

Tunable zero-index and metasurface optics in extreme optical platforms

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Abstract- We present our recent development on the use of tunable transparent conducting oxides to demonstrate electrically tunable epsilon-near-zero (ENZ) optical devices and to develop ENZ/metasurface nanostructured optical fibers.

Light harvesting and high-resolution optical technologies demand optical coatings with strong light absorption. Recent studies suggest that epsilon-near-zero (ENZ) materials can be useful to make perfect ultrathin film absorbers [1-3]. The ultrathin ENZ layers support radiative Berreman and bound ENZ modes [2, 4]. Excitation of these modes in two different incident light configurations leads to resonant absorption. In this work, a broadband perfect absorber has been demonstrated by using a stack of Transparent conducting oxide (TCO) nanolayers with gradually varying electron concentration and hence ENZ frequency. The light absorption dependence on the ENZ layer thickness in the multilayer stack was optimized so that absorption >95% was achieved at deep subwavelength ENZ thicknesses. Electronically tunable absorption via formation of electron accumulation/depletion layer in the field-effect devices was studied.

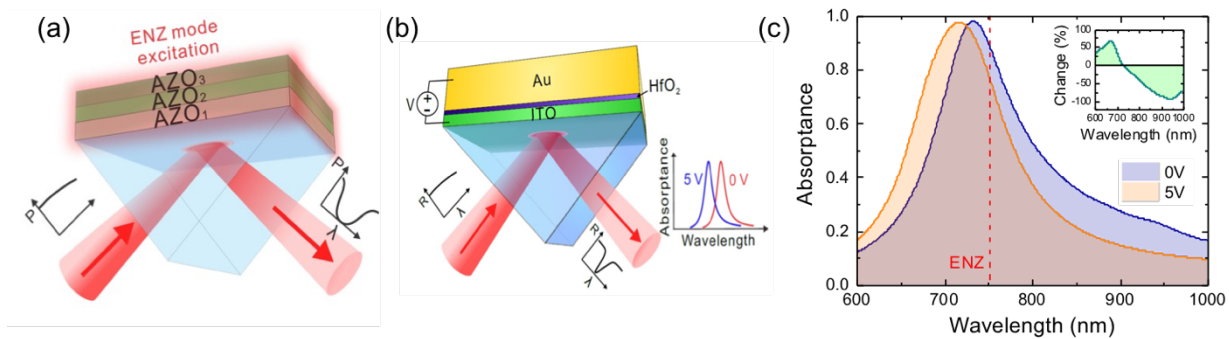


Fig.1 Schematic of (a) broadband and (b) field-effect tunable metal-oxide-semiconductor (MOS) ENZ perfect absorbers. Perfect absorption tuning: absorbance of the unbiased and 5V-biased MOS field-effect perfect absorber at the incidence angle of 60°.

The ENZ multilayers are composed of 3 AZO nanolayers (Fig. 1a). The optical properties of the AZO are modelled using free electron Drude model. We found that the highest absorption can be achieved with the AZO thickness of ~ 10-30 nm in the ENZ multilayers. The absorbance is attributed to the excitation of the radiative Berreman mode. The ENZ multilayer is supported by a thick gold reflector [5]. The electron concentration decreases, and ENZ wavelength increases, from the top to the bottom of the multilayer stack. Broadband maximum absorption >95% and field enhancement are observed at the ENZ wavelengths by exciting Berreman mode. Excitation of the bound ENZ mode in the Kretschmann-Raether configuration) results in resonant light absorption with much broader bandwidth than the

Berreman mode. The absorptance of $>95\%$ for more than 400 nm wavelength range is observed for the multilayer stack with 8-nm thin AZO layers [6].

Tunable absorption can be enabled by the field-effect dynamic in metal-oxide-semiconductor (MOS) configuration (Fig. 1b). The MOS device consists of a metal substrate, single 8-nm thin ITO layer, and 5-nm-thin HfO_2 layer between them. Electron accumulation occurs in ITO at the ITO- HfO_2 interface when bias is applied between metal and ITO, thus modifying the complex dielectric constant of the ITO. Electron accumulation increases plasma and ENZ frequency and therefore leads to a blue shift of the absorption peak in wavelength (Fig. 1c) [7]. The larger absorptance change ($> 300\%$) is observed at shorter wavelengths due to larger field enhancement in the accumulation layer. These results open the path to develop ultrathin tunable ENZ absorbers and thin-film modulators.

