SAND2019-14245B

Chapter

Metamaterials. How Close Are We to a Klingon Cloaking Device or Harry Potter Invisibility Cloak?

Michael Valley, Sandia National Laboratories

Introduction

Life conditions us to believe and react to what we see, hear, and feel; however, metamaterials may one day challenge our reliance on senses as scientists mold material behaviors with alchemy-like outcomes to get the edge on what nature provides. Such advances inspire dreams of invisibility cloaks, realizing fictional technologies from the universes of Harry Potter and Star Trek. Then again, this sleight of hand would require us to bend light and energy to our will. Clearly this is not possible – or is it? This chapter examines the burgeoning field of metamaterials and implications for Special Operations Forces (SOF).

The US is not alone in their pursuit of metamaterials. Rapid strides in global technology and dynamic adversary posture shifts contribute to future mission environment uncertainties. Preserving our national security advantage, deterring foreign actions, mitigating countermeasures, and ensuring adversaries share our confidence in SOF capabilities dictates we possess disruptive technologies. Currently, the US holds unrivaled responsive alternatives, but technological superiority is perishable. Metamaterials have the potential to provide an asymmetric advantage to erode the value of foreign technology advances. We must understand how to use them to our advantage and how to diminish their effectiveness when employed against us. Metamaterials may drive us to rethink everything about battlespace technologies.

The birth of metamaterials is debatable since mankind has long worked to improve materials, though the use of the term has only been prevalent for a few decades. What is clear is the accelerating pace of metamaterial developments and the promises they hold. Early work by pioneers such as Victor Veselago stirred beliefs that it is possible to create materials to control electromagnetic waves, providing the foundation for visions of metamaterials-enabled devices with tailored optical and energy wave control abilities.[1] Since the turn of the century, advancements in our ability to study metamaterial behavior at fundamental scales has contributed to the creation of powerful design tools that capture the necessary physics. Parallel advances in the synthesis of new materials and advanced manufacturing helped material designers translate their concepts into amazing fabricated parts. This rapid progress has excited researchers far and wide. Indeed, metamaterials is a dynamic, worldwide research topic with over 25,000 publications in the last two decades. Unfortunately, the greatest metamaterial research growth is outside the US, with 80% of publications coming from China since 2015. Breakthroughs are already making it into national security applications. What is already achievable is noteworthy, but it is nothing compared to what is on the horizon for this materials revolution. Our fascination with metamaterials has just begun and will grow as their use becomes more common.

Herein, we do not review metamaterial literature, which goes back a century. Many publications summarize key breakthroughs in topical areas within the metamaterials genre. Representative metamaterials overviews can be found in *History of Metamaterials, Mechanical Metamaterials Associated with Stiffness, Rigidity and Compressibility: A Brief Review,* and *3D Metamaterials*.[2, 3, 4]

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Unraveling the Metamaterial Mystery: Magical, Mythical, or Simply Marvelous?

The definition of what constitutes a metamaterial continues to evolve as creative researchers push the boundaries of science and manufacturing, allowing us to translate the art of the possible to field what has long seemed impossible. Essentially, metamaterials are natural materials fashioned to deliver unconventional properties through the integration of small engineered structures – often called meta-atoms – whose feature size can approach dimensions thousands of times smaller than the width of a human hair. The achievable material properties and behaviors resulting from the atomic and microstructural additions and rearrangements depends on the blend of the inherent constituent material composition and the small-scale structural arrangement of those materials through atomic, nanofabrication, lithography, and additive manufacturing. The possible combinations are limitless! Today's metamaterials already demonstrate tunable, reconfigurable, and spatially variable behaviors that go far beyond the well-recognized characteristics of even the most advanced "smart" materials.

Indeed, progress in design tools and manufacturing sciences enables us to translate our imagination into fabricated structures with unprecedented precision, including the ability to adjust individual atoms. Though manipulating atoms is powerful to create some materials, we are not limited to fabricating devices with molecular-scale structures. Additive manufacturing can assemble metamaterial products with features from grain scales (100-200 nm building block size using a Nanoscribe 3-D printer) to centimeters or larger. These larger sizes still manifest amazing properties, as has been demonstrated in reinforced composites, printed lattices, and compression pads, optics, and more.

