Active and Passive Metamaterials Research at CINT

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Scientific Thrust Area: Nanophotonics and Optical Nanomaterials

Research Achievement:

The recent discovery of metamaterials has led to the demonstration of unique optical behavior such as a negative index of refraction [1] and cloaking [2]. Metamaterials provide a new scale-invariant design paradigm to create functional materials thereby enhancing our ability to manipulate, control, and detect electromagnetic radiation.

This poster highlights some of the activity at CINT in the area of active and passive metamaterials both as internal CINT science that reaches into both National Laboratories and in collaboration with a number of users at several universities.

Passive Metamaterials:
Composite metamaterial elements with sub-wavelength scale ($\sim\lambda_0/10$), such as split ring resonators (SRRs), can be patterned in a periodic array to form metamaterials. Thus metamaterials can be considered as an effective medium and are well described by magnetic permeability $\mu(\omega)$ and/or electric permittivity $\varepsilon(\omega)$, Our early work concentrated on fundamental aspects of planar metamaterials and at Terahertz frequencies such as electrical resonator designs [3], demonstrations of complementary designs (Babinet's principle) in metamaterials [4], etc. Metamaterials however, offer new degrees of freedom that are not easily attainable through other approaches, such as large optical phase shifts and tunable resonators that can be designed throughout much of the infrared spectra. Recently, we have used taken advantage of the latter properties to design polarimetric components at terahertz frequencies [5]. We explored the sensor aspects of metamaterials by taking advantage of the sensitivity of metamaterial resonances to local changes in the dielectric environment [6]. For example, using appropriate linker molecules, planar metamaterials can be turned into protein sensors. Also, we investigated a number of approaches to improve the sensitivity of such sensors, for example, by fabricating samples on free standing sub-wavelength membranes [7].

Active Metamaterials:
Intentional modifications to the local dielectric environment of the subwavelength constituents of metamaterials allow for dynamic control of their transmission and reflection. For example, direct photoexcitation of carriers in planar metamaterials can provide an AC shunt to the small capacitive gaps in planar metamaterial designs and thus

decrease the resonance strength. This effect was demonstrated at THz frequencies in Ref. [8]. More recently, this was demonstrated also in the near IR using fishnet metamaterials with an amorphous silicon dielectric spacer, and fabricated using nanolithography. Using the latter scheme, we achieved sub-picosecond modulation speeds corresponding to data rates of Terabits per second.

A similar dynamic change can be obtained by fabricating metallic metamaterial samples on a doped semiconductor layer and utilizing the top metal as a Schottky gate. Upon reverse bias, carriers are depleted from the capacitive gaps and the metamaterial resonances appear in transmission. Removal of that bias causes the capacitive gaps to be shunted and then the resonance features disappear. This effect has been used to design amplitude [9,] and phase [10] modulators, and more recently multi-pixel spatial light modulators for IR beams.

Future Work

We will push the operating wavelength of active metamaterials to the mid and near IR. This will necessitate the use of nanolithography and the exploration of other semiconductors, metals and other types of conductors. Additionally, research into new schemes for 3D lithography of metamaterials are under way.

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References and Publications

1. J. B. Pendry, and D. R. Smith, "Reversing light with negative refraction," Physics Today **57**, 37-43 (2004).
2. D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," Science **314**, 977-980 (2006).
3. W. J. Padilla, M. T. Aronsson, C. Highstrete, M. Lee, A. J. Taylor, and R. D. Averitt, "Electrically resonant terahertz metamaterials: Theoretical and experimental investigations," Physical Review B **75**, - (2007).
4. H. T. Chen, J. F. O'Hara, A. J. Taylor, R. D. Averitt, C. Highstrete, M. Lee, and W. J. Padilla, "Complementary planar terahertz metamaterials," Optics Express **15**, 1084-1095 (2007).
5. X. G. Peralta, E. I. Smirnova, A. K. Azad, H. T. Chen, A. J. Taylor, I. Brener, and J. F. O'Hara, "Metamaterials for THz polarimetric devices," Optics Express **17**, 773-783 (2009).
6. J. F. O'Hara, R. Singh, I. Brener, E. Smirnova, J. G. Han, A. J. Taylor, and W. L. Zhang, "Thin-film sensing with planar terahertz metamaterials: sensitivity and limitations," Optics Express **16**, 1786-1795 (2008).
7. X. G. Peralta, C. L. Arrington, M. C. Wanke, I. Brener, J. D. Williams, E. Smirnova, A. J. Taylor, J. F. O'Hara, A. Strikwerda, R. D. Averitt, and W. J. Padilla, "Flexible, Large-Area Metamaterials Fabricated on Thin Silicon Nitride Membranes," 2008 Conference on Lasers and Electro-Optics & Quantum Electronics and Laser Science Conference, Vols 1-9, 314-315, 3638 (2008).
8. W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee, and R. D. Averitt, "Dynamical electric and magnetic metamaterial response at terahertz frequencies," Physical Review Letters **96**, - (2006).
9. H. T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," Nature **444**, 597-600 (2006).
10. H.T. Chen, W. J. Padilla, M. J. Cich, A. K. Azad, R. D. Averitt, and A. J. Taylor, "A metamaterial solid-state terahertz phase modulator," Nature Photonics **3**, 148-151 (2009).