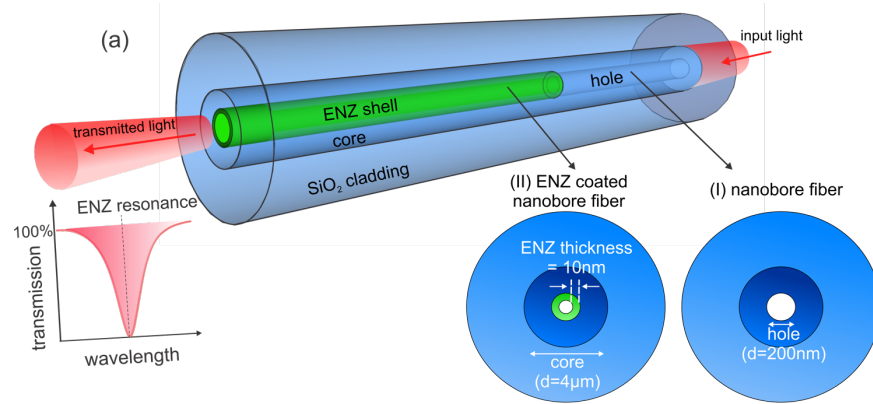


Fig.2. Schematic of the proposed ENZ fiber waveguide design. The inserts are cross-sections of the ENZ fiber (coated with ITO ENZ nano-shell) and hollow nanobore fiber (without ITO ENZ nano-shell).

We also report a novel optical waveguide design of a hollow step index fiber modified with a thin layer of indium tin oxide (ITO) (Fig. 2). We show an excitation of highly confined waveguide mode in the proposed fiber near the wavelength where permittivity of ITO approaches zero [8]. Due to the high field confinement within thin ITO shell inside the fiber, the ENZ mode can be characterized by a peak in modal loss of the hybrid waveguide. Our results show that such in-fiber excitation of ENZ mode is due to the coupling of the guided core mode to the thin-film ENZ mode. We also show that the phase matching wavelength, where the coupling takes place, varies depending on the refractive index of the constituents inside the central bore of the fiber. These ENZ nanostructured optical fibers have many potential applications, for example, in ENZ nonlinear and magneto-optics, as in-fiber wavelength-dependent filters, and as subwavelength fluid channel for optical and bio-photonics sensing.

Acknowledgement

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References

- [1] M. A. Badsha, Y. C. Jun, and C. K. Hwangbo, *Opt. Commun.* **332**, 206-213, 2014.
- [2] S. Campione, I. Kim, D. de Ceglia, G. A. Keeler, and T. S. Luk, *Opt. Express* **24**, 18782-18789, 2016.
- [3] J. Yoon, M. Zhou, M. A. Badsha, T. Y. Kim, Y. C. Jun, and C. K. Hwangbo, *Sci. Rep.* **5**, 12788, 2015.
- [4] S. Vassant, J.-P. Hugonin, F. Marquier, and J.-J. Greffet, *Opt. Express* **20**, 23971-23977, 2012.
- [5] A. Anopchenko, S. Gurung, L. Tao, C. Arndt, H. W. Lee, *Materials Research Express* **5**, 014012 (2018).

- [6] A. Anopchenko, L. Tao, C. Arndt, H. W. Lee, "Gate tunable and broadband Epsilon-near-zero perfect absorbers with deep subwavelength thickness," *ACS Photonics* (submitted) (2018).
- [7] Y. W. Huang *et al.*, "Gate-tunable conducting oxide metasurfaces," *Nano Lett.* **16**, 5319-5325, 2016.
- [8] K. Minn, A. Anopchenko, J. Yang, H. W. Lee, "Excitation of epsilon-near-zero resonance in ultra-thin indium tin oxide shell embedded nanostructured optical fiber," *Nature Scientific Reports* **8**, 2342(2018).