Optical Implementation of a Miniaturized ENNZ-Metamaterial-Lined Aperture Array

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Aperture arrays have been used as frequency selective surfaces and to demonstrate extraordinary transmission, and have been proposed for a multitude of applications. The operation of these devices requires large areas as they depend on either aperture size or array periodicity, respectively, on the order of a wavelength. It has recently been demonstrated that lining each circular aperture in an array with a thin epsilon-negative and near-zero (ENNZ) metamaterial dramatically lowers its resonance frequency while the aperture itself remains largely empty, obviating the need for both large apertures and large aperture spacing. Thus, aperture-array-based devices could be miniaturized in the microwave regime (E. Baladi, J. G. Pollock, and A. K. Iyer, Opt. Express, vol. 23, no. 16, 2015).

In this work, we present an optical implementation of ENNZ-metamaterial-lined aperture arrays, simulated using COMSOL Multiphysics. Challenges in achieving an optical implementation included the reliance of the microwave design on lumped circuit elements and near-ideal conductor properties, which cannot be reproduced directly at optical frequencies. The proposed optical aperture array was designed to improve transmission at optical-telecommunications wavelengths of $\lambda = 1.55$ µm ($f = 193$ THz) through apertures of size $\lambda/5$ and spacing $\lambda/4$. First, an infinite unlined-aperture array was simulated as a control, then an infinite lined-aperture array was developed. The designed ENNZ metamaterial liner employs feature sizes below 10 nm, suggesting fabrication based on focused ion-beam lithography or a similar high-resolution technology. A gold metallization layer was modeled using a realistic lossy Drude permittivity response and lumped-circuit elements were replaced by printed plasmonic elements: thin wires for inductors and small gaps for capacitors. Finally, the substrate supporting the gold film was modelled as quartz due to its low optical loss.

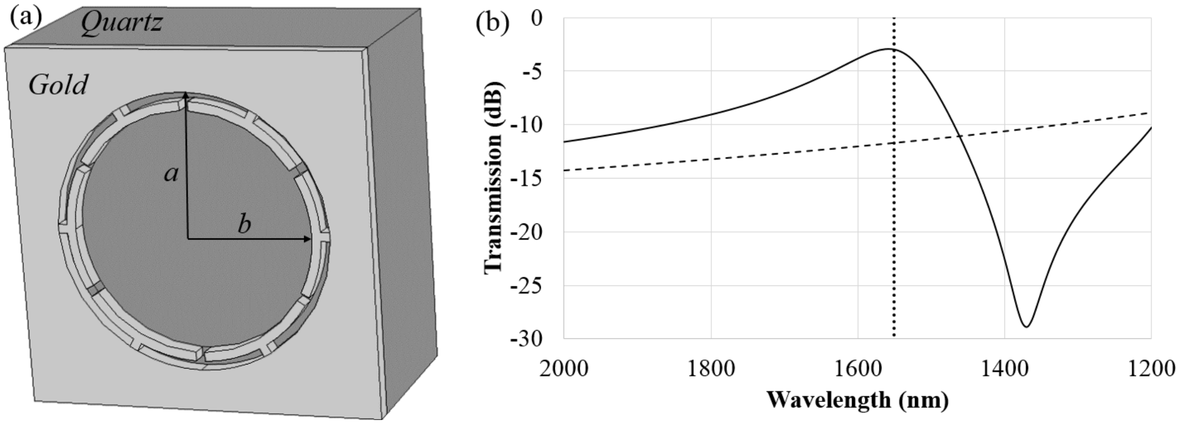

Figure 1: (a) Optical ENNZ-metamaterial-lined aperture unit cell. (b) Transmission spectrum of lined aperture array (solid) and unlined aperture array (dashed) in dB vs wavelength. 1.55 µm is denoted by a vertical line.

The final unit-cell design is shown in Fig. 1a. Important design parameters are as follows: a (outer aperture radius) = 154 nm = $\lambda/10$, b (inner aperture radius) = 134 nm = $\lambda/12$, and thickness of the liner region is 20 nm = $\lambda/78$. The light gray region denotes gold, where the small wires are 10 nm = $\lambda/155$ thick, and the capacitive gaps possess a width of 10 nm = $\lambda/155$. The dark gray region denotes quartz, and all other regions are vacuum. The gold film is 100 nm = $\lambda/16$ thick, and the array periodicity is 400 nm = $\lambda/4$. As shown in Fig. 1b, this design achieves an 8.7 dB transmission improvement over the unlined case at the operating wavelength (1.55 µm). We show that even further miniaturization of this optical implementation is possible, making it amenable to several applications in high-precision sensing, novel laser filters, beam splitters, and photonic switches.