Technical Evaluation Report

Organizers and Chairs:

Dr. Ekmel Ozbay
Bilkent University
Turkey

Dr. David Cardimona
Air Force Research Laboratory
United States

INTRODUCTION

Metamaterials are artificial periodic structures with lattice constants that are much smaller than the wavelength of the incident radiation. Thus, the light field "sees" an effective homogeneous material. In these artificially structured media the electromagnetic response results from a macroscopic patterning or arrangement of two or more distinct materials. By properly designing the "artificial atoms" within a metamaterial, one can create materials with optical properties which have no analogue among natural substances, e.g., a negative index of refraction. These artificial composites can achieve material performances beyond the limitations of conventional, naturally-occurring, composites. Thus, metamaterials open a whole new chapter of photonics connected with novel concepts and potential applications. They gain their properties from their structure rather than directly from their composition.

In late 2007, the Program of Work for the NATO Research Task Group SET-123/RTG-067 on “Nanomaterials for Sensors, Sources, and Electromagnetic Manipulation” proposed as one of its activities to organize a specialist meeting or a workshop on metamaterials for electromagnetic (EM) manipulation, specializing in “cloaking” or “stealth” applications. At the first meeting of the RTG in May 2008, a Workshop format was decided upon, with the overall topic to be ‘photonic metamaterials’, thus specializing in metamaterials for the optical regime. Chairs and Organizers were chosen to be Dr. Ekmel Ozbay of Bilkent University in Turkey and Dr. David Cardimona of the Air Force Research Laboratory in the US. At that time it was decided to propose to the SET Panel to hold the Workshop in conjunction with the SPIE Photonics Europe Conference in Strasbourg, France, 7-10 April 2008. With funding from NATO and EOARD (the European Office of Aerospace Research and Development of the US Air Force Office of Scientific Research), the Hilton Strasbourg Hotel was chosen as the Workshop location, since it was directly across from where Photonics Europe was to be held.

THEME OF WORKSHOP

Over the last several years there has been a surge of interest in artificial materials because of their potential to expand the range of EM properties in materials. Metamaterials are of particular importance in electromagnetism (especially optics and photonics), where they are promising for a variety of optical and microwave applications, such as new types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna radomes. Microwave and optical superlenses (lenses with resolutions that exceed the diffraction limit) have been created, and ‘cloaking’ devices have been proposed (in fact, a cloaking structure has been created for microwave frequencies).

PURPOSE AND SCOPE OF WORKSHOP

The purpose of the proposed activity is to assemble leading experts in the field of photonic metamaterials (metamaterials for the optical regime, i.e., infrared, visible, and ultraviolet wavelengths) to determine the state-of-the-art within this new field, including current capabilities and technological maturity, and to facilitate intensive information exchange and focused discussion on the possibilities to be found in metamaterials to address future military optical or photonic applications for NATO.

The topics to be covered by the workshop are: (1) Metamaterials for cloaking or stealth applications in the optical regime, (2) Metamaterials for light concentration or enhancement, and (3) Metamaterials for other optical or photonic applications and devices of use in defense scenarios.

SUMMARY OF TALKS

1. Vladimir Shalaev, Purdue University, USA – "Cloaking and transformation optics"

Dr. Shalaev talked about plasmonic scattering for invisibility of objects that are smaller than the wavelength of interest [Phys. Rev. E **72**, 016623 (2005)]. He then asked the pertinent question: How do we make an object invisible if it is larger than a wavelength? He described two techniques presently available: (i)'stealth' technology, where the radar cross-section is reduced by the presence of an absorbing paint, a non-metallic frame, and a shape that minimizes back-reflections; (ii) 'chameleon-like' technique, where a camera captures the scene behind an object and projects it in front of the object.

He next made the interesting comment that curving space/time in general relativity (like in black holes) is mathematically related to cloaking with metamaterials. In discussing this "curving optical space" concept, he said that the spatial profile of the permittivity (ε) and permeability (μ) tensors determine the distortion of coordinates. He said we would like to find an ε and μ profile that would make light avoid a particular region of space. He mentioned that mirages are an example of this in nature (where there is a gradient in the index of refraction, n, due to a temperature gradient in the air).

A metamaterial composed of split-ring resonators (SRRs) is one possibility he talked about. However, there is an intrinsic limit to scaling SRR sizes, there are high losses in resonant structures (you would loose light in the cloaking device), and there is a low magnetic response in the optical regime.

