room temperature radiates 460 W. Earth-based powerful mid-infrared sources can be used for nighttime powering of airborne platforms.

All these applications would benefit from the following components: (a) perfect absorbers of infrared radiation that can be installed on the receiving platforms, (b) efficient sources of thermal mid-infrared radiation. These two components are related to each other. Therefore, developing an ultra-thin perfect absorber of infrared radiation would be highly desirable. The ultra-thin aspect is important because it enhances the radiation-to-electricity conversion efficiency. For example, it is well known that carrier separation-collection efficiency in a solar cell improves as the cell gets thinner. The challenge is to combine this carrier separation-collection efficiency with sufficient absorption. Unfortunately, the absorption length of many semiconductors in the infrared is fairly small. Recent experiments provide the new metamaterials-based concept for increasing the absorptivity of otherwise semi-transparent materials. Below some of the (still unpublished) experiments and theoretical developments that might result in new metamaterials-based perfect absorbers are described.

Figure 20 (left) indicates a very instructive experimental result: reflectivity R from an ultra-thin (500 nm) SiC film backed up by a metal mirror. At $\omega = 762\ \mathrm{cm}^{-1}$ (or λ = 13.1 μm) reflectivity from the structure is less than 3 percent. That implies 97 percent absorption in a film of thickness $d = \lambda/25$. This remarkable absorptivity can be explained using the well-known microwave concept: the Salisbury screen. It turns out that at λ = 13.1 μm film thickness is $d = \lambda/4n$, where $n = n_{re} + in_{im}$ is the complex refractive index of SiC. A simple formula for the reflectivity from a metal-backed thin film can be derived:

$$R = \left| \frac{r_0 - e^{2i\delta}}{1 - r_0 e^{2i\delta}} \right|^2 \qquad (5)$$

where $r_0 = \dfrac{n-1}{n+1}$ is the reflection coefficient from the air/SiC interface and $\delta = nk_0 d$ is the complex phase shift across the film which includes losses. Fixing the laser frequency $\omega = ck_0$ and the sample's thickness d , we can plot the reflectivity as a function of $re(n)$ and $im(n)$. As can be clearly seen from Figure 20 (right), there is a "sweet spot" corresponding to specific values of $re(n)$ and $im(n)$ that results in vanishing reflectivity (or perfect absorption). R vanishes when the quarter-wavelength condition is approximately satisfied:

$$re(n)k_0 d = (2m+1)/2 \qquad (6)$$

where m is an integer. Finite reflection and imperfect absorption result from lower (or higher) values of $im(n)$. Note that, coincidentally, for the case of heavily doped SiC predicted reflection is only 3 percent. However, for most materials (that is, Si for visible light) absorption is too low for perfect absorption. Therefore, a question is posed: Can one modify the structure of the metal screen to enhance absorption? It is CMMs that enable such functionality?

Specifically, it has been found that by making the mirror slightly leaky, we can actually increase absorption. If the reflection coefficient of a mirror is given by r_2, then the reflection/transmission coefficients r, t through the structure are given by:

$$r = \frac{r_0 + r_2 e^{2i\delta}}{1 + r_0 r_2 e^{2i\delta}}, t = \frac{t_0 t_2 e^{i\delta}}{1 + r_0 r_2 e^{2i\delta}} \quad (7)$$

where $t_2 = 1 + r_2$ and $t_0 = 1 + r_0$. Note that Equation 7 turns into Equation 6 if $r_2 = -1$ (perfectly reflecting mirror). From Equation 7 it follows that it may be possible to engineer the reflectivity r_2 in such a way that minimizes reflection $|r|^2$ while keeping transmission $|t|^2$ small. The remainder of the energy is guaranteed to be absorbed by the quarter-wavelength thick absorber.

