Daniel Mittleman  
is in the Department of Electrical and Computer  
Engineering, Rice University, MS-366, 6100 Main  
Street, Houston, Texas 77005, USA.  
e-mail: daniel@rice.edu

Metamaterials — engineered  
composite materials with unique  
optical properties — have  
become one of the hot topics of photonics  
research in the past few years. By cleverly  
designing and assembling an array of  
subwavelength metallic structures, it is  
possible to construct a composite material  
with optical properties that cannot be  
found in nature. As the metallic structures  
are much smaller than the wavelength  
of the incident radiation, the composite  
material behaves as if it were a continuous  
dielectric but with uniquely engineered  
properties, such as a sharp resonance at a  
chosen frequency.

To a certain extent, this idea is not a  
new one. After all, the inductor–capacitor  
circuit in a radio tuner has a resonance at  
a wavelength that is much larger than the  
size of the circuit. Adopting this idea from  
the radiofrequency domain into the world  
of optics has produced a host of exciting  
phenomena, including negative refraction,  
perfect lensing and cloaking. However, as  
in a radio, the ability to tune the resonance  
is extremely valuable.

On page 295 of this issue,  
Hou-Tong Chen and colleagues describe an  
approach for tuning the resonant response  
of a metamaterial designed to operate  
in the terahertz region of the spectrum.  
The present work continues the authors’  
previous research into the development  
of active terahertz components that  
have a controllable response. Now, they show  
that it is possible to use a light beam to  
tune the resonance frequency of a specially  
designed metamaterial operating in the  
terahertz region. The results represent an  
important step towards the development  
of frequency-agile or broadband  
metamaterial devices.

Indeed, one of the main motivations  
for this research is the growing interest  
in active devices for the control of  
terahertz radiation. This long-neglected  
portion of the spectrum has recently  
attracted a great deal of attention,  
but still lags behind in the range of  
devices and components that are  
available for manipulating beams. In  
particular, convenient tunable filters that  
operate in the terahertz region are not  
readily available.

The field of metamaterial research was  
initiated in the late 1990s by John Pendry,  
who showed that assembling an array of  
appropriately designed subwavelength  
metallic structures can produce a  
material that has a resonant response in  
either the dielectric permittivity, \( \varepsilon \), or  
the magnetic permeability, \( \mu \), or both.  
This is interesting because it can give  
rise to materials with a narrow range of  
frequencies where \( \varepsilon \) or \( \mu \) falls below zero.  
Materials with a resonance in \( \varepsilon \) are fairly  
straightforward — for all metals \( \varepsilon \) is  
less than zero at frequencies below the  
plasma frequency. A resonant magnetic  
response does not occur in any natural  
material, but can be accomplished using a  
metal split-ring resonator with a gap that  
acts as a capacitor, so that over a narrow  
frequency range \( \mu \) has a negative value.

The split-ring resonator concept  
is significant for several reasons. It  
provides a material with a negative \( \mu \),  
and thus opens up a completely new  
realm for light–matter interactions. More  
generally, it represents a new technique  
for designing the optical response of a  
medium by simply varying the shape, size  
and orientation of the metallic structures.

For a given design of the  
subwavelength metallic structures, the  
metamaterial has an optical response  
that is a resonant line shape centred at a  
fixed frequency. As a result, the interesting
optical effects are usually only observed over a fairly narrow range of frequencies. The range cannot be adjusted or tuned and a new sample has to be fabricated if effects at other frequencies are desired. Essentially all of the interesting effects achieved with metamaterials so far, such as negative refraction\(^7\) and cloaking\(^8\) at microwave frequencies, and negative group and phase velocity in the infrared region\(^9\), have been limited to a fixed and relatively narrow spectral bandwidth.

