC measured under two polarizations ((a) for y-polarization and (b) for x-polarization). The vertical dot lines denote the corresponding of the transmission peaks of CBC to the stop bands of layer C.

In order to understand the mechanism why two structures demonstrate different transmission characteristics, the fractal pattern is reduced to an “H”, the simplest fractal version, and such structure is investigated experimentally and theoretically. The results are shown in Fig. 4(a) and 4(b) for the cases of H-slits and H-strips (metallic H). As the property of self-similarity is invalid in this simplified configuration, the H-slits and H-strips show only one pass-band and one stop-band respectively, it nevertheless agrees with our observation made in the 10-level fractal structures earlier that the transmission peaks are located to the right of the *pass-band* of the H-slits in the ABA sample, and to the left of the *stop-band* of the
H-strips in the \textit{CBC} sample. It should be pointed out here that in our measurement we observed (see Fig. 4) that the transmission magnitudes through the samples were larger than 1, which is probably due to the diffraction effect of the finite-sized samples. The experimental results also indicated that the frequency of transmittance of layer \textit{A} located at 4.386 GHz is equal to the reflectance of its complimentary layer \textit{C} appeared at 4.382 GHz with a 90° rotation of \textit{E}, which is agreement with Babinet’s principle.

Fig. 4. The measured (open symbols) and simulated (solid lines) normal transmissions of the individual layers and the composite layers for the simplified fractal—"H".

We performed the finite-difference time-domain (FDTD) simulation \cite{18}, where periodic boundary conditions were adopted and perfect conductor approximations, excellent for microwave frequencies, were applied to the metal/air interfaces. The simulation results for single \textit{A}, \textit{B}, and \textit{C} layers as well as \textit{ABA} and \textit{CBC} structures are also plotted in Figs. 4(a) and 4(b), respectively, which agree with the experimental results. After investigating the \textit{CBC} structure, it was found that the perfect transmission for the composite is located to the left side of the layer \textit{C}’s stop-bands where the electric resonance is induced and plays a key role in allowing the EM wave to tunnel through layer \textit{B} \cite{14}. Because layer \textit{A} is complementary to layer \textit{C}, its pass-band can be attributed to the excitation of a magnetic resonance with the
magnetic current induced in the slots, according to Babinet’s principle [19]. Therefore, it can be speculated that the change in nature of resonance from electric in the H-strips to magnetic in the H-slits causes the transmission peak of the composite to shift from the left side of layer C’s stop-band to the right side of layer A’s pass-band.

4. Conclusions

We measured the normal transmission of microwave through a subwavelength metallic mesh sandwiched either between two metallic plates with periodic fractal slots or with metallic fractals. Comparing to the spectrum of the metallic mesh alone, the layered structures exhibit multiple transmission peaks which appear near the bands of the sandwiching layers, either on the left or right side. The transmission enhancements are attributed to the local resonances induced in sandwiching layers. In addition, we observed from the experiments that the transmittance of $ABA$ or $CBC$ structures becomes weaker when the separation between $A(C)$ and $B$ layers decreases or increases to certain range which may be resulted from the decease of Q factor due to loss of EM field caused by the mismatch of sandwiched layers.

Acknowledgments

This work was supported by RGC Hong Kong research grants through Grant Nos. CA02/03.SC01 and 603603, respectively.