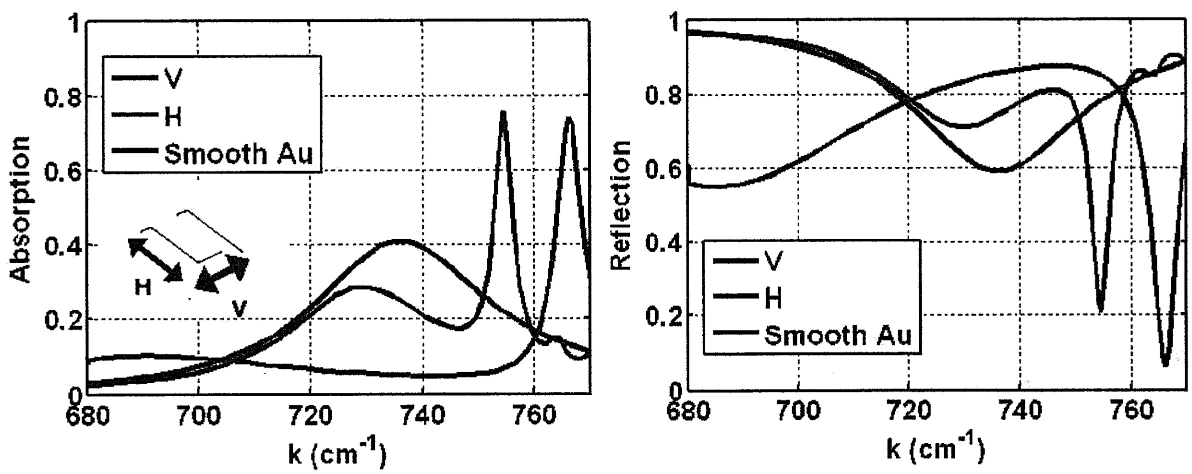

Figure 22. Preliminary Attempts to Design a Better Absorber Using Complementary MetaMaterials (U-shaped CMM). Note that only 40 percent absorptivity is possible with a smooth gold film. Paradoxically, this absorptivity increases to 75 percent when the metal mirror is made "leaky" by perforating it with an array of CMMs (left panel).

The design process for engineering r_2 using the simplest CMMs, U-shaped apertures, has been started. Some of the preliminary results are shown in Figure 22. Figure 22 illustrates how the (relatively low) 40 percent absorptivity of the SiC film covered by a smooth Au mirror (black line) can be boosted up to 75 percent by patterning the mirror using CMMs. We call such a "leaky mirror" patterned by CMMs a *MetaMirror*. It is clear from Figure 23 that a MetaMirror can be used for making absorptivity polarization-dependent (if that is desirable for applications demanding a reflector-polarizer). MetaMirror can also be used for shifting the absorption wavelength which would be highly desirable for developing broadband absorbers. We have found that there are two mechanisms capable of making MetaMirrors: (a) excitation of the Long Range Surface Plasmon Polaritons (LR-SPPs) on the patterned MetaMirror, and (b) excitation of highly-localized (shape-dependent but period-independent) SPPs. An example of the mechanism (a) is shown in Figure 23, but we also have preliminary results indicating that both mechanisms can be operational in the same MetaMirror for close-by frequencies resulting in multiple dips of the reflectivity coefficient $|r_2|$. By comparing

Figure 23 with Figure 22, it is observed that the dips correlate with drops of the total reflectivity and increases of the total absorption of the absorber/MetaMirror structure.

The MetaMirror approach to infrared energy harvesting is one of the very promising applications of metamaterials. A number of aspects of MetaMirrors must be investigated and several important questions must be answered before practical applications can be pursued. Some of those questions are:

- What is the angular dependence of absorptivity, and can it be made wide-angle as we have recently demonstrated in Reference 20 for negative-index metamaterials?
- Can absorptivity be made broad-bandwidth by combining localized resonances with the LR-SPPs? That could be potentially accomplished by using U-shapes with different geometries, yet spaced in a regular periodic pattern, or by using quasi-periodic arrangements of CMMs shapes.
- What are the most promising polarization-independent unit cells of CMMs that result in enhanced absorptivity?
- Is it possible to apply the MetaMirror concept in the visible and contribute to solar energy harvesting?

As more researchers are investigating energy-harvesting applications of CMMs (or MetaMirrors), it is believed that these questions will be answered very soon.