In Cai, et al., Nature Photonics **1**, 224 (2007), it is mentioned that if you have $\mu = 1$, then no magnetic response is required. Also, they said that if $\varepsilon_\theta > 1$ (e.g., glass), and ε_r changes from 0 to 1 radially, a cloak could be designed for any part of the spectrum (although, not every wavelength simultaneously).

Dr. Shalaev mentioned that in Cai, et al., Appl. Phys. Lett. **91** (2008), it is mentioned that using a nonlinear transformation might avoid scattering losses. He said that "loss might be the ultimate limiting issue" in metamaterials used for cloaking.

He also mentioned the need/desire for the following items: (i) A less complicated fabrication process, (ii) better loss features, (iii) tunability of the structure (so many wavelengths will experience the 'cloaking'), and (iv) broadening the bandwidth of the response (closely related to the tunability issue, only for simultaneous operation).

Finally, Dr. Shalaev mentioned that another possible application for this 'cloaking' technology is 'shielding' – where the light source inside does not leak out.

2. Stefan Maier, Imperial College, UK – “Tailoring electromagnetic field localization with plasmonics”

Dr. Maier talked about plasmonics (which he considered a relatively mature technology) and metamaterials (which he called an emerging technology) in surface-enhanced spectroscopy for use in the optical detection of explosives and bio-agents.

Metamaterials for surface field concentration has been described in Science **305**, 847 (2004), Nature Photonics **2**, 145 (2008), and Materials Today **11**, 15 (2008). He mentioned that the biggest challenge in this emerging technology is increasing the bandwidth of operation.

He described plasmonic metamaterials having conducting surfaces with sub-wavelength structures (like holes, dimples, etc.) that support EM waves that *mimic* surface plasmon polaritons (called “spoof” plasmons). The wavelengths of interest in this particular field are of the order of 300 μm. This topic was discussed by Pendry, et al., Science **305**, 847 (2004), and connected to Drude plasmas.

He next talked about waveguides and how to create a narrow-band defect waveguide for concentrating and propagating light. He described how it was very important to optimize the in- and out-coupling, which has been discussed in Nature Photonics **2**, 145 (2008). He said that sub-wavelength confinement can be obtained by filling in the holes with Si. This works with plane waveguides as well as wires for cylindrical waveguides. He thought this might also be a way to superfocus a probe field.

Finally, Dr. Maier talked about ring or disk nanogaps for resonance tuning of the surface enhancement, and he wondered about plasmon hybridization, and whether that might enhance fields to a greater extent than metamaterials.

3. Shanhui Fan, Stanford University, USA – “Explorations of metamaterials and plasmonics”

Dr. Fan talked about new EM effects with sub-wavelength states (broadband nano-manipulation of light, high-index and non-Maxwellian metamaterials, and one-way EM waveguides). He described how optical and electrical components have been getting smaller and smaller (from 10 μm single-mode fibers to 1 μm Silicon-on-Insulator waveguides to transistors that are less than 100 nm). He imagined that the field of plasmonics bridges the gap between conventional optics and nano-optoelectronics. But, the limiting factor of surface plasmon polaritons (SPPs) is that they exist only in the vicinity of the plasma frequency of the material they appear within.

He described his work in broadband plasmonic slot waveguides (good from 1-10 μm) [Opt. Lett. **30**, 3359 (2005) and J. Lightwave Tech. **25**, 2511 (2007)]. Then he described his work using these slot waveguides applied to input coupling waveguides [Opt. Express **15**, 1211 (2007)], bends and splitters [Appl. Phys. Lett. **87**, 131102 (2005)], and dense packing [Opt. Express **16**, 2129 (2008)].

Dr. Fan then discussed high-index metamaterials [Phys. Rev. Lett. **94**, 197401 (2005), and J. Phys. B **19**, 076208 (2007)] for broadband slow light and solar cells. He said that, in general, when one has a large dielectric constant (ε), one usually gets a small permeability (μ), so that the resulting index of refraction isn’t too large. He noted that ε can be controlled by the top and bottom of the structures in a metamaterial, and μ can be controlled by the sides. So, if you keep the top and bottom, and remove the sides, you should be able to keep the large dipole for large ε while removing the diamagnetic response for large μ. He described how one can approach broadband high index materials by moving from a cube to plates to slit arrays.

For his next topic, Dr. Fan moved to the realm of non-Maxwellian metamaterials, formed by interlocking 3D metallic structures [Phys. Rev. B **76**, 113101 (2007)]. Here he talked about an effective field with large numbers of components. He described structures which may allow the probing of physics that is usually not associated with the Maxwell equations.