Though the ability to manufacture ultra-large metamaterial structures has been elusive, developers will achieve this capability within the foreseeable future. Even today, metamaterials-based technologies are making it to the marketplace within the defense and national security, telecommunications, consumer electronics, medical, environmental, and energy industries (e.g., solar, batteries, energy storage).

A desirable attribute and well-recognized metamaterial characteristic are their ability to be designed to control energy flow – how much energy is reflected, absorbed or dampened, transmitted, redirected through steering or focusing, or filtered as a function of wavelength or frequency. This energy flow control applies across the electromagnetic regime, providing utility in the optical, infrared (IR), microwave, radio frequency (RF), and radar domains. Similarly, it applies to acoustic, mechanical, and thermal energy. Imagine if we can capture energy of interest and regulate what happens to the undesirable energy! It is this aspect of metamaterials that inspires hope for invisibility cloaks. Though large-scale cloaking has not yet materialized, the practical value of energy flow control provides new functionalities that control device behaviors, as well as material signatures and observables. This energy manipulation attribute of metamaterials holds the promise of delivering capabilities to strengthen the Special Operations Forces' technology options in an uncertain and rapidly changing global environment.

Metamorphic Manufacturing

Manufacturing turns science knowledge into action. Progress fielding disruptive technologies must follow advances in process sciences and manufacturing methods that transition research from the lab to operational systems. The challenge is to devise cost-effective, scalable, fast, flexible manufacturing platforms to explore and exploit the power of metamaterials in complex architectures. Today, the acceleration of metamaterial development and transition to use is fueled by a confluence of advanced tools, including user-friendly modeling software to design material geometry and property distributions, agile manufacturing to achieve feature and inclusion control at physical dimensions that govern material performance, and high-resolution microscopy to measure as-built structural details and chemical composition to verify designs have been achieved. With this rich suite of capabilities, clever designers examine countless combinations of one dimensional (1-D), 2-D, and 3-D arrays of engineered structural microelements and materials across the periodic table to yield incredible material behaviors.

Metamaterial characterization capabilities, combined with state-of-the art testing systems, elucidate relationships between engineered microstructures and their resulting material performance, helping design tool developers mature modeling software that captures the phenomenology that drives material behavior. It is important to understand the underlying physics to use these materials with high confidence. The ability to capture small-scale feature attributes is particularly important, because metamaterial properties are governed by their constituents' fundamental material physical properties, inclusions and defects, shape, and the characteristics of integrated engineered material sub-structures.

Early on, metamaterials were chiefly fabricated using particle beam lithography (e.g., electron-beam, focused-ion-beam lithography). Lithography remains an important fabrication method as research overcomes its historic limitations. Today, there are more than a dozen lithography options, each addressing a specific fabrication need. Unfortunately, the size of what can be made is a few centimeters. This is not to infer lithography is not viable for creating disruptive technologies. Consider, for example, the Defense Advanced Research Projects Agency (DARPA) *Extreme* project that uses membrane projection lithography to construct 3-D metamaterial structures with the promise of compact conformal, hyperspectral, and night vision technologies. The utility is immense for this reconfigurable, small, low-power, lightweight device that provides simultaneous multispectral, polarimetric, and classical imaging.

Additive manufacturing, which is discussed in a separate chapter in this book, is poised to fabricate product sizes orders of magnitude larger than what lithography can produce. For example, though not using a metamaterial, Oak Ridge National Laboratories printed an entire car body in a day. Additive manufacturing systems provide controlled fabrication of 3-D structures using polymers, metals, ceramics, and multi-material combinations, as well as metamaterials. These machines can provide sub-micron resolution, and they can provide large build volumes, but typically not both at the same time; however, the pace of innovation in additive manufacturing, driven by a worldwide market exceeding $20 B annually, will rapidly advance metamaterial manufacturing over the next decade. Forecasted systems will fabricate metamaterials measured in meters with improved fabrication tolerances.

