SAND2013-0705C

# Epsilon-Near-Zero (ENZ) Subwavelength Optoelectronics: Electrically Tunable ENZ Strong Coupling

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**Abstract:** We demonstrate a new type of electrically tunable strong coupling between a planar metamaterial layer and an ultra-thin (~ 30 nm) epsilon-near-zero layer made of a doped semiconductor. This can find novel applications in chip-scale infrared optoelectronic devices.
**OCIS codes:** (160.3918) Metamaterials; (130.0250) Optoelectronics; (130.3120) Integrated optics devices.

Epsilon-near-zero (ENZ) materials have attracted great attention for their highly unusual optical properties. ENZ materials were employed for perfect coupling through a narrow channel [1, 2], optical switching and bistability [3], and directivity control of antennas [4]. It was also pointed out that a thin ENZ layer supports a new type of guided modes near the epsilon zero frequency ($\mathrm{Re}[\varepsilon(\omega)] = 0$) [5]. In this talk, we report a new type of optical strong coupling between a planar metamaterial (MM) layer and an ultra-thin doped semiconductor layer that works as an ENZ material in the infrared (IR) region. The ENZ frequency can be tuned in a wide range of IR frequencies by controlling the doping density. Furthermore, using our MM layer as an electrical metal gate, we deplete the doped semiconductor and electrically control the optical coupling between MM and ENZ layers.

Gold split ring resonator (SRR) arrays were patterned by electron beam lithography on a semiconductor substrate which includes a 30 nm $n^+$-doped GaAs layer ($N_D \sim 5.5 \times 10^{18}$ cm$^{-3}$). Figure 1a shows the schematic and dimension of the metamaterial sample. Incident light is polarized orthogonal to the gap to excite a SRR resonance. The resonantly excited SRRs provide strong normal electric field component, which is further intensified at the ENZ layer due to the boundary condition $\varepsilon_1 E_{1\perp} = \varepsilon_2 E_{2\perp}$. A series of SRR MMs with different scale factors were fabricated, so that the MM resonance frequency gradually shifted across the epsilon zero frequency (~ 780 cm$^{-1}$ for the given doping density, $N_D \sim 5.5 \times 10^{18}$ cm$^{-3}$). We performed Fourier transform infrared (FTIR) transmission measurements and observed clear anti-crossing behavior in the transmission spectra (Fig. 1b). When the MM resonance matched the ENZ frequency of the doped semiconductor layer, we could observe a clear spectral splitting (around Scale factor 1.6 in Fig. 1b). The obtained spectral splitting was as large as 200 cm$^{-1}$. This anti-crossing was also verified by numerical simulations (Fig. 1c).