Finally, Dr. Fan talked about his work in plasmonics for one-way EM waveguides. He noted that the presence of disorder in a typical dielectric waveguide induces radiation and back-reflection losses. Photonic bandgap materials (photonic crystals) surrounding the lossy waveguide should be able to eliminate radiation loss by eliminating all radiation modes within the bandgap. However, for each forward mode, there is a backward mode, so this sort of material cannot eliminate back reflections. He described how one might put a photonic crystal on top of a metal, and use non-reciprocal surface plasmon waves, coupled with the photonic bandgap effects to eliminate both the radiation and backward propagation modes [Phys. Rev. Lett. **100**, 023902 (2008)]. This should result in complete transmission independent of any scattering particles in the waveguide.

4. Maria Kafesaki IESL-FORTH and University of Crete, Greece – "Status of left-handed and negative index materials for applications"

Talking for Dr. C. M. Soukoulis (Iowa State University and FORTH) who could not make it, Dr. Kafesaki described the status of left-handed and negative index materials [Science **315**, 47 (2007)] for zero reflection, perfect focusing and flat lenses. She mentioned that left-hand materials (LHMs) have lattice periods much greater than the wavelength of interest, while photonic bandgap (PBG) materials have lattice periods of the order of the wavelength of interest. Her vision of possible applications include: near-field optical microscopy and nanolithography, wireless and optical communications with RF sensing, and antenna and microwave device miniaturization. However, we need breakthroughs and new concepts in materials processing at the nanoscale for $n < 0$ in the THz (terahertz) and optical regime. She noted that the number of publications on LHMs has exploded from around 20 in 1999 to over 450 in 2006.

Dr. Kafesaki described how the use of multilayer processing (with a "fishnet' design, for example) can be used to fabricate metamaterials that give both negative ε and μ, as well as negative n. She described how the "2-cut split-ring resonator" was transformed into the "fishnet" structure [Opt. Lett. **31** 1800 (2006), Opt. Lett. **31**, 3620 (2006), Science **312**, 5775 (2006), Opt. Lett. **32**, 53 (2007)] that shows much promise for low-loss negative index materials.

The applications she envisions include: optical switching, zero reflectance (as an anti-reflection coating), modulators (phase, electro-optic, etc.), zero index of refraction, optical isolators, magnetic levitation, and the miniaturization of RF devices. She said that a key idea is the direct control of the magnetic component of EM waves to get magnetic effects at THz and optical frequencies. She described optical switching using nonlinear photonic metamaterials; zero reflection for any incident angle using a metamaterial with an index of approximately -1 when surrounded by air ($n = 1$); electro-optic modulators using layers of the 'fishnet' structure; zero-index materials for beam collimation, beam steering, and beam concentration; optical isolators (transmitting light in only one direction) using optical activity and optical chirality of thin-film metamaterials (using bilayered metamaterials consisting of pairs of mutually twisted planar metal patterns rather than using the Faraday effect with bulky permanent magnets that are required now).

5. Nader Engheta, University of Pennsylvania, USA – "Metaplasmonic materials, nanocircuits with light, and wireless elements at nanoscales"

Dr. Engheta talked about metaplasmonic materials, and how to get ε-near-zero (ENZ) and μ-near-zero (MNZ) materials. He also talked about using such materials to squeeze waves through narrow channels and bends (called 'supercoupling') [Phys. Rev. Lett. **97**, 157403 (2006), Phys. Rev. B **76**, 245109 (2007), Phys. Rev. Lett. **100**, 033903 and 245109 (2008)]. He described some experimental verifications of this in Appl. Phys. Lett. **91**, 234109 (2007), Phys. Rev. Lett. **100**, 023903 (2008), and Phys. Rev. Lett. **100**, 033903 and 245109 (2008). When $\varepsilon \rightarrow 0$, then $n \rightarrow 0$. This implies that the group velocity becomes large, and thus the phase becomes quite uniform. One problem to be overcome is the impedance mis-match between the $n = 1$ material and the $n \sim 0$ material [Phys. Rev. Lett. **97**, 157403 (2006)]. He said that as the cross-section of the narrow channel becomes very small, the reflection goes to zero (when this narrow channel is composed of an ENZ material). In this channel that connects two waveguides, the electric field becomes very large. Experimental verification of the above was accomplished in the microwave regime. Optical waveguides are more complex and more difficult – and resemble the enhanced transmission through holes phenomenon, even though the channels can be very long.