Additive manufacturing systems fabricate parts not achievable through conventional methods. They take advantage of design concepts such as topological optimization[5, 6] to construct components customized for the mission need while increasing strength, decreasing size and weight, and providing shape agility for novel packaging and form factors. Considerable efforts are underway to expand additive manufacturing material feedstock choices, which will extend technology development options. For example, chemists are synthesizing novel additive manufacturing printer inks to create materials with unusual attributes to advance products such as flexible electronics. Further, state-of-the art system controls are improving part quality and reducing the achievable feature size, which can be smaller than a micron. Nevertheless, fabricating large parts for defense and national security uses is still difficult.

To overcome metal part size limits, researchers are crafting additive manufacturing concepts that use multiple high-powered lasers to better control heating at increased fabrication speeds. Early tests show these approaches reduce defect formation and control the metal grain structure to achieve desired properties. Another advance is the Fraunhofer Institute for Laser Technology' hybrid system which combines conventional and additive manufacturing processes to take advantage of the best attributes of each technology. This system's fabrication process chain increases manufacturing speed and achievable part size while ensuring consistent part quality and not compromising small feature control.

For fabricating flexible electronics, roll-to-roll methods such Metamaterial Technologies Inc.'s Rolling Mask Lithography method and MICROGRAVURE™ printing are proving effective. These production-scale printing systems are cost-effective, flexible, and avoid chemical etching issues. Active research in roll-to-roll printing of metasurfaces continues.[7,8] With breakthroughs in self-assembled nanomaterial synthesis methods and the invention of printable inks that fully embrace the periodic table, it is likely that the roll-to-roll manufacturing methods will become a future workhorse for fabricating metamaterial surfaces.

As shown by the University of Delaware and the US Army Communications-Electronics Research, Development and Engineering Center, roll-to-roll systems can insert electromagnetic materials into large structural composites. This ability may prove impactful for building microwave devices and radomes with integrated, high-end antennas. Alternately, electromagnetic structures, including microwave metamaterials that integrate metals and dielectrics, can be fabricated with current multi-material additive manufacturing systems. For example, fused deposition modeling 3-D printing can now generate high quality gigahertz microwave metamaterials, overcoming the need for metallization after printing.

Similarly, metamaterials can be spun into fabric textiles using screen printing combined with standard composite processing methods. Lightweight metamaterial devices (e.g., communications, sensors, self-cooling) woven into uniforms could enhance soldier capabilities and reduce carried gear weight.

Metamaterials by Design

Until recently, exploiting the promise of metamaterials has challenged engineers and designers. Classical design methods require solving complex equations governing the multi-scale, multi-physics behavior of the devices and materials of interest – a daunting task requiring significant compututational capabilities and expertise in corresponding fields of science. Fortunately, tremendous progress in solution methods are easing design burdens. Technical skill requirements are partially mitigated by commercial software that aids the design process. Examples include the ANSYS High Frequency Structure Simulator and COMSOL Multiphysics® software, which use finite element methods to solve 3-D device design problems; however, some expertise and model iterations are still needed to optimize device designs.

An approach applied to reduce computational loads in metamaterials design uses reduced-order models that capture the core physics of the material phenomena being modeled and reduces problem-solving complexity. An example is the perturbative metamaterial method applied to mechanical, acoustic, thermal, and phononic design efforts where dynamic metamaterial performance is required.[9]

Other design approaches overcoming metamaterial design challenges come from the field of artificial intelligence. For example, a Tel Aviv University team demonstrated an artificial intelligence deep learning approach to nanophotonic metamaterials design.[10] Similarly, a team from Pohang University of Science and Technology used a deep-learning-assisted inverse design method to improve the efficiency of designing photonic structures.[11] These data-driven artificial neural network approaches reduce the number of iterations required to optimize a design. They are well-suited to designs where the metamaterial devices will be quasi-static and where data is available to train the neural network.

