Planar Wallpaper-Group Metamaterials Display Multiple Terahertz Resonances

Metamaterials—artificial structures with unusual properties—are aptly named (the Greek prefix “meta” means “beyond”). Although the recent upsurge in metamaterials research can be traced to several remarkable achievements, including the fabrication of materials with negative index of refraction, the demonstration of the “perfect lens” (capable of subwavelength focusing), and the demonstration of materials able to cloak themselves from interrogating light of a particular wavelength, the ultimate potential of metamaterials may lie in researchers’ ability to fabricate materials with exact magnetic and electric responses. One obstacle to metamaterials applications is that their electromagnetic responses are narrow band, typically less than 5%. Using designs found in nature to overcome this impediment, C.M. Bingham of Boston College, H. Tao and W.J. Padilla of Boston University, and their co-researchers recently proposed, simulated, fabricated, and characterized two-dimensional metamaterials that are based on planar wallpaper groups and are composed of multiple sublattice elements, each exhibiting a distinct resonant frequency in the terahertz range. The new metamaterials displayed a multifrequency response without significantly compromising the degree of the electromagnetic response.

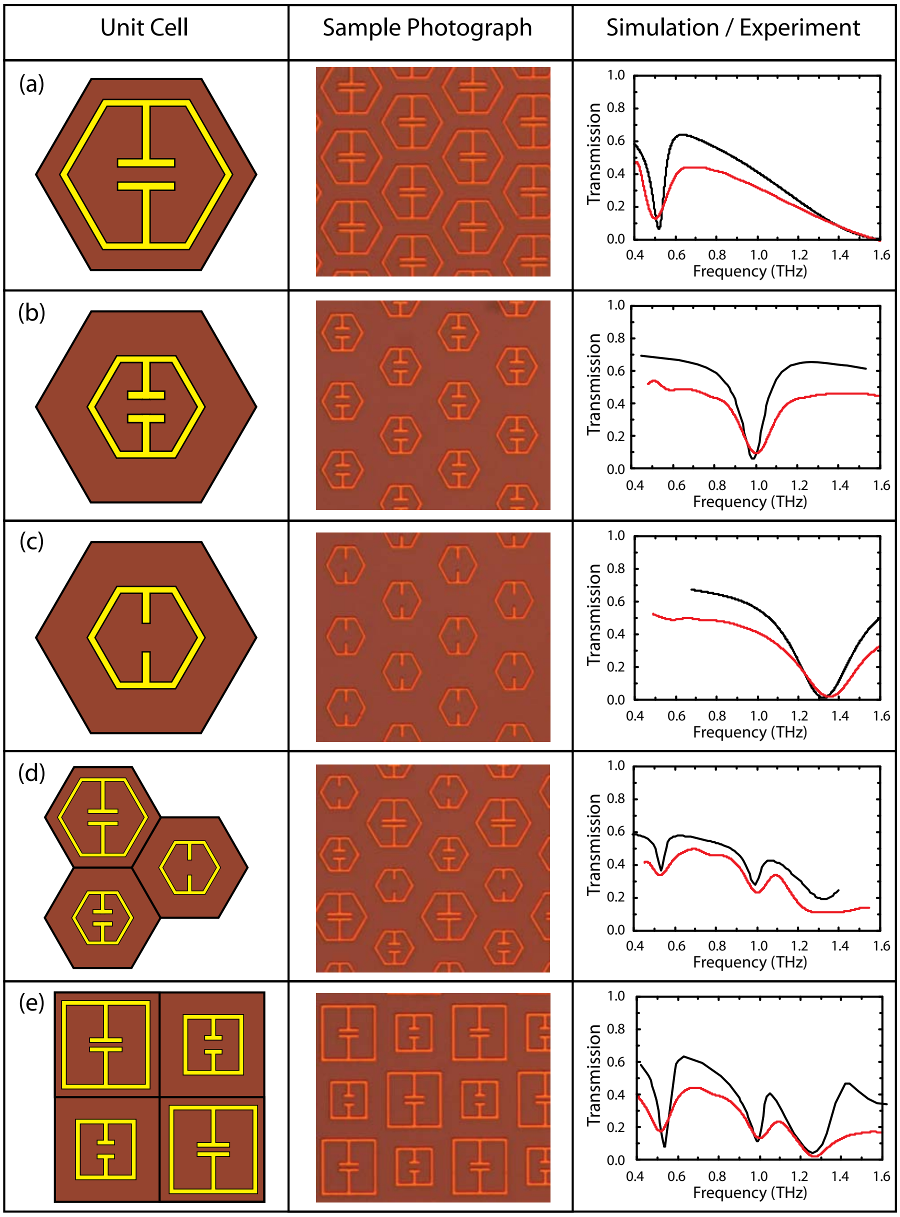

Figure 1. Simulation and experimental results of two-dimensional metamaterials composed of a 200-nm thick patterned layer of Au on a SI-GaAs wafer. The left column shows the unit cell models, the center column shows images taken of the fabricated samples, and the right column shows plots of simulated (black curve) and experimental (red curve) data. Reprinted with permission from *Optics Express* **16** (23) (2008) p. 18565. ©2008 by the Optical Society of America.