He next introduced his concept of circuits with light at nanoscales, or optical lumped circuit elements – which he calls 'metactronics' ('meta-nanocircuits', metamaterial-inspired nanoelectronics) [Phys. Rev. Lett. **95**, 095504 (2005), J. Opt. Soc. Am. B **23** (2006), J. Appl. Phys. 0703600 (2007), and Science **317** (2007)]. He showed how to get capacitors, inductors, and resistors using nanoparticles with $\text{Re}(\varepsilon) > 0$, < 0, and $\text{Im}(\varepsilon)$ not equal to 0, respectively. He said that SiO_2 nanoparticles can behave like capacitors and Ag nanoparticles can behave like inductors. A SiO_2 nanoparticle surrounded by a coating of Ag can behave like an LC circuit. Using these concepts, he described his ideas concerning nanoparticle arrays as optical nanoantennas [Phys. Rev. B **76**, 245403 (2007)], using Ag-coated SiO_2 nanoparticles. He noted that an RF antenna can be tuned by connecting a wire antenna to an LC circuit. He compared that to the above ideas of LC circuits using nanoparticles. His concept for a nano-optics antenna is to connect a silver nanowire to the LC-equivalent in nanoparticles (e.g., silver nanoparticles separated by dielectric nanoparticles).

Finally, Dr. Engheta talked about his ideas in cloaking, based on scattering cancellation [IEEE Trans. Ant. Propag. **51** (2003), Phys. Rev. E **72**, 016623 (2005), Opt. Express **15**, 3318 (2007), Phys. Rev. E **75**, 036603 (2007), Opt. Express **15**, 7578 (2007), and Phys. Rev. Lett. **100**, 113901 (2008)]. He described the possibility of getting multi-wavelength cloaking using a multi-layered structure.

6. Sergei Tretyakov, Helsinki University of Technology, Finland – "Various approaches to cloaking using metamaterials in the microwave and optical domains"

Dr. Tretyakov defined "cloaking" as a device that minimizes the total scattering cross section of an object for arbitrary illumination, and "stealth" as a technology that minimizes the backscattering cross section of an object for arbitrary illumination. A general cloak will hide an arbitrary object (arbitrary to some extent). Sometimes specific objects (having specific ε) can be made "hardly visible" by some techniques (like layering around the object another material that has an ε that will cause a cancellation of scattering from the object).

He described the Pendry-Schurig-Smith cloak [Science 312, 1780 (2006)] as a spatial transformation that makes "a hole in space" so that the region within the cloak "does not exist" as far as the light is concerned. He noted that the first step towards realization of this sort of cloak was built by researchers at Duke University using copper rings patterned onto fiberglass sheets perpendicular to the radial direction surrounding the object to be cloaked, and worked for a particular polarization of an incident RF field. He noted that Cai, et al. [Nature Photonics, April (2007)] described a cloak in which metal wires are aligned radially around the object to be cloaked, and works for the other polarization of an incident RF field. Then, Asghar at Helsinki University of Technology combined these two ideas (perpendicular rings connected to radial wires) to produce a cloak that works for both polarizations. One problem for realizing this sort of cloak in the visible is to fabricate electrically small but resonant nano-sized spiral metal particles. Another interesting fact he pointed out is that if you put an antenna inside one of these cloaks, it won't radiate out (radiation can't get in, or out).

Dr. Tretyakov then introduced his new concept of a transmission-line mesh cloak, which is composed of an area filled with a conducting mesh. He said that with this sort of mesh cloak, if you put an antenna within the open areas of the mesh, it will radiate out, but will not be seen. To create a cylindrical cloak, you could put perfectly electrically conducting (PEC) rods in the cylindrical axis direction [IEEE Trans. Antennas Propagation **56**, 416 (2008)]. He showed that an application of this mesh cloak is to create an 'invisible' nonreflecting lens. He suggested that a possible realization in the visible is to fabricate nano-transmission lines formed by arrays of metal and dielectric nanoparticles.

One of Dr. Tretyakov's conclusions was that fundamental limitations (mainly dispersion) will probably not allow "perfect" cloaking in practice.

7. Sir John Pendry, Imperial College, UK – "Metamaterials open new horizons in electromagnetism"

Sir John Pendry was the Keynote Speaker for this Workshop, as he was the first (in collaboration with Professor David Smith of the University of California, San Diego, now at Duke University) to create a metamaterial structure that had a negative index of refraction. He began his talk by describing his recent work on "extremely dark materials" for stealth applications. The material was a low-density nanotube array that absorbs visible light, and has an effective index of refraction of 1.026 and a reflectance of 0.02% (where the NIST standard for 'dark' materials presently stands at 1.4% reflectance).