Hou-Tong Chen and co-workers have overcome this limitation using a clever metamaterial design, which allows the resonant response to be tuned by a near-infrared light beam. They have constructed a planar metamaterial consisting of a two-dimensional array of split rings on a silicon–on–insulator substrate. They selectively remove the silicon by etching, leaving just a thin silicon layer in two strips within each split-ring resonator (see Fig. 1). These two strips form the two plates of a capacitor. The mechanism of the tuning is that when a near-infrared laser pulse illuminates the entire array, it modifies the conductivity of the exposed silicon through photoexcitation of charge carriers. This changes the effective capacitance of all of the split rings simultaneously, and consequently shifts the resonant frequency of the material.

For initial tests, the results are impressive. The authors show that the resonance (initially at 1.06 THz) broadens with little shift when the photoexcitation is weak, but that a pronounced redshift of the resonance of about 20\% can be obtained under a stronger photoexcitation. Interestingly, at the highest excitation level, the charge density in the silicon is high enough to mimic metallic behaviour, which lowers the damping. As a result, the resonance narrows again, but it remains centred at the lower frequency. This behaviour is reproduced by a detailed finite-element simulation. Chen \textit{et al.} have also performed simulations on two other types of array element, where photoexcitation of the silicon is used to modify the inductance of the ring rather than the capacitance. Using this approach, they show that they can shift the resonant response to a higher frequency rather than to a lower frequency, on photoexcitation.

Despite the significance of these results, several important challenges and open questions remain to be addressed. Various parameters need to be investigated, such as the degree of tuning, the depth of modulation, and optimization of the resonance line width. If this device were to be used as a dynamic modulator, its maximum modulation rate is unknown. This rate could possibly be influenced, to some degree, by ion implantation in the active silicon region, but this idea is yet to be investigated. Also, the ability to tune the resonance using an electrical approach rather than an optical approach would be extremely useful\(^6\). And, of course, the idea of scaling these effects to infrared or optical frequencies is appealing. This work opens up a rich new area of study in the field of active terahertz devices.

**References**


---

**QUANTUM OPTICS**

**Beyond single-photon counting**

The ability to distinguish how many photons comprise a particular state of light leads to significant benefits in practical quantum information processing and quantum cryptography. Superconducting nanostructures provide an effective solution at telecom wavelengths.

Alexander V. Sergienko

is in the Department of Electrical & Computer Engineering and the Department of Physics, Boston University, 8 Saint Mary’s Street, Boston, Massachusetts 02215-2421, USA. e-mail: alexserg@bu.edu

Optical quantum information processing is at the frontier of modern physics and optics. It is a topic that relies heavily on manipulating single-photon states: exciting experimental applications, such as quantum cryptography, entanglement swapping and quantum-state teleportation, would be impossible without single-photon-counting detectors\(^1\). The most critical parameters that must be considered when designing such detectors are high speed, low noise and high quantum efficiency; a poor-quality single-photon detector has a deleterious effect on the fidelity of the quantum-state manipulation. On page 302 of this issue\(^2\), Aleksander Divochiy and an international team of researchers working on the European collaborative project SINPHONIA has demonstrated a detector capable of counting the number of photons in an optical state at telecom wavelengths — achieving so-called photon-number resolution (PNR). The integrated, parallel, multisection device combines their expertise in creating superconducting single-photon detectors (SSPDs) based on NbN nanowires with modern technological advances in nanoscale lithography.

The problem of detecting single photons and evaluating their statistical behaviour was brought to the forefront of physics about 50 years ago by the famous Hanbury Brown and Twiss experiment\(^3\). This demonstration of the non-classical properties of light gave rise to the field of quantum optics. However, it would have been impossible without single-photon-counting detectors, which can convert the energy of a single incident quantum of light into a macroscopically detectable pulse of voltage or current. Photomultiplier tubes (PMT) are one example of a single-photon-counting detector. Initially developed for the purpose of counting high-energy quanta in nuclear physics, they have found their way into optical applications.

---

© 2008 Nature Publishing Group