Metamaterials for Active Photonics and Energy Conversion

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Abstract

Metamaterials have compelling potential applications in active photonics and solar energy conversion. Highly compliant substrates allow generation of actively tunable metamaterials based on split ring resonators with frequency tunability over several resonant linewidths, and applications in sensing and spectroscopy. Metamaterials can also enable control of light-matter interactions in solar energy conversion, leading to enhanced light-trapping and absorption, as well as increased open circuit voltage and enhanced quantum efficiency in solar photovoltaic structures.

1. Greater-than-Linewidth Active Tuning in Photonic Metamaterials

Metamaterials are artificially engineered composites that exhibit optical responses that are not typically found in nature[1-2], such as super-lensing[3-4], and cloaking[5-6]. With few exceptions[7-12] , most metamaterial designs have been limited to operation over a fixed, narrow bandwidth dictated by the dimensions of the constitutive resonator elements and the dielectric environment of the host medium. Extending the operation wavelength of optical frequency metamaterials by tuning the resonance frequency over a broader range is desirable for active optical devices such as filters, modulators, and sensors. To date, frequency tuning of optical metamaterials has been limited to a narrow ranges[8-9,12] and a wide tunability has not yet been achieved at optical frequencies due to limitations in the material properties of the active materials used. Here, we discuss frequency tunable metamaterials with greater-than-line-width tunability (~400 nm) in the 2 – 5 µm range, using the mechanical deformation of an elastomeric substrate to modify the distance between resonant elements thus changing the coupling strength. Surprisingly, coupled split ring resonator arrays subjected to tensile strains as high as 50% can be reproducibly strained without plastic deformation of the metallic resonator elements. We also demonstrate that our compliant optical metamaterial can be used to perform tunable surface-enhanced infrared absorption by tuning the metamaterial resonant frequency through a molecular vibrational mode at infrared wavelengths, enhancing the infrared reflection signal from the vibrational mode by a factor of almost 200.

Metamaterials are usually designed as arrays of individual unit cells much smaller than the operating wavelength. The response of the bulk material to the incident electromagnetic wave can be engineered by careful manipulation of the size, pattern, and composition of the metamaterial elements. However, this response is usually fixed at the time of fabrication yielding materials that are essentially "passive" and operate over a limited bandwidth. The response of otherwise "passive" metamaterials can be rendered active by integrating dynamic components into the unit cell design. Resonant amplitude modulation has been achieved via carrier injection in semiconductor substrates[7] or mechanical reorientation of resonant elements using microlectromechanical systems[10]. These approaches modulate the intensity of the response at the resonance wavelength simply by turning the resonance on and off. On the other hand, frequency tunability has been demonstrated by changing the dielectric environment of the resonator with phase-transition materials[9,11], liquid crystals[12],and optical pumping[8]. Here we take a different approach by exploiting the elasticity of a compliant polymeric substrate to tune the resonant frequency of a planar metamaterial in the near infrared by changing the distances and thus coupling

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strength between pairs of resonator elements. Stretchable electronics have recently garnered increasing interest[13], however mechanical deformation of elastomeric substrates to tune the resonance wavelengths of nanophotonic structures has been used to induce spectral shifts for nanoparticle dimer extinction [14] and gratings[15] but the reported tunability range was limited. Our results demonstrate broad tunability of metamaterials by the elastic and plastic deformation of compliant substrates.