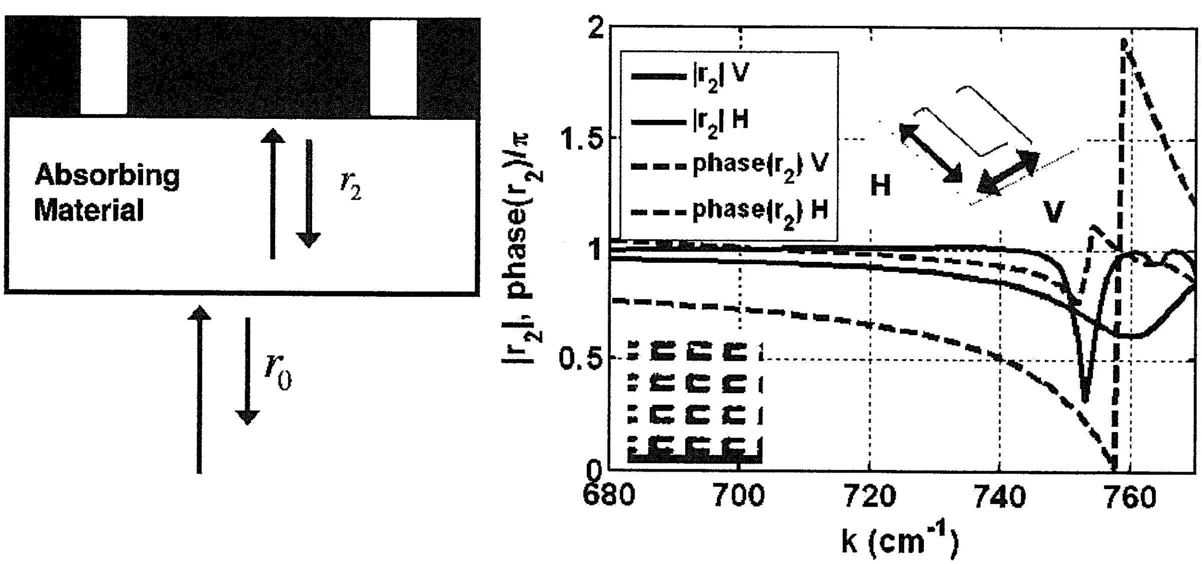

Figure 23. Engineering the Complex Reflectivity Coefficient r_2 Defined on the Left Panel Using the Concept of a MetaMirror. Dips of $|r_2|$ shown in the right panel correspond to reflection dips (and absorption peaks) in Figure 2. The physical reason for these dips is the excitation of long-range SPPs on the MetaMirror surface. Inset: Fabricated MetaMirror.

Nonlinear Non-Reciprocal Chiral Metamaterials: For Developing Novel Optical Isolators and "One-Way" Microwave Mirrors

Optical isolators play a pivotal role in fiber-optic communication systems by protecting their active components (for example, optical amplifiers) from unwanted reflected signals that could potentially destabilize them. Such protection is especially important in the context of advanced aerospace platforms, where repairs must be avoided at all costs. At the core of isolator design is an element which provides non-reciprocity by breaking time reversal symmetry. Non-reciprocity can only be caused by magnetic fields or nonlinearities. The most common approach using magnetic Faraday rotators results in a rather bulky implementation of an isolator. It is believed that metamaterials are uniquely positioned to enhance the other approach of breaking non-reciprocity: use of nonlinear effects. It is very natural to use metamaterial in the context of enhancing nonlinearity. As was explained previously, metamaterials can be used to slow down light and, therefore, compress electromagnetic energy. Any intensity enhancement increases nonlinear effects, and larger nonlinear effects translate into more compact devices. Another aspect that makes metamaterials very appealing for non-reciprocal applications is the ability to make their properties tunable to almost any frequency range.

One concept that is being explored (still unpublished) relies on the nonlinearity and several other aspects of engineered chiral metamaterials. A novel type of a nonlinear optical isolator based on adiabatic time-irreversible mode conversion (ATIMC) between two electromagnetic modes supported by the chiral metamaterial is envisioned. As an example of such metamaterial, a twisted optical fiber shown in Figure 24 is used. It supports a tightly-confined core mode (CoM) which can be coupled to/converted into a loosely confined cladding mode (ClM) of the same fiber. Coupling and conversion between the core and cladding modes is accomplished by twisting the fiber with a variable pitch $\Lambda(z) = 2\pi / \beta_{tt}$. Time irreversibility is achieved due to the combination of the Kerr nonlinearity of the core material (resulting in the intensity-dependent propagation constant of the CoM) and small but finite loss of the ClM. As a result, the CoM, when injected in the *forward* direction, passes through the isolator with a negligible conversion into the ClM. If subsequently reflected back into the isolator (this is equivalent to time reversal), it gets entirely converted into the ClM and subsequently damped as illustrated by Figure 25. Preliminary simulations indicate that, for sufficiently large nonlinearity, one can find the loss rate α for the ClM such that two conditions are satisfied: (a) α is small enough so that virtually no power is lost in the forward direction, and (b) α is large enough so that the time-reversal is strongly violated, resulting in near-perfect optical isolation.

