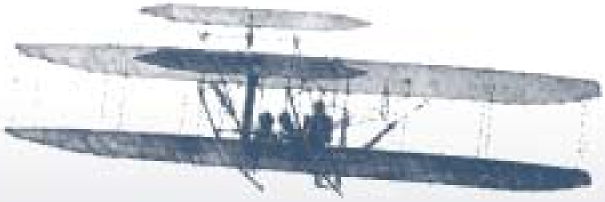
THE WRIGHT FLYER PAPERS

The Cheshire Jet

Harnessing Metamaterials to Achieve an Optical Stealth Capability

Timothy E. Beers
Major, USAF

Air Command and Staff College
Wright Flyer Paper No. 44



Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **The Cheshire Jet: Harnessing Metamaterials to Achieve an Optical Stealth Capability**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air University,Air Command and Staff College,Maxwell AFB,AL,36112**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Laboratory research that melds physics with materials science has ventured into the design of matter with unique electromagnetic characteristics and response functions. This new class of ordered composites?known as metamaterials?exhibits exceptional, unnatural properties derived from their structure rather than from their composition. These materials promise to provide significant advances in stealth and survivability technology both of which are highly applicable for future Air Force capabilities against a counter-low observable, directed energy?equipped integrated air defense system. This paper addresses the question, ?Will metamaterials facilitate an operationally feasible and significant optical stealth capability for the US Air Force?? To answer this question, the author?s research is directed at the advances and development patterns of optical band metamaterials specifically, it addresses the leading indicators of frequency bandwidth, and energy loss. Following that, a backcasting futures technique helps uncover the obstacles of metamaterial durability, suitability, and manufacturability. This paper concludes with a 20-year timeline for optical band metamaterial capabilities and applications. This paper highlights the need for continued Department of Defense (DOD) funding and pursuit of metamaterial ?cloaking? technology. The near-term objective of such a program should be the development of infrared laser protection and the reduction of the optical signature of currently fielded systems and their follow-ons.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**56**	

Air University
Allen G. Peck, Lt Gen, Commander

Air Command and Staff College
Anthony J. Rock, Brig Gen, Commandant
Zoë M. Hale, Col, PhD, Dean
Brett E. Morris, Col, PhD, Director of Research
Brett E. Morris, Col, PhD, and John L. Mansuy, Maj, Series Editors
Joseph A. Thill, Lt Col, PhD, Essay Advisor

Air University Press
John A. Shaud, General, USAF, Retired, PhD
Director, Air Force Research Institute
Belinda L. Bazinet, Content Editor
Tammi Long, Copy Editor
Nedra O. Looney, Prepress Production
Daniel Armstrong, Cover Design

Please send inquiries or comments to
Editor
The Wright Flyer Papers
Air Command and Staff College (ACSC/DEI)
225 Chennault Circle, Bldg. 1402
Maxwell AFB AL 36112-6426
Tel: (334) 953-6810
Fax: (334) 953-2269
E-mail: ACSC@maxwell.af.mil

AIR UNIVERSITY

AIR COMMAND AND STAFF COLLEGE

The Cheshire Jet

Harnessing Metamaterials to Achieve an Optical Stealth Capability

TIMOTHY E. BEERS
Major, USAF

Air Command and Staff College
Wright Flyer Paper No. 44

Air University Press
Air Force Research Institute
Maxwell Air Force Base, Alabama

July 2010

This Wright Flyer Paper and others in the series are available electronically at the Air University Research Web site http://research.maxwell.af.mil. and the AU Press Web site http://aupress.au.af.mil.

Foreword

It is with great pride that Air Command and Staff College presents another in a series of award winning student research projects from our academic programs that reach nearly 11,000 students each year. As our series title indicates, we seek to promote the sort of imaginative, forward-looking thinking that inspired the earliest aviation pioneers, and we aim for publication projects which combine these characteristics with the sort of clear presentation that permits even the most technical topics to be readily understood. We sincerely hope what follows will stimulate thinking, invite debate, and further encourage today's air war fighters in their continuing search for new and better ways to perform their missions—now and in the future.