He next compared the "transformational optics" [J. Mod. Opt. **43**, 773 (1996)] that describes negative index materials to Einstein's General Theory of Relativity, relating the gravitational matrix of relativity to the index of refraction in optics. He noted that for EM invisibility, a region of space needs to be surrounded by a negative index material. Then, transformational optics would compress the trajectories of all incident rays so that they avoid the central region and remain confined to the negative index region. He referred to a cloaking concept of Shalaev's in Nature Photonics **1**, 224 (2007), that was composed of metallic wires oriented along radii that provided the necessary graded refractive index for RF radiation (see Dr. Shalaev's talk summary above).

Dr. Pendry next described several applications of engineered permittivities: a magnifying hyperlens, a "perfect" corner reflector, an open cavity in a photonic crystal, stopping different frequency components of a guided wave packet in a waveguide, and sub-wavelength focusing. Using concentric rings (or cylinders in 2D or spheres in 3D) of alternating Ag ($\varepsilon < 0$) and SiO_2 ($\varepsilon > 0$) [Opt. Express **14**, 8247 (2006)], one can create a magnifying optical hyperlens. The Zhang Group at the University of California, Berkeley has experimentally projected a line-pair object in the near-field with a width of 35 nm and a spacing of 200 nm to a 2x magnified image in the far-field, where the diffraction limit was 260 nm. Under certain incident-light conditions, the direction of each incident wave vector can be reversed in a negative-index corner reflector. A combination of air and photonic crystals with effective refractive index equal to -1, can have a net index < 1 and can form an open optical cavity. In a tapered left-handed waveguide (with both ε and μ < 0) the different frequency components of an incident guided wave packet can be stopped without being reflected [Nature **450**, 397 (2007)]. Surface plasmons (electron density waves) result from a negative ε, have an electrical character, and are dispersive. Sub-wavelength focusing requires two magneto-electric surface modes that are not dispersive. Loss is a big problem in plasmonic applications. Many plasmonic applications require resonances with high quality factors, or surface plasmons that propagate over large distances. Silver (with the best defined plasmon) has dominated the plasmonics field. However, an order of magnitude decrease in losses is required for most useful applications. He said that we should "talk to materials people and persuade them to seek better materials."

Finally, Sir Pendry talked about Mark Stockman's Theorem on loss in negative index of refraction materials. Stockman argued that his theory necessarily implies some loss whenever μ or ε are < 0. Pendry claimed that it should be physically possible to concentrate *all* the loss in a delta function at the resonant frequency, leaving all other frequencies free of loss. Thus, he says, "Stockman's Theorem places no meaningful bounds on loss in the presence of negative refraction." Sir Pendry concluded that losses are, indeed, an issue, but certainly NOT an insurmountable one. New materials, possibly alloys, will be needed.

8. Didier Lippens, Universite des Sciences et Technologies de Lille, France – "Cloaking via Mie resonances (EM wave control)"

Dr. Lippens listed several new functionalities possible with negative index materials: smart mirrors, balanced phase-shifters (for backward or forward wave propagation), superlens/hyperlens (for focusing below the diffraction limit in the near/far fields), and transparency cloaks. He mentioned that in the Drude model, if the incoming light frequency is less than the plasma frequency, then you can have ε < 0, whereas for frequencies greater than the plasma frequency, you have ε > 0. He briefly described single split-ring resonators (SRRs) and double SRRs (both concentric and parallel to each other), as well as Ω-shaped rings, as elements in metamaterials for affecting the magnetic properties. He made the important observation that "engineering the index is NOT the whole story, but one must match impedances."

Dr. Lippens described some work on tunability of the resulting resonance phenomena using liquid crystals. He also described the design of an EM cloak using Mie resonances [Opt. Exp. (2008)], with both a layer-by-layer homogeneous model and a BST microstructure model.

Finally, Dr. Lippens talked about negative index materials with photonic crystal (PhC) technology (he showed experimental demonstrations of a flat lens using a PhC). He described a possible cloak using PhCs, in which light is directed around an interior region [Appl. Opt. **47**, 1358 (2008)].