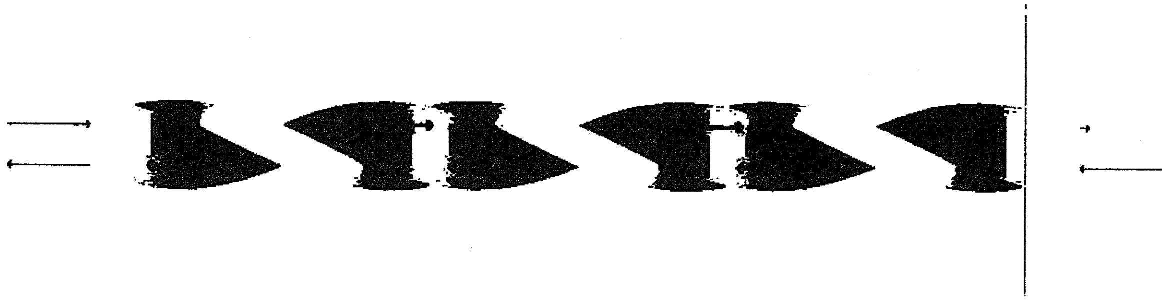

Figure 24. Example of a Generic Chiral Metamaterial: An Optical Fiber with a Rectangular Cross Section Core Twisted During the Drawing Process Forms a Double Helix. If the core index is nonlinear, then one can engineer a variable helix pitch in such a way that the core (localized) modes can be selectively coupled to cladding modes depending on the direction of propagation.

Under a highly simplified assumption of just two interacting mode (core and cladding), we have developed a coupled-mode theory describing the evolution of the mode amplitudes a_{co} and a_{cl} along the fiber axis z. The set of the generic equations for a_{co} and a_{cl} is given by:

$$\begin{aligned} &\frac{\partial a_{co}}{\partial \tau} - i(\beta_0 + \gamma \mid a_{co} \mid^2 - \delta / 2) a_{co} = iW a_{cl}, \\ &\frac{\partial a_{cl}}{\partial \tau} - i(\beta_0 + \delta / 2) a_{cl} = iW^* a_{co} \end{aligned} \qquad (8)$$

where $\beta_0 = c(\beta_{c0} + \beta_{cl}) / 2\omega$ is the average normalized propagation constant, $\delta(\tau) = c(\beta_{c0} - \beta_{cl} + 2\beta_{u}) / \omega$ is the distance-dependent mode detuning, γ is the nonlinearity coefficient, W is the coupling strength between the modes, and $\tau = \omega z / c$ is the normalized propagation distance.