Determining how energy will flow in a structure is straightforward if you understand the governing equations or use a commercial design code. Regrettably, the possible design variations are innumerable, often requiring countless iterations to achieve an acceptable design. To overcome this challenge, developers have examined a new design paradigm called Metamaterials-By-Design (MBD).[12, 13] MBD considers the design process from an application-oriented perspective driven by the device's performance requirements. In other words, MBD methods solve the inverse problem, starting with the end in mind and working backwards. While this would seem logical, it is far from easy.

Working metamaterial designs backwards requires the use of optimization methods to find the best solution given a myriad of design choices. Imagine finding the deepest dimple on a rough surface without measuring each one. This solution search challenge is similar to solving an inverse design problem. Many methods such as topological optimization tackle this hunt for the best design, though they still require many trials.[5, 6] Fortunately, a strategy called Modified Error in Constitutive Equations, together with an adjoint optimization solver for sensitivity calculations that are independent of the number of design variables, has proven efficient at finding the best solution without the need for a supercomputer and many iterations.[14] This approach has been validated under harsh mechanical test conditions. For example, recently a metamaterial designed with this approach and implemented with 3-D additive manufacturing demonstrated 3-5 orders of magnitude reduction in shock and vibration wave energy transmission and tunable frequency transmission across a 10 kHz frequency range.

The aforementioned approaches, though powerful, require technical expertise to use them properly. It is well-known that metamaterial properties are tightly associated with the size, shape, composition, and internal feature distribution of the material constituents. Change this slightly, and you are apt to create a different material response. This places a burden on the metamaterials design and manufacturing. To realize the potential of metamaterials requires we have practical, easy to use design tools. This is the goal of the DARPA *Mirage* program. As explained by Ihab El-Kady, the *Mirage* project lead, "*Mirage* is shifting the burden of design from the subject matter expert to the practitioner. Emerging software lets users design science fiction-like materials with the same ease and efficiency that architects use when they draft building plans, speeding up metamaterials R&D. No longer is a large cross-disciplinary team of experts required – you just need your imagination, and the new tool will do the rest. These nascent tools are driving a perspective shift in material selection and conventional design approaches."[15] This achievement is exactly the design breakthrough needed to accelerate the development and adoption of metamaterial-enabled devices. Currently, *Mirage* software is applied to electromagnetic metamaterial device designs, but work is ongoing to extend this software to acoustic and mechanical applications.

Anticipating the Surprise and Realizing the Dream

Continued progress coupling material physics into user-friendly design tools and fabrication methods for metamaterials is enabling extraordinary control of the flow of energy, creating lightweight, damage-tolerant, high-performance materials with attributes that have long been unreachable. The way creative designers are choosing to use this energy control is making us reimagine what is possible.

While the greatest near-term use of metamaterials may be communications and radar systems, early signs indicate they will soon broadly proliferate into commercial and military products. For example, metamaterial super lenses may someday image details beyond diffraction limits for higher resolution microscopes to study basic material sciences, as well as the physics of metamaterials themselves. With these lenses, we may push past manufacturing barriers to fabricate more capable microelectronics processors with smaller feature sizes, particularly if matched with thermal materials such as phononic metamaterials for heat management. Already, progress has been made with making thin, super-lightweight flat optics for cameras and viewfinders. Researchers have demonstrated metamaterial optical resolution above 80% of diffraction limits and products are making it to market. For example, firms such as Metalenz Inc., Phoebus Optoelectronics LLC, Nano-Meta Technologies, Inc and Multiwave Technologies are incubating optical metamaterial technologies from lab to market at an increasing rate.

For microelectronics and electronic packaging, researchers at the Toyota Research Institute are developing thermal composite metamaterials for thermal energy cloaking and shielding, printed circuit board temperature control, energy harvesting, and electrothermal power conversion for next generation electronics, optoelectronics, and photonic devices.[16] Also for microelectronics, magnetic metamaterials are helping developers to move past silicon to field a new class of low power transistors and superconductors for next generation electronics and high-performance computers. These same electromagnetic metamaterials could lead to extreme magnetic field sensing for ground penetrating radars, space-based and underwater magnetometers, and improved anti-ship missile-defense radar.