9. Ekmel Ozbay, Bilkent University, Turkey – "Negative refraction and subwavelength focusing using metamaterials"

Dr. Ozbay talked about negative index materials in the GHz (gigahertz) regime. His group is attempting to achieve negative refraction and subwavelength imaging using photonic crystals (PhCs); they are looking at composite metamaterials with true left-handed transmission, negative refraction, and subwavelength focusing; and they are investigating planar metamaterials, fishnet structures, and miniaturized metamaterials and antennas.

In PhCs, the negative index range seems to occur just below the bandgap. Negative index, and superlensing, has been observed in the GHz regime. His group has been able to get both ε and μ negative around 4 GHz, for composite metamaterials composed of alternating layers of SRRs and wires. They found that the negative refractive index values obtained from refraction and phase shift experiments were in good agreement [Appl. Phys. Lett. **86**, 124102 (2005)]. They also found that there is an optimum thickness of the composite metamaterial when used as a flat lens for both transmission and sub-wavelength resolution.

When working with a fishnet structure, Dr. Ozbay found that the structure operates well for both TE and TM polarizations, in fact for any arbitrary linear polarization, due to its symmetric geometry. He also found that a transmission band appeared where both wire-pair-only and a slab-pair-only arrays do NOT transmit EM waves. His group has also investigated various cutwire/wire bilayer structures, multi-SRRs, and spiral resonators as metamaterials.

Finally, Dr. Ozbay described some security applications of metamaterials:

Detectors (better coupling, higher efficiency, wavelength selectivity, improved noise performance, UV, IR, THz)
Counter-detection (cloaking, reduced thermal emission, thermal signature modification)
Sensors (THz metamaterials, plasmonic metamaterials, enhanced nonlinearities)
Imaging for Security (THz metamaterials)
Smart RF Systems (small electrical antennas, metamaterial transmission lines, perfect absorbers)

THE PANEL DISCUSSION

At the end of the Workshop, a discussion was led among the speakers and participants. The following questions and comments were made:

Will cloaking work for a range of wavelengths? Will it work with losses included? Can any material be put inside a cloak? “Possibly” was the answer to each of these questions.

An ‘easier’ application of the cloaking technology might be EM Shielding.

Tunability might be possible using liquid crystals, and their voltage-tunable properties.

This is an excellent time to fund materials development!

Power consumption is very important.

Cloaking is possible! Broadband cloaking is NOT impossible!

Optical Transformations will change the parameters of optics!

There has been great progress in dispersion control in optical fibers. Metamaterials should take advantage of this progress.

Thermal and acoustic cloaks follow the same transformations as the optical cloaks talked about in this workshop. In the near-field scale, metamaterials can affect thermal transport properties, and thermal science in general.

When one concentrates light into the deep sub-wavelength regime:

- one can increase the signal-to-noise ratio

- one can increase speed, decrease physical size, and increase optical signal in optical components for information processing
- in plasmonic structures, once a device is designed, large-scale production should not be a problem

There could be great opportunities in the time domain, not just the spatial domain.

Metamaterials might lead to new approaches to amplification!

In the RF regime, lots of work is being done in antennas and transmission lines. Metamaterials have already been shown to have applications here, and this regime serves as a testbed for ideas in the optical regime.

Application to antennas is to make them smaller and more efficient. If you use the antenna as a filter, then you WANT it to be narrowband (natural for resonant metamaterials).

Tunability is of use in the RF, as well.

Direct Voltage or Optical or Mechanical control of metamaterial devices would be desirable.

In the THz regime, high-power sources and good detectors do not yet really exist. Can metamaterials help here?

In the THz regime, some semiconductors have $\varepsilon_{real} < 0$, but $\varepsilon_{imaginary}$ is NOT small (i.e., loss is not small).

Any applications in metamaterials related to energy?

- battery efficiency can be improved using plasmonics
- should be able to engineer loss, improve efficiency, and utilize the near-field concentration effect to modify solar cells

How about ‘active’ metamaterials?

- maybe the chameleon effect (for camouflage).

RECURRING THEMES THROUGHOUT THE WORKSHOP

- “curving optical space” by designing a material’s permittivity and permeability

- losses in the designed metamaterials: might be the ultimate limiting issue
  - perhaps using a nonlinear transformation would eliminate some losses
  - perhaps surrounding a lossy metamaterial with a photonic bandgap material will be a way to stop losses (in waveguides, at least)
  - perhaps new structure designs (such as the ‘fishnet’ structure) will reduce losses

- the ‘resonant’ character of most metamaterials – thus not allowing the desired response to occur for a broad spectrum of incident light
  - perhaps varying the permittivity radially around an object (either continuously, or in a multi-layered structure) might allow the object to be cloaked in many wavelengths
  - perhaps broadband high-index metamaterials will be a solution
  - perhaps liquid crystals might be able to tune resonances