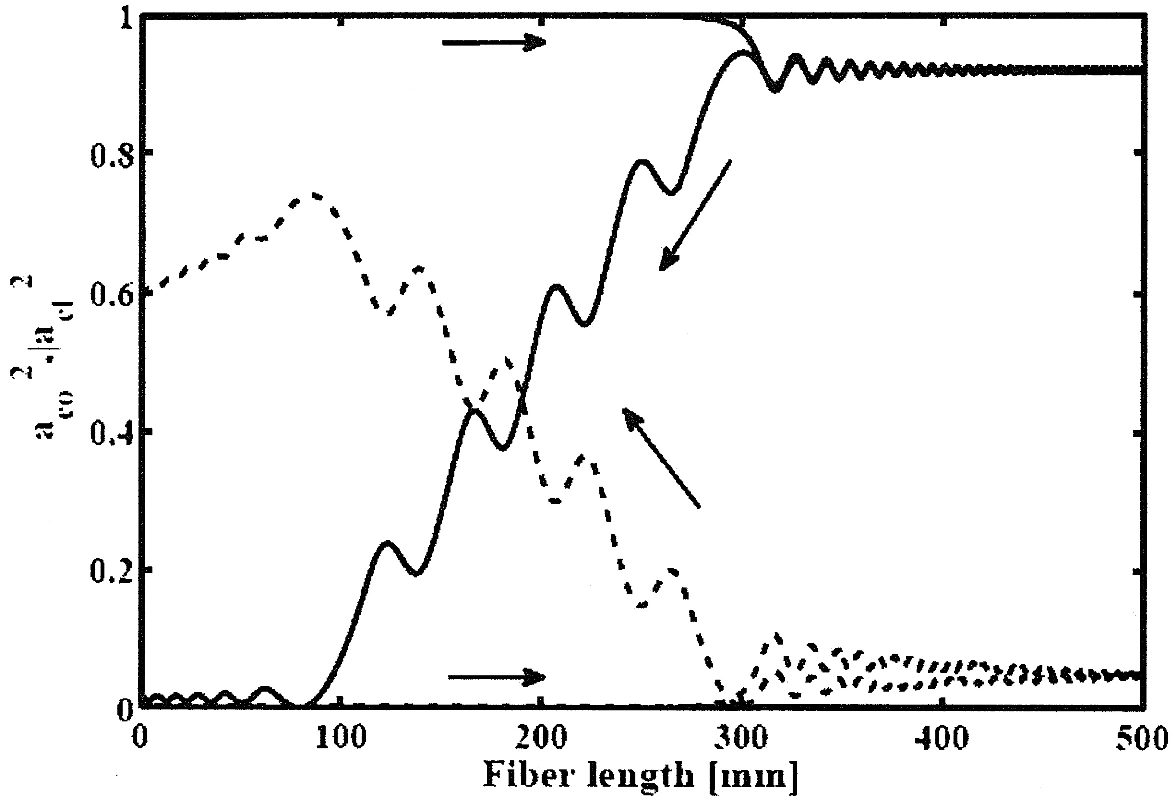

Figure 25. Example of Time-Irreversibility of Light Propagation Inside the Twisted Fiber Core: the core mode propagates with almost no loss from left to right (purple solid line), reflects back, and gets dissipated/mode converted on its way back (red line). Input mode is assumed to be right-hand circularly polarized (RCP). Mode conversion: into LCP cladding mode (dashed line). Propagation from left to right is represented by the red lines, from right to left: by the purple lines.

As an example, we have used a Chiral Fiber (CF) with the following properties: a 2 µm x 1.8 µm elliptical core with refractive index of $n_{co} = 2.2$ surrounded by a round cladding with radius $R = 20$ µm and refractive index $n_{cl} = 2.15$. The helical pitch is assumed to linearly vary over $l_{max} = 500$ mm by 6 percent around $\Lambda = 166$ µm. The assumed γ corresponds to the nonlinear refractive index $n_2 = 5.4 \times 10^{-16}$ m^2/W at the operating vacuum wavelength λ = 1.5 µm and the peak power P = 3.5 W. The cladding mode was assumed to be lossy with the loss coefficient $\alpha = 10$ dB/m . Results are shown in Figure 25. A core mode injected from the left end of the fiber (z = 0) propagates through the fiber without converting into the cladding mode (purple solid line) with minimal losses. After getting reflected at z = 500 mm, the principal core mode (red solid line) gets converted into the delocalized cladding mode (red dashed line) and damped out. This example clearly demonstrates that the interplay between mode-coupling, nonlinearity, and losses can result in the dramatic loss of time-reversal.

Future research will be looking at other metamaterial systems that support two distinct modes (one with a strongly nonlinear response and strong spatial localization, the other essentially linear and delocalized), orthogonal polarizations, and investigate non-reciprocal wave propagation in such metamaterials. Structures from the previous sections, such as shown in Figures 15 and 16, will be primary candidates for implementing optical and microwave non-reciprocity. Such metamaterials would be comprised of a unit cell containing a non-radiative element (that is, a two-strip capacitor-loaded antenna supporting a "dark" magnetic mode) and a single "bright" dipole antenna. Such a system exhibits EIT when the frequencies of the "dark" and "bright" resonances coincide. EIT results in energy compression and enhanced nonlinearity. The source of the nonlinearity could be, for example, a variable capacitance diode (varactor) used as a capacitive load of the double-strip antenna. The second (linear) mode could have an orthogonal polarization, and the coupling between the two could be accomplished via spatially-periodic displacement of the single-strip and double-strip antennas with respect to each other.