Though we currently cannot upsize metamaterial optical systems to larger scales, ongoing work will someday field more capable military reconnaissance systems, including agile spectral and polarization filters, and lighter-weight flat lenses. Possibly, designers will soon couple sparse array metamaterial with computational imaging software to field larger airborne and space optics. Already, metamaterials show promise in adaptive optics, laser tracking anti-glare and laser protection coatings (e.g., Metamaterials Technologies Inc.); it is a matter of time before they expand into larger optical systems.

Research is yielding improved resolution and measurement sensitivity in commercially available sensors. Examples including strain sensors, biomedical sensors (e.g., MRI, glucose sensors), optical gas sensors, ultrasonic imagers, and thermal imagers such as nanoantenna-enabled cameras that can boost the signal by up to three times and improve image quality by reducing dark current by up to 100 times. Evolv Technology employs metamaterials for imaging and high-speed walkthrough firearm and explosive detection portals, which might enable portable entry control systems for gray zone urban environments. Firms such as TeraView use metamaterials in a terahertz inspection system that is so sensitive it can determine paint thickness or find small defects at semiconductor device scales, possibly providing a process control or supply chain trust assurance tool. TeraView's terahertz and millimeter-wave imaging systems extend from explosives detection and vehicle collision avoidance to higher-resolution radar and sonar systems. Also, for autonomous vehicle collision avoidance, Lumotive is developing solid-state Light Detection And Ranging (LIDAR) systems with a metamaterial beam-steering technology.

Visualize what is possible with responsive sensors attuned to their surroundings. Environmentally activated passive sensors can indicate package tampering (e.g., food, microelectronics, medical) to improve safety and trust in the international supply chain. This capability could also autonomously activate remote devices when exposed to a targeted signal (e.g., heat, humidity, shock, vibration, RF).

Metamaterials can play a role in controlling mechanical energy, which is the energy source for what we feel from shocks, vibrations, impacts, and blast waves. Consider a woodpecker's beak that impacts a tree about 20 times per second with a deceleration of 1200 g's without hurting itself.[17] Metamaterials seek to achieve similar protective capabilities. The same principles that allow us to regulate sound can be employed to control how we absorb, reflect, focus, or redirect mechanical waves.

Indeed, mechanical metamaterials have been assessed in rocket flights, isolating sensitive parts from dynamic flight loads. These same materials may reduce the jostling from a bumpy road by blocking the energy as it passes through tires, allowing military vehicles to safely and comfortably speed through undeveloped regions. Focusing mechanical energy would enhance shape charge effectiveness, placing more energy on a small spot. Metamaterials for absorbing and redirecting incoming shocks or blast waves could improve shielding, be used for safety equipment, cushion falls, and improve footgear. Further, we can design intentional failure mechanisms to control energy absorption, such as a crumple zone in a car, thereby protecting something precious, such as a human life or a delicate instrument.

Because we can control the distribution and metamaterial constituents in what we build, we can design stiffness and load response variations in devices and structures, allowing for new types of actuators that can be tuned to respond to specific forces, such as strain or loads. This may allow us to build better exoskeletons to enhance soldier performance as well as form the basis for the development of better prosthetics and artificial muscles needed when serious injuries are sustained.

In the arena of battlefields and aeroacoustics, efforts are underway to develop lightweight tunable metamaterials for acoustics and vibration control. An intriguing area of this research involves resonant metamaterials for aerodynamic flow control to delay the onset of turbulent flow transition, thereby reducing skin friction drag.[18] As another flow control option, a research team from the Italian University of Niccolo Cusano and the Chinese Academy of Aerospace Aerodynamics is studying a porous metamaterial ultrasonically absorptive coating to delay the transition from laminar to turbulent flow in order to reduce the boundary layer drag and heat transfer rates for a hypersonic vehicle.[19]

One intriguing class of metamaterials is auxetic materials. They exhibit high energy absorption and fracture resistance through the material microstructure, which can flex and stretch in phenomenal ways. These materials have a negative Poisson ratio, which means they expand in all directions when stretched and contract in all directions when compressed. Possible uses for auxetic metamaterials include materials for engines and thermal protection, stronger ropes, foams and packaging materials to protect parts from shocks, and blast protection applications. For example, Auxetix Ltd demonstrated an auxetic material called Zetic that can survive a car bomb. They suggest Zetic could provide superior body armor and protective clothing, blast resilient ultra-light ultra-strong stretchable backpacks and military tents, and strong flexible medical sutures compatible with body tissues. Further, a team from MIT's Self-Assembly lab demonstrated heat-activated auxetic materials, adding a new dimension to what is possible. It is likely these magic materials will one day find their way into military applications.