ANTHONY J. ROCK
Brigadier General, USAF
Commandant

Preface

In truth, this paper came about by chance. I stumbled across metamaterials while researching another technology. I was fascinated, finding myself quickly drawn into this exciting new realm of science and technology. Something about invisibility must ring a primeval note. Who among us has never daydreamed of being invisible? Who among us never laughed in amusement while playing peek-a-boo with an infant who believes that something somehow vanishes, or ceases to exist because he or she cannot see it? As the saying goes, "Out of sight, out of mind." Invisibility is a veritable wellspring, finding mention in religion, mythology, and popular culture worldwide. Interestingly enough, it is usually villains and our enemies that we imbue with this ability. Perhaps no single thought creates more fear in our hearts than the adversary who catches us unaware, or one who can deliver an attack we cannot anticipate.

The last time I sat in a physics class was 14 years ago. That said, I never could have understood this topic, nor ultimately have written this paper, without the patient guidance, direction, and insights of Professors Steven A. Cummer from Duke University and Nicholas X. Fang from the University of Illinois. Their enthusiasm for the subject is nothing short of contagious and their ability to explain such a technical concept as cloaking is equally awe-inspiring.

A very special thanks to my family for their saint-like forgiveness toward my countless vanishing acts while I tackled this topic.

Abstract

Laboratory research that melds physics with materials science has ventured into the design of matter with unique electromagnetic characteristics and response functions. This new class of ordered composites—known as metamaterials—exhibits exceptional, unnatural properties derived from their structure rather than from their composition. These materials promise to provide significant advances in stealth and survivability technology, both of which are highly applicable for future Air Force capabilities against a counter-low observable, directed energy–equipped integrated air defense system.

This paper addresses the question, "Will metamaterials facilitate an operationally feasible and significant optical stealth capability for the US Air Force?" To answer this question, the author's research is directed at the advances and development patterns of optical band metamaterials; specifically, it addresses the leading indicators of frequency, bandwidth, and energy loss. Following that, a backcasting futures technique helps uncover the obstacles of metamaterial durability, suitability, and manufacturability. This paper concludes with a 20-year timeline for optical band metamaterial capabilities and applications.

This paper highlights the need for continued Department of Defense (DOD) funding and pursuit of metamaterial "cloaking" technology. The near-term objective of such a program should be the development of infrared laser protection and the reduction of the optical signature of currently fielded systems and their follow-ons.

Why Metamaterials?

Any sufficiently advanced technology is indistinguishable from magic.

—Arthur C. Clarke
Profiles of the Future

1 October 2029

The bright midday sun glints off the East China Sea. Several miles above the water, a sleek aircraft streaks across the cloudless azure sky. Its revolutionary skin, an advanced engineered electromagnetic shell, makes the aircraft impossible to detect by radar and infrared energy. Even light seems to curve around the aircraft's structure, making it seem smaller than it really is and shrouding it in a distorted, shadowy effect. The navigation system indicates that the initial point is rapidly approaching and, soon thereafter, the aircraft will enter the heavily defended airspace surrounding the enemy's operations center. Already the self-protection sensors are detecting the probing energy of the hostile integrated air defense system. Based on these emissions, and further confirmed by the enemy electronic order of battle database, the shell reconfigures, tuning itself to maximize protection from the numerous incoming frequencies. With a push of a button, the aircraft's skin is pumped with energy. Instantly the vehicle vanishes from sight; light bends around the craft like water flowing around a stone. The enemy does not expect the audacity of a daylight strike. In minutes, the world's first invisible jet will make history.

Is this scenario mere science fiction, or is it reality waiting to happen? Humans have always dreamed of the power of invisibility. In Greek mythology, the hero Perseus used an enchanted helmet to disappear, allowing him to approach unnoticed and slay the Gorgon Medusa.[1] Invisibility was thus an equalizer, the ancient equivalent of a force multiplier, allowing man to battle a terrible monster. Another character that many might recognize is the fictional Cheshire Cat, who could appear and disappear at will, or even disappear gradually until nothing but a grin remained.[2] More recently, invisibility and cloaking have been made popular through countless movies, books, video games, and television shows that rationalize the ability through magic and alien technology. Science, however, may now be presenting this ability as fact, rather than a mysterious phenomenon.