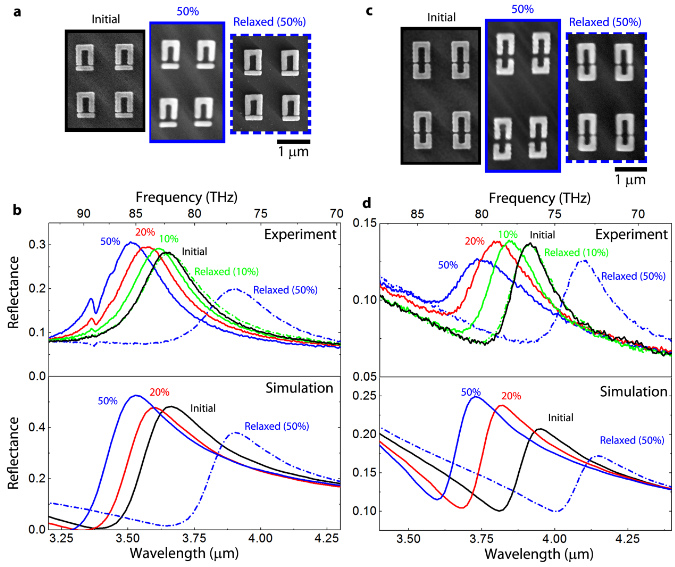

Figure 1. Reflectance measurements of stretchable metamaterials – arrays of SRR-bar structures and ACSRRs. **a.** ESEM images of an array of 2x2 SRR-bar unit cells initially, relaxed, and under 50% strain. **b.** The experimental FTIR reflectance data for an array of SRR-bar structures under applied strains of up to 50% are shown in the top panel and the corresponding simulated reflectance data are shown in the bottom panel. **c.** ESEM images of an array of 2x2 ACSRR unit cells initially, relaxed, and under 50% strain. **d.** The experimental FTIR reflectance data for an array of ACSRRs under applied strains of up to 50% are shown in the top panel and the corresponding simulated reflectance data are shown in the bottom panel.

2. Light Trapping and Spectrum Splitting Metamaterials for Photovoltaics

Conventionally, photovoltaic cells have a physical thickness comparable to their 'optical thickness' for full light absorption and photocarrier current collection. Solar cell design and material synthesis considerations are strongly dictated by this simple optical thickness requirement. Dramatically reducing the absorber layer thickness or volume confers several fundamental and practical benefits, including increased open circuit voltage and conversion efficiency, and also expansion of the scope and quality of absorber materials that are suitable for photovoltaics. Light absorption in thin film and wire array solar cells enable enhanced absorption and photocurrent compared with conventional photovoltaic cells, and limits to enhanced absorption will be explored. Plasmonics and metamaterials designs can also be exploited advantageously in photovoltaics to increase the photocurrent and open-circuit voltage. We describe metamaterial thin film photovoltaic designs for light absorption and conversion efficiency that exceed what is achievable in conventional solar cell designs, and we report on experiments illustrating enhanced light absorption and in turn the photocurrent in thin film Si and GaAs and polymeric photovoltaic structures[13]. We also describe design approaches using metallic nanostructures to enhance the radiative emission rate and hence also the effective photovoltaic material quantum efficiency relative to conventional light-trapping structures, which in turn leads to increased open-circuit voltage. Finally, future designs of metamaterials for broadband resonant absorption and spectrum-splitting will be discussed.

Thermodynamic arguments predict the maximum absorption enhancement in the ray optics limit for bulk dielectric materials to be $4n^2$, where n is the index of refraction of the absorbing layer [14] and a similar analysis for thin waveguide structures found a maximum absorption enhancement of $<4n^2$ [15]. Using a combination of analytical and numerical methods, we describe why these structures do not surpass the conventional light trapping limit, and show how to design structures that can. The conventional limit can be exceeded in waveguide-like structures with elevated local density of optical states (LDOS) compared to that of the bulk, homogeneous material. To achieve this, modes of the structure must also be populated via an appropriate incoupling mechanism. We find using full wave simulations that ultrathin solar cells incorporating an artificially-structured back reflector can achieve spatially averaged LDOS enhancements of 1 to 3, and a metal-insulator-metal (MIM) structure can

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achieve enhancements over 50 at a wavelength of 1100 nm, the band edge of Si. We also report in detail on plasmon-enhanced light trapping in thin film amorphous silicon solar cells that achieve near-record photovoltaic conversion efficiency.
Resonant guided wave networks (RGWNs) were recently reported as a new class of artificial material [8] where localized waves resonate in closed paths throughout a network of isolated waveguides connected by wave splitting elements. The resulting multiple resonances within the network give rise to wave dispersion that is sensitive, and thus tunable, according to the network layout. Here we utilize these RGWNs properties to design photonic components for spectrum splitting, as illustrated in Fig. 2.