Metamaterial adoption has been greatest in communications, antennas, and radar systems, with related RFID applications for tagging, tracking and locating. The move to 5G communications and extraordinary radar capabilities will push developments even faster, with commercial sales forecasted to exceed $10 B annually by 2030. Metamaterials are integral to future high performance, high impedance, low profile, conformal, and fractal antennas for communications and radar systems. The potential for game changing shifts in military communications and radar systems through metamaterials is immense!

It is now feasible to produce dramatically smaller electric and magnetic dipole antennas with enhanced radiating power, and patch antennas with increased directivity, enhanced gain, and reduced return loss.

This size reduction does not mean performance is compromised. For example, tiny metamaterial antennas can be tuned across entire communications bands, overcoming narrow operating bandwidths to make smaller radios possible. Also possible are remarkable frequency and polarization agility and improved multiband operations with reconfigurability for microwave devices and custom antennas.

The antenna technology push to smaller sizes will continue. With it will come operational resilience. For noisy RF environments, metamaterials mobile communications smart antennas can adjust to their environment to strengthen communications of interest while mitigating competing signals. Further, Pivotal Commware sells a wireless system that reuses the same spectrum bands, possibly providing a means to ensure communications are sustained in congested and contested RF environments.

Many companies already take advantage of the special attributes only metamaterials can provide for RF devices. For example, Fractal Antenna Systems, Inc. employs metamaterials for RFID tags, smart sensors, novel antennas, and flat lens technologies for microwave applications for telecommunications and surveillance systems. Their metamaterials allow for multiband and wide bandwidth fractal antennas that can be positioned in non-typical locations. For example, they claim their recessed antennas can even be located next to metal without disrupting antenna operations. These antennas are small, thin, lightweight, have no electrical connections and reduced circuitry, and offer increased gain.

Another firm, Kymeta, uses metamaterials in thin, lightweight broadband systems for vehicle-to-vehicle communications, enabling a new secure communications paradigm for military forces in remote areas. Well known for their satellite communications systems for land and sea, Kymeta now produces a thin, lightweight flat-panel satellite antenna. They use electronically-activated metamaterials to steer their Ku-band communications beam to a satellite. Together with satellite constellations under development, such as the DARPA Blackjack program, this should support direct satellite to soldier communications.

Metamaterial advances are also transforming radar systems. For instance, Echodyne makes a handheld radar able to track people, cars, and even a small plane at a distance of a few miles. Likewise, Metawave has combined artificial intelligence with metamaterials to create radar for autonomous driving vehicles, including an ability to see around corners, which could be powerful in contested urban environments!

Metamaterial adeptness in redirecting and sensing energy flow has opened a research path, exploring “compute by feel” to dynamically sense an environment, assess conditions, and autonomously react or respond without a human in the loop. Such a reflexive ability to enable functions at the speed of battle could dramatically increase survivability and weapon system effectiveness, particularly if it reduces multi-input data analysis to simplify situational awareness. These metamaterials might obviate computer-based feedback loops to reduce power and system complexity. Triggering autonomous action, including system reconfiguration, could protect systems from damage and soldiers from harm, or improve performance, such as communications link optimization through origami structure change methods.[20, 21] Autonomous navigation and maneuvering will be achieved when “compute by feel” metamaterials prove capable of discerning normal loads from hostile conditions. This will provide a marked advantage in contested environments with mobile targets, particularly for unmanned aerial, underwater, and hypersonic vehicles that need to avoid countermeasures or adverse flight conditions.