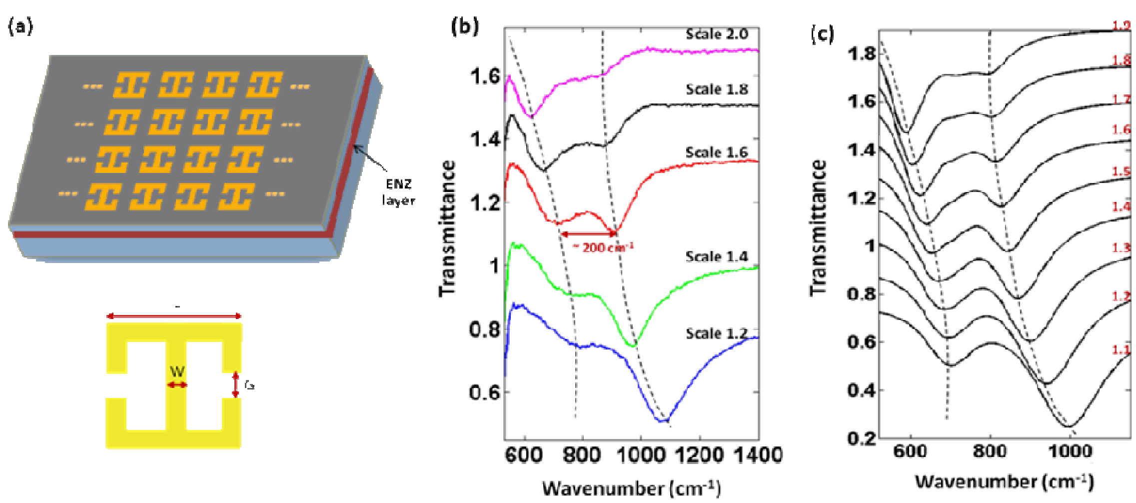


Fig. 1: Optical characterization of ENZ strong coupling. (a) Schematic of the sample. L = 720 nm, W = 130 nm, G = 110 nm, and the period is 1.4 µm for Scale factor 1. (b) FTIR transmission spectra for a series of SRR scale factors. (c) Numerical simulation of transmission spectra.

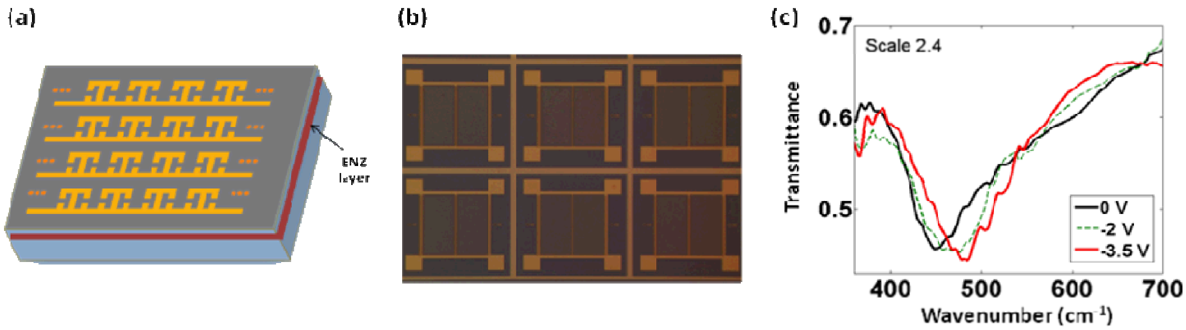


Fig. 2: Electrical tuning of ENZ strong coupling. (a) Schematic of the device. (b) Optical microscope image of the device. (c) FTIR transmission spectra with biasing.

This strong coupling can be tailored by adjusting growth conditions of the doped semiconductor layer, or by tuning carrier densities in the ENZ layer electrically. We used interconnected gold SRR arrays as an electrical metal contact and demonstrated dynamic tuning of optical coupling (Fig. 2a). Arrays of gold SRR metamaterials were patterned on a 30 nm n-doped GaAs layer ($N_D \sim 2.2 \times 10^{18}$ $cm^{-3}$). MM and ENZ layers are separated by a 30 nm $Al_{0.4}Ga_{0.6}As$ barrier layer. With a negative bias, we deplete the doped layer and effectively reduce the ENZ layer thickness. This weakens the coupling between MM and ENZ layers. Figure 2b shows the optical microscope image of the fabricated device. The MM layer is connected to the metal gate, and these are surrounded by the outer Ohmic contact which electrically contacts the bottom contact layer below the ENZ layer. We performed FTIR transmission measurements with voltage biases (Fig. 1c) and obtained clear electrical tuning of transmission spectrum. At zero bias, the spectrum was broadened in the region of 500 ~ 700 $cm^{-1}$ due to optical coupling (black curve). With negative biases, we depleted carriers and removed this coupling. Thus, the spectrum became more symmetric at -3.5 V (red curve). Leakage current was negligible during this biasing. The principle of operation of this new type of tunable metamaterial is fundamentally different from the early work reported on THz metamaterials, where the tuning was achieved by changing a local permittivity after depletion of carriers [6].

The IR spectral range is technologically important for a number of applications, including chemical/biological sensing, thermal imaging, and free-space optical communication. Therefore, we expect that this novel optical strong coupling and its electrical tuning can find exciting, new applications for chip-scale active IR devices.

**Acknowledgments**

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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