As reported in the November 10, 2008 issue of *Optics Express* (DOI: 10.1364/OE.16.018565; p. 18565), the researchers designed two-dimensional metamaterials computationally by using a commercial simulation package. A standard lift-off process was used to fabricate the metamaterials onto a semi-insulating (SI) GaAs wafer (see Figure 1) coated with hexamethyldisilazane to assist adhesion of photoresist. The wafer was spin-coated with photoresist, which was processed and then removed from the areas intended for metallization. The metallization was composed of a 200-nm thick patterned layer of Au on an adhesion layer of 10 nm of Ti. The metamaterials’ unit cells consisted of 1, 2, or 3 square or hexagonal primitive cells (the number of different primitive cells is given by n). The researchers selected specific sublattices with resonant responses of roughly 0.5 THz, 1 THz, and 1.25 THz, which coincide with the electromagnetic resonances of biotin, to investigate biodetector applications and electromagnetic mimicry. Metamaterials characterization was performed with Fourier transform infrared spectroscopy. The researchers achieved good agreement between experimental and simulated transmission for all metamaterials. The hexagonal metamaterial with $n = 3$ (Figure 1d) displays the same three resonant frequencies observed in the three different $n = 1$ metamaterials (Figure 1a–c), demonstrating that the combined metamaterial behaves as if it was a single-element structure over a specific frequency range.

The researchers also demonstrated the engineering versatility of their approach by designing an $n = 2$ metamaterial (composed of square primitive cells in a checkerboard pattern, see Figure 1e) that displays the same electromagnetic response as the hexagonal metamaterial with $n = 3$.

The researchers discussed several applications for their new metamaterials, including an identification method that involves detecting the sub- or superharmonic modes created upon excitation. The researchers said that “nonlinearities associated with overlapping resonant metamaterials and molecular responses, through engineering metamaterials to a bio or chemical hazard of interest, will provide an interesting approach beyond simple dielectric induced resonance shifts."

STEVEN TROHALAKI

Nonlinear Optical Mixing Enables Silicon-Chip-Based Ultrafast Oscilloscope with Sub-Picosecond Resolution

As high-speed optical communications and ultrafast science have pushed the envelope on the meaning of "fast," they have created a corresponding need for ultrafast measurement technologies. Techniques based on nonlinear optical mixing and repeated averaging can achieve very high time resolutions, but are not useful for measuring single, nonperiodic, or asynchronous optical events. Now A.L. Gaeta, M. Lipson, and colleagues at Cornell University have developed a device that may lead to a new class of ultrafast oscilloscopes based on nonlinear optical mixing in silicon. Their device has a resolution of 220 fs and a record length of 100 ps, and is fully compatible with complementary metal oxide semiconductor (CMOS) technology. They reported their results in the November 6, 2008 issue of *Nature* (DOI: 10.1038/nature07430; p. 81).

The research team's device uses the technique of time-to-frequency conversion, in which a quadratically varying phase shift is added to the optical signal to be measured. This phase shift causes the signal to evolve so that at a later period its amplitude in time is a scaled replica of its original frequency spectrum, and its frequency spectrum is a scaled replica of its original amplitude in time. The group accomplishes this phase shift addition by injecting the optical signal (centered at 1580 nm wavelength) into a 1.5-cm length nanoscale silicon-on-insulator waveguide (with a cross-sectional area of 300 nm by 750 nm) along with a suitably prepared pump signal wave. Four-wave mixing in the waveguide leads to a quadratic phase shift (or linear frequency shift) that is equivalent to 1 nm of wavelength shift for every 5.2 ps shift in time. After the waveguide and an appropriate signal propagation time, the signal spectrum is measured by an optical spectrometer, and the spectrum is scaled to obtain the original signal amplitude in time.

