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Experimental demonstration of the enhanced transmission through circular and rectangular sub-wavelength apertures using omega-like split-ring resonators

Damla Ates [a,b,*], Filiberto Bilotti [c], Alessandro Toscano [c], Ekmel Ozbay [a,b]

[a] *Department of Electrical and Electronics Engineering, Nanotechnology Research Center, Bilkent University, 06800 Ankara, Turkey*
[b] *Department of Physics, Bilkent University, 06800 Ankara, Turkey*
[c] *"Roma Tre" University, Via della Vasca Navale, 84, 00146 Rome, Italy*

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Abstract

Enhanced transmission through circular and rectangular sub-wavelength apertures using omega-shaped split-ring resonator is numerically and experimentally demonstrated at microwave frequencies. We report a more than 150,000-fold enhancement through a deep sub-wavelength aperture drilled in a metallic screen. To the authors' best knowledge, this is the highest experimentally obtained enhancement factor reported in the literature. In the paper, we address also the origins and the physical reasons behind the enhancement results. Moreover, we report on the differences occurring when using circular, rectangular apertures as well as double-sided and single-sided omega-like split ring resonator structures.

Keywords: Electromagnetic wave transmission; Metamaterials; Resonators

1. Introduction

Recently, electromagnetic transmission through sub-wavelength apertures is receiving a growing interest in the scientific community, due to its potential applications in different scientific fields. Power transmission through electrically small apertures drilled in an opaque screen (e.g. a metallic screen at microwave frequencies) can be controlled in both intensity and frequency by properly designing the geometry of the aperture. Bethe has reported the relation between the transmission and the linear dimension (r) of the aperture compared to, the wavelength (λ) of the electromagnetic field impinging on the screen as $(r/\lambda)^4$ [1]. This means that, as expected from intuition, power transmission is extremely low when the apertures are characterized by deeply sub-wavelength dimensions. However, in several applications in science, such as high-capacity optical memories, high-resolution laser lithography, high-capacity optical switches, high-efficient and electrically small microwave aperture antennas, high-resolution microwave and optical imaging and screening systems, it is needed to extract even more power from electrically small apertures. In order to get the required transmission enhancement, different physical phenomena can be used.

The experiments have been conducted at optical frequencies, where researchers investigated the effects

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* Corresponding author at: Department of Electrical and Electronics Engineering, Nanotechnology Research Center, Bilkent University, 06800 Ankara, Turkey.
E-mail address: damla@ee.bilkent.edu.tr (D. Ates).

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on the transmission efficiency of surface plasmon polaritons excited on the metallic surface of the screens. Particularly, it has been demonstrated that the transmission through sub-wavelength apertures can be enhanced by using the surface plasmon polariton phenomenon [3,4].

Perturbing surface plasmon propagating on a metallic screen by the means of corrugations with proper periodicity surrounding the aperture [5,6], in fact, it is possible to couple the impinging electromagnetic wave with the surface plasmon polaritons and excite the aperture [7]. After Pendry and his colleagues have shown that surface plasmons not only exist in the optical regime but can also exist as spoof plasmons at microwave frequencies, enhanced transmission by periodic corrugations has been demonstrated also in the microwave regime [8,9].

When, metamaterials came into play, it has been demonstrated that enhanced transmission at microwave frequencies can be obtained by replacing corrugations around the aperture with proper metamaterial covers made of epsilon-near-zero or mu-near-zero materials [10,11]. A similar but more compact setup in terms of cover thickness has been also demonstrated, by using conjugate-matched layers of epsilon-negative and mu-negative metamaterials [12].

However, both the corrugation-based approach and the metamaterial approach, rely on the coupling between the impinging waves and propagating surface mode. This leads to an electrically large transverse extension of either corrugations or the cover around the aperture [13,14].

In order to overcome this limitation, another approach to the enhanced transmission has been presented by Aydin et al. and is based on the employment of a single ring resonator placed in front of the aperture [15,16]. Since the dimensions of the split ring resonator are comparable to the ones of the aperture, this setup is extremely compact. The experimentally achieved transmission at microwave frequencies demonstrated a 740-fold enhancement factor. Recently, Ates et al. have demonstrated that the transmission enhancement can be increase up to 70,000-fold (with the same dimensions of the screen and the same free-space measurement setup) by inserting connected split-ring resonators across the aperture [17]. The dramatic increase of the enhancement factor compared to the previous setup was due to: (a) the employment of a symmetric structure (i.e. one split-ring resonator at either side of the screen) and (b) the physical connection between the two split-ring resonators.

In this paper, we report further increased enhancement factors by using a different type of metamaterial resonator, such as the design of omega-like split-ring resonator. The design of omega particles has been first introduced by Saadoum and Engheta in 1992 in order to synthesize bi-anisotropic and ‘‘pseudo-chiral’’ artificial materials and then deeply investigated also by Tretyakov, Simovski and Sochova [18,19]. Recently, it has been demonstrated that omega-like inclusions can be successfully used to obtain also left-handed metamaterials. In this case, in order to eliminate the intrinsic chirality of the medium, two omega-like resonators are deposited in opposite directions on the two sides of a printed circuit board, leading to a low, moderate bandwidth left-handed material design [20,21]. Aydin et al. have also reported on the characteristics of such omega-like structures experimentally and numerically [22].

The advantages of using omega-like split-ring resonators instead of conventional split-ring resonators encouraged us to use such structures in the transmission enhancement experiments, in order to obtain better enhancement factors with respect to other reported results [15–17].

2. Omega-like split-ring resonator configurations

We connect together two omega shaped split-ring resonators through their arms and we obtain the particle depicted in Fig. 1(a). The samples are produced by printing two identical particles in opposite directions on the two sides of a 0.5 mm thick FR-4 dielectric board with 0.035 mm copper thickness as in Fig. 1(a) and (b). The dimensions of the geometrical parameters of the omega samples and metallic screen (see Fig. 1(a)) are $r = 3$ mm, $w = 1$ mm, $h = 7.5$ mm and $l = 4$ mm.

3. Experimental environment

In the experiments, two large copper screens with dimensions 700 mm × 700 mm × 0.5 mm were used. The first metallic screen had a circular aperture in the center with a radius of 3.75 mm, whereas the second metallic screen had a rectangular aperture with dimensions 3 mm × 7.5 mm. The omega samples are inserted across the apertures as shown in Fig. 1(c) and (d), respectively.

Transmission measurements have been conducted in free-space illuminating the screen by using the conventional waveguide antennas operating in the