- Rather than ‘cloaking’ an object, how about the opposite: ‘shielding’ an object, i.e., keeping radiation confined within a region of space

- Plasmonics coupled with metamaterials – meta-plasmonic materials or plasmonic metamaterials

CONCLUSIONS

During this Workshop, numerous applications related to defense and security were discussed, as were numerous areas that required further research. The possibilities of optical, thermal, and acoustic cloaks were discussed for counter-detection and electromagnetic shielding applications. Such cloaks could provide invisibility, or merely stealth, capabilities. But they could also reduce acoustic or thermal emissions, modify thermal signatures, and change thermal transport properties. The concentration of light using metamaterials may produce optical or RF signal amplification, and may result in increased signal-to-noise ratios, increased speed, decreased size, and increased range in optical sensor systems. Metamaterials have been studied quite extensively in the RF regime, where smaller and more efficient antennas and transmission lines have been investigated, and miniaturization of RF devices becomes possible. Negative index materials could lead to reduced reflection (for antireflection coatings) and subwavelength focusing in optical systems, superlenses or hyperlenses (with resolutions that exceed the diffraction limit in the near field or far field, respectively, useful in optical lithography and optical microscopy – there was even talk of a magnifying hyperlens), and flat lenses (for reduced weight and cost of large optical imaging systems). Such materials also show promise for improved optical components such as: switches, modulators, isolators, perfect reflectors, smart mirrors, and balanced phase-shifters. They also show promise for improved optical beam steering, beam collimation, and beam concentration. Meta-plasmonic materials (or plasmonic metamaterials) produce surface-enhanced spectroscopy, for improved optical detection of explosives and bio-agents. Metamaterials can be used to improve optical waveguides (coupling efficiencies, transmission, etc.), and may even be of use in THz imaging. Finally, there was mention of metamaterials and plasmonic metamaterials being used to improve battery efficiencies and improve the efficiency and absorption of solar cells.

Metamaterials seem to be on the brink of great breakthroughs, and show promise in many diverse areas.

RECOMMENDATION

Recommend topic of metamaterials, especially for optical or photonic applications, be further pursued in an Exploratory Team.

Appendix I: Attendees and Speakers

WORKSHOP PARTICIPANTS

	NAME	Organization	E-mail
1.	Ekmel Ozbay	Bilkent University, Turkey	ozbay@bilkent.edu.tr
2.	Dave Cardimona	US Air Force Research Labs	dave.cardimona@kirtland.af.mil
3.	Rimas Vaisnoras	Vilnius Pedagogical University, Lithuania	vaisnoras@vpu.lt
4.	Dorota Anna Pawlak	Institute of Electronic Materials Technology, Poland	Dorota.Pawlak@itme.edu.pl
5.	Judith Spiegel	Universite Catholique de Louvain, Belgium	judith.spiegel@uclouvain.be
6.	Michel Sirieix	Sagem Defense Securite	michel.sirieix@sagem.com
7.	Stian Lovold	Norwegian Defence Research Extablishment, Norway	stian.lovold@ffi.no
8.	Dan Huang,	US Air Force Research Laboratory	danhong.huang@kirtland.af.mil
9.	Rachel Jakubiak	US Air Force Research Laboratory	rachel.jakubiak@wpafb.af.mil
10.	Bruno Desruelle	Delegation Generale pour l'Armement, Ministry of Defence, France	bruno.desrelle@dga.defense.gouv.fr
11.	Julio Plaza del Olmo	Centro de Investigacion y Desarrollo de la Armada, Spain	jplazao@oc.mde.es
12.	Paul Alsing	US Air Force Research Laboratory	paul.alsing@kirtland.af.mil
13.	Koray Aydin	Bilkent University, Turkey	aydin@fen.bilkent.edu.tr
14.	Atilla Ozgur Cakmak	Bilkent University, Turkey	atilla@ee.bilkent.edu.tr
15.	Steven Weiss	US Air Force Research Laboratory	sweiss@arl.army.mil
16.	William Miceli	U.S. Office of Naval Research Global	wmiceli@onrglobal.navy.mil
17.	Hamza Kurt	TOBB University, Ankara, Turkey	hkurt@etu.edu.tr
18.	Doug Imeson	Dstl (UK MoD)	dimeson@dstl.gov.uk
19.	Lucio Vegni	University Roma Tre	vegni@uniroma3.it
20.	Anna Maria Fiorello	Selex-SI	afiorello@selex-si.com
21.	Rasit Turan	METU, Turkey	turanr@metu.edu.tr
22.	Charlotte Rachel Helen Bennett	Qinetiq, UK	CRBENNETT@qinetiq.com
23.	Alejandro Martinez	Valencia Nanophotonics Technology Center, Spain	amartinez@ntc.upv.es
24.	Gerard Berginc	Thales Group, France	gerard.berginc@fr.thalesgroup.com
25.	Isabelle Huynen (CANCELLED)	Université Catholique de Louvain, Belgium	isabelle.huynen@uclouvain.be
26.	Alex Schuchinsky	Queen's University Belfast, UK	a.schuchinsky@qub.ac.uk
27.	Vasily Klimov	Lebedev Physical Institute Russian Academy of Sciences	vklim@sci.lebedev.ru, klimov@nline.ru
28.	Philippe Mérel	Defence Research and Development Canada	philippe.merel@drdc-rddc.gc.ca
29.	Shadrivov	Australian National University	ivs124@rsphysse.anu.edu.au
30.	Andreas Hakansson	DAS Photonics S.L., Spain	ahakansson@dasphotonics.com
31.	Mikhail A. Noginov	Norfolk State University, USA	mnoginov@nsu.edu
32.	Ortwin Hess	University of Surrey, UK	o.hess@surrey.ac.uk