The concept of “compute-by-feel” metamaterials operating like a nervous system in a cybernetic mode to drive complex actions is not far-fetched. Classic examples exist through smart materials, self-assembly fabrication and material synthesis methods, and biomimicry where we learn from nature. It is often suggested that nature produces the best materials adapted over time to deliver exquisite attributes. For example, a spiderweb is a distributed sensor platform where the web materials capture vibrations, interpret, and communicate them to the spider using only mechanoreceptors on their legs. Such concepts can now be translated to complex metamaterials.[22, 23]. Metamaterials may be a key building block that allows us to borrow from nature and create functionalities that heretofore have been limited to plants, animals, and insects. Imagine if we could replicate the capabilities of a chameleon!

Metamaterials are also finding a home in advanced computing. For example, professor Nader Engheta and his team at the University of Pennsylvania have used metamaterials to demonstrate an analog computer which could someday result in low power computers that operate by light instead of electricity.[24] Also, the DARPA Defense Sciences Office has sponsored brain-inspired neuromorphic computing research that uses metamaterials and will take advantage of the revolutionary breakthroughs in machine learning and artificial intelligence. Indeed, as described by the project lead, Francois Leonard, "imagine a window that turns blue if a bear walks by but turns red if it's a giraffe. Even better, this window could learn to respond to different stimuli by repeated exposure to a training dataset, much like the human brain." By showing metamaterials themselves can extract useful information from optical fields without the need to process optical signals with electronics, this project will create neuromorphic optical media building blocks to increase processing speed and reduce power requirements. This could also transform optical sensing, image processing, and recognition for national security applications.

The aforementioned metamaterials will someday provide SOF forces with robust, effective, and flexible technologies to assure mission success across the full detect-deter-deny-destroy mission spectrum. However, cloaking may be the most impactful for irregular warfare – but what is possible?

Metamaterial Stealth – A Vanishing Advantage

The same class of metamaterials that improves our communications and radar systems can absorb energy. Of interest is the ability of these materials to deliver low radar cross-section and IR stealth characteristics. Narrow band, multi-band, and broadband high absorption metamaterials have been demonstrated from the optical to microwave spectral regions. For example, a team led out of the University of Electronic Science and Technology of China has demonstrated a metamaterial with 98% absorption for discrete wavelengths that can be designed within the 600 - 1500 nm wavelength range. Applications for this capability range from improved sensing, spectral filtering and reduced thermal emissions, and night vision goggles.[25] Similarly, metamaterials can be designed to control the direction thermal energy is emitted. Beyond providing metasurfaces for thermal management on satellites, such a capability is valuable in tailoring IR signatures for stealth and camouflage uses.

As another example, a research team at Zhejiang University published results for an optically transparent broadband radar stealth material with a frequency selective microwave transmission window and low IR emissivity.[26] Their test results showed strong broadband performance from 1.5 GHz to 9 GHz, with a radar transmission window at 3.8 GHz. This radar transparent metasurface simultaneously demonstrated low surface IR emissivity, which would make systems fabricated with this material hard to detect with radar or IR imagers. Further, emerging research in polymeric photonic crystals indicates chameleon-like tunability in the RF range may also be achievable. In general, by manipulating a surface's energy scattering properties using a metasurface, the signal return can be altered to make an object appear differently or disappear completely.[27] These attributes seem like what we might expect from a military Digital Radio Frequency Memory (DRFM) system, where we seek to obfuscate electromagnetic signatures, but without the need for power and software.

Consideration of metamaterial invisibility frequently targets inanimate objects like tanks, planes, and ships; however, such a capability to provide protection of our forces on the ground would be equally compelling. The proven capability to weave metamaterials, microelectronics, and micro-power systems (including solar power) into clothing provides the tools for an adjustable camouflage and concealment capability that could be fine-tuned in real time to the soldier's environment. Combine such a uniform with creams and face paints with nano-metamaterial additives to reduce visible and IR signatures, and we would be one step closer to having a Predator outfit right out of the movies!