Tunable Switchable Metamaterials

Electromagnetic properties of most metamaterials are "hard-wired", meaning they are determined during fabrication. That can be a serious impediment to using them in the context of space exploration. Being able to change optical/electromagnetic properties of a metamaterials-based device without having to re-manufacture it would be highly desirable. Therefore, this survey is concluded by describing some of the recent progress in making reconfigurable/switchable metamaterials. This is a new exciting area of metamaterials research that is worth watching for applications. One of the first electrically-controllable THz metamaterials has been reported in Reference 36, where resonant properties of the electric split ring were controlled by applying reverse bias between metal and highly-doped in GaAs layer. The schematic of the experiment is shown in Figure 25. Without reverse bias there is no resonant response of the split ring to incident THz pulse because highly-conductive electrons of the n-GaAs layer are shorting the gap of the resonant split ring as schematically indicated in Figure 26(b). With the applied reverse bias, electron density is depleted inside the gap. The resulting transmission spectrum shows spectral dips which were converted into the effective dielectric permittivity $\varepsilon_{eff}(\omega)$ that exhibited resonant peaks. The strongest of the peaks corresponded to the Inductance-Capacitance (LC) resonance of the split ring. One possible application of such electrically tunable metamaterial suggested in Reference 36 was a modulator. The authors claim that the performance of their device as a *THz* modulator already exceeds current state-of-the-art electrical THz modulators (based on semiconductor structures) by one order of magnitude on resonance. Moreover, their device operates at room temperature. Needless to say, this metamaterial-based modulator can be improved. For example, configurations exploiting EIT could result in stronger modulation strength.

Another interesting possibility for tuning microwave metamaterials has been suggested in Reference 37. Ferroelectrics (such as BST) can be tuned by applying DC voltage which changes their dielectric permittivity. This property of BST was utilized to develop frequency tunable magnetic metamaterials using metallic split rings loaded with barium-strontium titanate thin film capacitors. The resonant frequency of this medium is voltage tunable across a 140 MHz band centered at 1.75 GHz. The effective relative permeability of the slab was shown to have Lorentzian shape that reaches minimum values between −2 and −3 for biases from 0 to 5 V. Therefore, permeability of the slab can tune between positive and negative values, making it useful in applications requiring a state switchable magnetic permeability.

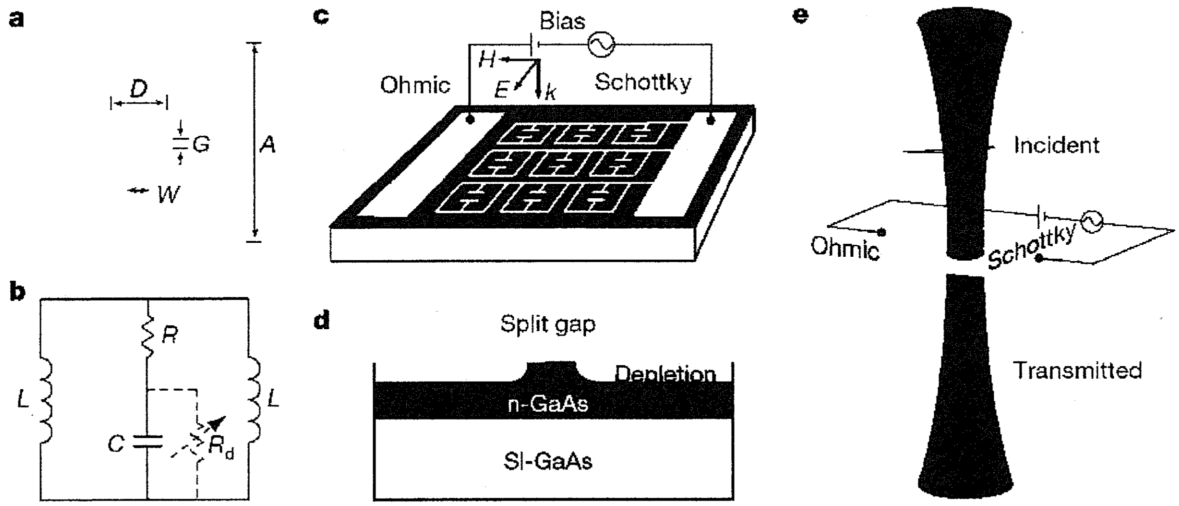

Figure 26. *THz* Properties of an Electric Split Ring Resonator. (a) Are controlled by applying voltage between Schottky and Ohmic contacts (c,d). (b) Schematic of circuit with inductance. Applied voltage controls charge density inside the split gap (d). The structure is investigated using a single-cycle THz pulse (e). (Reference 36)