	NAME	Organization	E-mail
33.	Thomas G. Philbin	Friedrich-Alexander University, UK	tgp3@st-andrews.ac.uk
34.	Lina Huang	Swiss federal institute of technology Lausanne, Switzerland	lina.huang@epfl.ch
35.	Filippo Capolino	University of Siena, Italy	capolino@ing.unisi.it
36.	Michael Zedler	TU Munich, Germany	michael.zedler@tum.de
37.	Maria Antonietta Vincenti	Dipartimento di Elettrotecnica ed Elettronica – Politecnico di Bari	vincentiantonella@gmail.com
38.	Ehud Galun	ELOP, Electro Optics industries, Ltd., Israel	ehudg@elop.co.il
39.	Nigel P Johnson	University of Glasgow, UK	njohnson@elec.gla.ac.uk
40.	José Sánchez-Dehesa	Universidad Politecnica de Valencia, Spain	jsdehesa@upvnet.upv.es
41.	Joachim Krenn	University of Graz, Austria	joachim.krenn@uni-graz.at
42.	Alexandra Boltasseva	Technical University of Denmark	aeb@com.dtu.dk
43.	Carsten Rockstuhl	IFTO Friedrich Schiller University Jena, Germany	carsten.rockstuhl@uni-jena.de
44.	Concita Sibilia	Universita' di Roma La Sapienza, Italy	concita.sibilia@uniroma1.it
45.	Dmitri Gramotnev	Queensland University of Technology, Australia	d.gramotnev@qut.edu.au
46.	Herbert O. Moser	National University of Singapore	moser@nus.edu.sg
47.	Tomasz Szoplik	University of Warsaw, Poland	tszoplik@mimuw.edu.pl
48.	Allan Boardman	University of Salford, UK	a.d.boardman@salford.ac.uk
49.	Ryszard Buczynski	University of Warsaw, Poland	rbuczyns@igf.fuw.edu.pl
50.	Ali Erdem Ozzcan	ASELSAN Inc., Turkey	aeozcan@mgeo.aselsan.com.tr
51.	Latif Sungu	ASELSAN Inc., Turkey	lsungu@mgeo.aselsan.com.tr
52.	Jose M. Llorens	Unkown	jose.llorens@gmail.com

INVITED SPEAKERS

	NAME	Organization	E-mail
1.	Dr. John Pendry	Imperial College, UK	j.pendry@imperial.ac.uk
2.	Vladimir M. Shalaev	Purdue University, USA	shalaev@purdue.edu
3.	Sergei Tretyakov	Helsinki University of Technology, Finland	sergei.tretyakov@tkk.fi
4.	Maria Kafesaki	FORTH, Crete	kafesaki@iesl.forth.gr
5.	Didier Lippens	Lille University, France	didier.lippens@iemn.univ-lille1.fr
6.	Stefan A. Maier	Imperial College, UK	s.maier@imperial.ac.uk
7.	Nader Engheta	University of Pennsylvania, USA	engheta@ee.upenn.edu
8.	Shanhui Fan	Stanford University, USA	shanhui@stanford.edu