Dreams of cloaking drew excitement in the early days of metamaterials research, and it is on the horizon for sound. Acoustic metamaterials were first demonstrated by Liu and others in 2000, laying the foundation for sound attenuation and control through metamaterials.[28] Today we find acoustics and sound control in consumer audio systems, and signature management is now possible to some extent. Indeed, companies such as Metasonics control sound without impeding air flow, and the Acoustic Metamaterials Group provides high performance noise dampening metamaterials. Many research teams worldwide have demonstrated an ability to control which acoustic frequencies can penetrate through metamaterials, as well as which acoustic signals will be released. Complete noise silencing has been demonstrated, offering the hope that one day any vehicle, engine, or noise source can be completely silenced, whether operating on the ground, in the air, or in marine domains. Also, by manipulating sound we can alter emissions from audio to ultrasound to sonar frequencies, potentially creating an ability to replicate the noise signatures of anything we choose to simulate.

Considering demonstrated capabilities to control energy flow into and out of surfaces, it is logical to anticipate advanced stealth, camouflage, and signature management technologies will become commonplace in arenas where concealments, deception, and subversions may be employed. By bending light and energy with space-age metamaterials, we may also be able to further reduce visibility by removing shadows. What we do with the incident energy – be it light, heat, mechanical, or electromagnetic – will be important for enabling stealth. One possibility would be to harvest energy intended to harm and reapply it for useful purposes, like storable power.

Stealthy metamaterials may prove to be both a blessing and a curse for intelligence, surveillance, and reconnaissance (ISR) systems as innovations provide more capable sensing systems, as well as the ability to reduce signals from what we wish to sense. We will be driven to consider a wider range of measurements of potential observables to achieve ISR mission goals against metamaterials that provide static signature management. For materials that provide tunable or autonomous chameleon adaptations, we will be challenged to develop countermeasures that can discriminate signals and targets from background clutter. This may prove to be a pivotal technology area where the US must sustain an advantage and be the first to field robust capabilities to shape the future battlespace.

Conclusions – Making a Material Difference in National Security

Today's global landscape reflects an unprecedented mix of conflicts, stress points, and potential threats. Threats are evolving, and US policy has not constrained adversaries. The SOF community remains an essential component of our response options to protect US and ally interests in these times of growing uncertainty. SOF capabilities, training, skills, motivation, and effectiveness remain high, but as strong as they are, they must continually adapt to disrupt the actions of adversaries. In fact, adversaries are actively performing R&D to nullify the US advantage at a pace exceeding US development-to-deployment cycles. In the face of these aggressive foreign efforts, the US may need to expand its research, production capabilities, and supplier base to meet this national security and domestic economy need. Indeed, metamaterials may become a critical base technology and pivotal enabler to engineer capabilities that keep SOF forces on the forefront of international technologies. If so, the US will need to accelerate its cycles of learning and rate of insertion into mission toolkits.

In the coming years, we will gaze in awe at the incredible revolution made possible by the science of metamaterials and abilities to design and shape them into asymmetric technology advantages. In the next 5-10 years, we can expect controllable metamaterials will contribute to SOF capabilities through advanced radar and communications systems, enhanced tagging-tracking-locating and targeting devices with greater geolocating accuracy and operating ranges, compact highly capable electronics and sensors, "smart uniforms", and lightweight materials and armored vehicles resilient to shocks, blasts, projectiles, lasers, radiation, and electromagnetic attacks. So too can we see the day when cloaking and stealth become mainstream capabilities, realized through cutting-edge camouflages, concealments, and surface materials that manage radar, RF, and IR signatures and observables, as well as noise emanations.

While we must be on guard to avoid the hype, we must also be open to the new realm of metamaterial possibilities. Achieving the metamaterial dream requires we nurture and advance national capability-based science and engineering foundations. If we do so, through remarkable innovations we will deliver more agile and effective tools to SOF forces and avoid adversary surprises in future warfare. Our quest to design materials that can be fabricated with predictable and controllable qualities remains, but design tools like *Mirage* and additive manufacturing advances put metamaterials within our grasp, adding radical new dimensions to what is possible.[15] Indeed, metamaterials hold the promise of delivering strengthened SOF technology options in an uncertain and rapidly changing battlespace.

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Acknowledgement

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.