Summary and Conclusions

While it is difficult to pinpoint the exact applications that metamaterials will find in advanced aerospace industry, metamaterials possess several features that uniquely suit them for aerospace applications. First, they enable miniaturization of a variety of optical components. Making space-born devices small and light-weight is essential. These opportunities have been covered in detail. Second, metamaterials enable new modalities for sub-diffraction imaging: super-lenses, hyperlenses, and far-field superlenses. Those modalities dispense with the near-field scanning microscopes, which are complex, slow-scanning, large devices that are not appropriate for advanced aerospace platforms. Harvesting infrared photons, whether from coherent laser sources on Earth (for guidance, energy recharging, and so forth), from thermal Earth glow, or from the stars, is likely to be important for aerospace platforms. Metamaterials offer unique opportunities for making efficient wavelength-tunable, wide-angle absorbers. As discussed in the numerous examples in this report, metamaterials are going to revolutionize the way light is captured, manipulated, and used for imaging. Although metamaterials are still an academic area of research, these examples illustrate that there is great potential for practical applications.

References

[1] Smith D R, Padilla W J, Vier D C, Nemat-Nasser S C, Schultz S 2000 PRL 84 4184.

[2] J. B. Pendry, "A Chiral Route to Negative Refraction", Science 306, 1353 (2004).

[3] D. Schurig and D. R. Smith, "Spatial filtering using media with indefinite permittivity and permeability tensors", Appl. Phys. Lett., 82, 2215 (2003).

[4] D. R. Smith and D. Schurig, " Electromagnetic wave propagation in media with indefinite permittivity and permeability tensors", Phys. Rev. Lett., 90, 77405 (2003)

[5] A. Alu, M. G. Silveirinha, A. Salandrino, and N. Engheta, "Epsilon-Near-Zero Metamaterials and Electromagnetic Sources: Tailoring the Radiation Phase Pattern," Physical Review B 75, 155410 (2007).

[6] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith, "Metamaterial Electromagnetic Cloak at Microwave Frequencies", Science 314, 977 (2006).

[7] Hu Tao, Nathan I. Landy, Christopher M. Bingham, Xin Zhang,Richard D. Averitt, and Willie J. Padilla, "A metamaterial absorber for the terahertz regime: Design, fabrication and characterization", Opt. Express 16, 7181 (2008).

[8] R. Liu, Q. Cheng, T. Hand, J. J. Mock, T. J. Cui, S. A. Cummer, and D. R. Smith, "Experimental Demonstration of Electromagnetic Tunneling Through an Epsilon-Near-Zero Metamaterial at Microwave Frequencies", Phys. Rev. Lett. 100, 023903 (2008).

[9] 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," Opt. Express 15, 1084-1095 (2007).

[10] J. Valentine, S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov, G. Bartal & X. Zhang, "Three-dimensional optical metamaterial with a negative refractive index", Nature| 455, 376 (2008).

[11] A. F. Hoffman et. al., „Negative refraction in semiconductor metamaterials", Nature Materials 6, 946 (2007).

[12] Y. A. Urzhumov and G. Shvets, "Optical magnetism and negative refraction in plasmonic metamaterials", Solid State Comm. 146, 208 (2008).

[13] R. Merlin, "Metamaterials and the Landau–Lifshitz permeability argument: Large permittivity begets high-frequency magnetism", PNAS 106, 1693-1698 (2009).

[14] G. Shvets and Ya. A. Urzhumov, "Engineering Electromagnetic Properties of Periodic Nanostructures Using Electrostatic Resonances", Phys. Rev. Lett. 93, 243902 (2004).