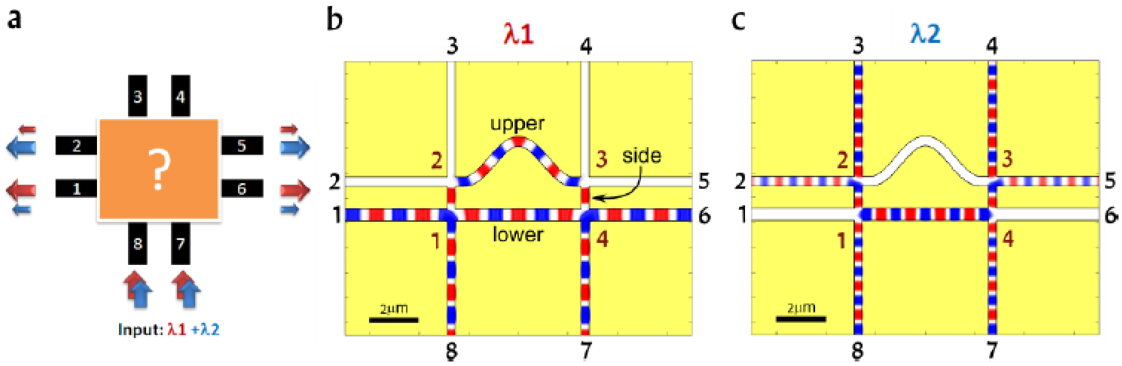

Figure 2. 2x2 RGWN programmed to function as a dichroic router: (a) schematic drawing, and snapshots of the H-field at the two operation frequencies: (b) λ_1 = 2000 nm and (c) λ_2 = 1260 nm.

Overall, we find many opportunities for controlling optical dispersion and power flow in metamaterials designed for solar energy conversion. These opportunities include solar spectrum splitting and exceeding the previously anticipated intensity enhancement and light trapping factor in dispersive dielectric and metallodielectric photovoltaic structures. These results can guide future solar cell designs that incorporate dispersive dielectric structures, plasmonics and metamaterials to achieve unprecedented light trapping and increases in conversion efficiency.

References

[1] Shalaev, V. M. Optical negative-index metamaterials. *Nat Photonics* **1**, 41-48 (2007).
[2] Smith, D. R., Pendry, J. B. & Wiltshire, M. C. K. Metamaterials and negative refractive index. *Science* **305**, 788-792 (2004).
[3] Pendry, J. B. Negative Refraction Makes a Perfect Lens. *Phys Rev Lett* **85**, 3966 (2000).
[4] Zhang, X. & Liu, Z. Superlenses to overcome the diffraction limit. *Nat Mater* **7**, 435-441 (2008).
[5] Cai, W. S., Chettiar, U. K., Kildishev, A. V. & Shalaev, V. M. Optical cloaking with metamaterials. *Nat Photonics* **1**, 224-227, doi:DOI 10.1038/nphoton.2007.28 (2007).
[6] Valentine, J., Li, J., Zentgraf, T., Bartal, G. & Zhang, X. An optical cloak made of dielectrics. *Nat Mater* **8**, 568-571 (2009).
[7] Chen, H.-T. *et al.* Active terahertz metamaterial devices. *Nature* **444**, 597-600 (2006).
[8] Chen, H. T. *et al.* Experimental demonstration of frequency-agile terahertz metamaterials. *Nat Photonics* **2**, 295-298, doi:DOI 10.1038/nphoton.2008.52 (2008).
[9] Dicken, M. J. *et al.* Frequency tunable near-infrared metamaterials based on VO2 phase transition. *Opt. Express* **17**, 18330-18339 (2009).
[10]Tao, H. *et al.* Reconfigurable Terahertz Metamaterials. *Phys Rev Lett* **103**, 147401 (2009).
[11]Samson, Z. L. *et al.* Metamaterial electro-optic switch of nanoscale thickness. *Appl Phys Lett* **96**, -, doi:Artn 143105 Doi 10.1063/1.3355544 (2010).
[12]Xiao, S. M. *et al.* Tunable magnetic response of metamaterials. *Appl Phys Lett* **95** (2009).
[13]H.A. Atwater and A. Polman, Nature Materials, **9** pp 205-213 (2010).
[14] Yablonovitch and Cody. IEEE Trans. Elect. Dev. **29** 300 (1982).
[15] Stuart and Hall J. Opt. Soc. Am A **14** 3001 (1997).
[16] E. Feigenbaum, and H. A. Atwater, Phys. Rev. Lett. **104**(14), 147402 (2010).