To characterize the device, the researchers first measured several 342-fs optical pulses with varying delays, determining that the device's record length is 100 ps and its inherent resolution is 220 fs. These limits are likely caused by high-order dispersion in the optical fibers carrying the signal and the performance of the spectrometer, and not by the four-wave mixing in the silicon waveguide. The researchers next measured several more complicated signals, and compared the results with measurements of the same signals using an average of many conventional cross-correlation measurements. The results clearly demonstrate the accuracy of the device and its ability to maintain a long (100 ps) record with high time resolution in a single shot.

According to the researchers, the use of dispersion-flattened fiber or dispersion-engineered waveguides may enable sub-100-fs resolution, and the technique can be used with other CMOS-compatible waveguiding materials such as SiN or SiON. Additionally, the individual components of the device are all the subject of extensive current research in photonics, suggesting that it may soon be possible to integrate the entire device on a chip. If that is correct, both telecommunications engineers and ultrafast scientists may one day think of bulky, super-picosecond oscilloscopes as a thing of the past.

COLIN MCCORMICK

Spin-Echo Technique in Nitrogen-Vacancy Diamond Impurities Enables Nanoscale Magnetic Sensing

The ability to detect extremely weak magnetic fields at short distances would enable important applications in a wide range of fields, from probing individual nuclear spins in complex biological molecules to storing and controlling quantum information encoded in electronic or nuclear spins. In pursuit of this ability, researchers M.D. Lukin and A. Yacoby of Harvard University, R.L. Walsworth of Harvard and the Harvard-Smithsonian Center for Astrophysics, J.S. Hodges of Harvard and the Massachusetts Institute of Technology, J.M. Taylor of the Massachusetts Institute of Technology, M.V.G. Dutt of the University of Pittsburgh, and their colleagues have demonstrated the use of coherent control of an individual electronic spin in nitrogen-vacancy diamond impurities to detect magnetic fields at the nano-Tesla level. In combination with diamond nanocrystals, this technique may lead to a new class of sensitive, extremely short-range magnetic sensors.

Electronic spin in nitrogen-vacancy (NV) impurities in diamond has been extensively studied as a candidate quantum bit because of its relative isolation from environmental effects that would cause quantum decoherence. Since ^{12}C has no nuclear magnetic moment, the primary source of local magnetic field for NV impurities comes from the nuclear spin of the small number (roughly 1% isotopic abundance) of ^{13}C atoms in the diamond lattice. As reported in October 2, 2008 issue of *Nature* (DOI: 10.1038/nature07279; p. 644), the researchers used a standard spin-echo technique to manipulate the electronic spin of a single NV impurity in a bulk, ultra-pure diamond sample. By matching the length of the spin-echo sequence to the period of the Larmor precession of the ^{13}C nuclei caused by an external dc magnetic field, the researchers were able to decouple the NV electronic spin from the nuclear magnetic field, and obtain strong spin-echo signals at times exceeding 0.5 ms. They then imposed a weak (~100 nT) ac magnetic field on the sample, and observed a sinusoidal variation of the decoupled spin-echo signal as a function of the ac field strength, caused by the accumulation of additional magnetic-precession phase from the time-varying Zeeman shift of the NV electronic spin during the spin-echo sequence. The system achieved a resolution of a few nano-Teslas for a 3.2-kHz ac magnetic field after 100 s of averaging, limited by the photon shot noise in the optical readout of the spin-echo signal.

The researchers also conducted a similar experiment using NV impurities in 30-nm-diameter diamond nanocrystals. These samples contained more spin impurities, leading to a shorter spin-coherence time (4–10 μs), and the technique displayed a sensitivity of 0.5 $\mu T\ Hz^{-1/2}$ for a field at 380 kHz. A higher sample purity and higher efficiency optical detection would likely improve this sensitivity significantly. In related work, a group at Stuttgart and Texas A&M Universities led by F. Jelezko, P. Hemmer, and J. Wrachtrup has used diamond nanocrystals to create a scanning magnetic-field sensor. In combination, these results may soon enable an extremely short-range (~10 nm), high-sensitivity (~1 nT) magnetic field sensor, with important applications in fields ranging from molecular biology to quantum information.

COLIN MCCORMICK

Silicon Nitride Membrane Dynamic Masking Allows Improved Shapes of Near-Field Optical Apertures Fabricated by FIB

Plasmonic devices structured on the scale of tens of nanometers for applications in optical interconnects, data storage, near-field lithography, and bio-sensors are often produced by directly milling the metal surface with a focused ion beam (FIB) (direct metal milling, DMM). However, obtaining high-quality structures by using this technique is difficult, as the ion beam's