Epsilon-Near-Zero Subwavelength Optoelectronics

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Subwavelength optics has emerged as an important research field in optical science. Among its various topics, epsilon-near-zero (ENZ) materials have attracted great attention for their highly unusual optical properties. For example, ENZ materials were employed for perfect coupling through a narrow channel, optical switching and bistability, and directivity control of antennas [1-4]. More recently, it was also pointed out that a thin ENZ layer supports a new type of guided modes near the epsilon zero frequency (Re[ε(ω)] = 0), termed ENZ modes [5, 6]. Strong field enhancement in ENZ modes can be useful for enhancing light-matter interactions at the nanoscale. Here, utilizing strong field enhancement caused by these ENZ modes, we demonstrate a novel type of optical strong coupling between a planar metamaterial (MM) layer and ENZ modes in an ultra-thin doped semiconductor. The ENZ frequency can be tuned in a wide range of infrared (IR) frequencies by controlling the doping density. Furthermore, using the interconnected MM layer as an electrical metal gate, we deplete the doped semiconductor and electrically control the optical coupling between MM and ENZ layers. This work opens a path to a new type of IR optoelectronic devices based on ENZ materials of deep-subwavelength-scale thickness.

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 ~ 5.5 x 10^{18} cm^{-3}). Figure 1a shows the schematic and dimension of the MM 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 ε1E1┴ = ε2E2┴. A series of SRR MMs with different scale factors were fabricated, so that the MM resonance frequency gradually shifted across the epsilon zero frequency of the doped GaAs. We performed Fourier transform infrared (FTIR) transmission measurements at room temperature 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 (SRR Scale 1.6). 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. All measurements were performed at room temperature. (c) Numerical simulation of transmission spectra.
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 (Fig. 2a) and demonstrated dynamic tuning of optical coupling. Arrays of gold SRR MMs 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. 2c) 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 IR spectral range is technologically important for a number of applications, including chemical/biological sensing, thermal imaging, and free-space optical communication [7]. Therefore, we expect that this novel optical strong coupling and its electrical tuning can find exciting, new applications for chip-scale active IR devices.

![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. All measurements were performed at room temperature.](image)

References