[15] M. Davanco, Y. Urzhumov, and G. Shvets, "The complex Bloch bands of a 2D plasmonic crystal displaying isotropic negative refraction", Opt. Exp. 15, 9681 (2007).

[16] Y. A. Urzhumov, G. Shvets, J. Fan, F. Capasso, D. Brandl, and P. Nordlander, "Plasmonic nanoclusters: a path towards negative-index metafluids", Opt. Exp. 15, 14121 (2007).

[17] V. Lomakin, Y. Fainman, Y. Urzhumov, and G. Shvets, "Doubly negative metamaterials in the near infrared and visible regimes based on thin film nanocomposites", Opt. Exp. 14, 11164 (2006).

[18] X. Zhang, M. Davanco, Y. Urzhumov, G. Shvets, and S. R. Forrest, "From Scattering Parameters to Snell's Law: A Subwavelength Near-Infrared Negative-Index Metamaterial", Phys. Rev. Lett. 101, 267401 (2008).

[19] T. Taubner, D. Korobkin, Y. Urzhumov, G. Shvets, and R. Hillenbrand, "Near-field microscopy through a SiC superlens", Science 313, 1595 (2006).

[20] Yoav Avitzour, Yaroslav A. Urzhumov, and Gennady Shvets, "Wide-angle infrared absorber based on a negative-index plasmonic metamaterial", Phys. Rev. B 79, 045131 (2009).

[21] J. B. Pendry, "Negative Refraction Makes a Perfect Lens", Phys. Rev. Lett. 85 (2000) 3966.

[22] Zubin Jacob, Leonid V. Alekseyev and Evgenii Narimanov, "Optical Hyperlens: Far-field imaging beyond the diffraction limit", Opt. Exp. 14, 8247 (2006).

[23] A. Salandrino and N. Engheta, "Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations," Phys. Rev. B 74, 075103 (2006).

[24] A. A. Govyadinov, and V. A. Podolsky, "Material photonic funnels for subdiffraction light compression and propagation", Phys. Rev. B 73, 155108 (2006)

[25] Zhaowei Liu, Hyesog Lee, Yi Xiong, Cheng Sun, Xiang Zhang, "Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects", Science 315, 1686 (2007).

[26] G. Shvets, S. Trendafilov, J. B. Pendry, and A. K. Sarychev, PRL 99, 053903 (2007).

[27] Zhaowei Liu, Stephane Durant, Hyesog Lee, Yuri Pikus, Nicolas Fang, Yi Xiong, Cheng Sun, and Xiang Zhang, "Far-Field Optical Superlens" 7, 403 (2007).

[28] R. Merlin, Science 317, 927 (2007).

[29] Yoav Avitzour and Gennady Shvets, "Manipulating Electromagnetic Waves in Magnetized Plasmas: Compression, Frequency Shifting, and Release", Phys. Rev. Lett. 100, 065006 (2008).

[30] Kosmas L. Tsakmakidis, Allan D. Boardman, & Ortwin Hess, " 'Trapped rainbow' storage of light in metamaterials ", Nature 450, 397 (2007).

[31] G. Shvets and J. S. Wurtele, Phys. Rev. Lett. 89, 115003 (2002).

[32] Shuang Zhang, Dentcho A. Genov, Yuan Wang, Ming Liu, and Xiang Zhang, "Plasmon-Induced Transparency in Metamaterials", Phys. Rev. Lett. 101, 047401 (2008).

[33] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect Metamaterial Absorber", PRL 100, 207402 (2008).

[34] Hu Tao, Nathan I. Landy, Christopher M. Bingham, Xin Zhang, Richard D. Averitt, and Willie J. Padilla, "A metamaterial absorber for the terahertz regime: Design, fabrication and characterization", Opt. Exp. 16, 7181 (2008).

[35] T. J. Coutts, Renewable Sustainable Energy Rev. 3, 77 (1999).

[36] Hou-Tong Chen, Willie J. Padilla, Joshua M. O. Zide, Arthur C. Gossard, Antoinette J. Taylor, and Richard D. Averitt, "Active terahertz metamaterial devices", Nature 444, 597 (2006).

[37] Thomas H. Hand and Steven A. Cummer, "Frequency tunable electromagnetic metamaterial using ferroelectric loaded split rings", J. Appl. Phys. 103, 066105 (2008).