Materials science promises to provide significant advances in cloaking technology that will be highly applicable for future Air Force capabilities. Recent laboratory research in physics has ventured into the design of materials with unique electromagnetic (EM) characteristics and response functions.[3] This new class of ordered composites, known as metamaterials, exhibits exceptional, unnatural properties derived from their structure rather than from their composition.

Why does structure, in the context of order and scale, matter? Take, for example, a single, tiny quartz crystal. A small amount of light reflects from its surface, but for all practical purposes, the crystal is transparent. Place a handful of these same crystals together and all the little reflections from the many scattering surfaces result in a pile of white sand that is no longer transparent. However, if the crystals were all the same size, shape, and arranged in an orderly fashion, it would be possible to guide light in distinct patterns through and around them. In this way metamaterials affect EM waves by having meticulously patterned design features, smaller than the wavelength with which they interact, to guide energy in a precise way.

In the near future, it will be possible to dictate the optical constants of objects using engineered nanostructures. These materials are able to suppress the scattering of energy and vary its indexes of refraction, thus curving, even sharply turning, the path of EM waves. This feat effectively renders the object invisible to the designed wavelengths and has already been demonstrated in the laboratory with microwaves at frequencies as high as 16 gigahertz (GHz).[4] Achieving this phenomenon within the broad optical spectrum of light is possible. Furthering metamaterial efforts ensures an optical stealth capability, thus increasing aircraft survivability, specifically against a counter-low observable (LO), directed energy (DE)-equipped integrated air defense system (IADS).[5] This paper provides research for the required advances in metamaterial science to facilitate an operationally feasible and significant optical stealth capability.

Understanding Optical Stealth

By design, most combat aircraft employ some form of low visibility. To date, this essential facet of comprehensive stealth has been achieved through geometric design, isoluminosity,and painting aircraft to blend into the environment.[6] For instance, high-altitude U-2 reconnaissance planes are painted black to match the dark background sky. B-2 stealth bombers fly at night to minimize visual signature and are also painted black. Likewise, fighter aircraft, like the F-22, are painted "air superiority grey" to better blend in with the daytime sky. In addition, bright reflections from cockpit glass or other smooth surfaces are minimized using special coatings. These efforts are commonly referred to as elements of visual stealth. What has yet to be achieved, however, is the broader goal of optical stealth.[7]

Today's Air Force has an impressive portfolio of attack capabilities but lacks sufficient numbers of stealthy aircraft that can survive in a dangerous antiaccess environment, operating effectively around the clock, prosecuting critical targets.[8] The future will only exaggerate this predicament. As stated in the 2009 *Capstone Concept for Joint Operations*, "We will need to develop new capabilities and change the capacities of existing ones. . . . We will need to develop new technologies and adapt existing ones to new missions."[9] To ensure victory against any future counter-LO, DE-equipped IADS, the United States must embrace new disruptive technology.

In 2006 the National Research Council published a report entitled *Future Air Force Needs for Survivability*. This report described the various factors that determine the signature characteristics of an aircraft and its weapons systems, the status of the technologies involved, and the Air Force's goals for future strike systems. The report concluded by highlighting the longer-term research and development programs needed for air vehicles in the 2025 timeframe and beyond. The report stated,

> Visual signature sources can provide foreign elements an additional source to enable alert,

detection, and cueing . . . *provides both airborne and ground-based threat system operators with valuable knowledge that can then be applied in the effective operation of their systems. . . . Visual signature control continues to be an area that should be considered for future development.*[10] (emphasis added)

Just as radar signature reduction represented a revolution in military operations, the same must be done for the optical spectrum. Operating LO aircraft only at night is no longer an option. Furthermore, advanced weapons, those possessing antiaccess and area-denial capabilities, are increasingly proliferating among less developed states and nonstate actors.[11] Metamaterial cloaking represents the new fog of war, the superior covertness required to "penetrate and persist" in, or near, heavily defended airspace.[12]

How Cloaking Works

To make something invisible, the nature of visibility must be understood. Electromagnetic radiation can have wavelengths from thousands of kilometers to a tiny fraction of the size of an atomic nucleus. Specifically, and of interest to this discussion, visible light consists of relatively high-frequency, short-wavelength emissions: 10^{14}–10^{15} hertz and 400–750 nanometers, respectively. We see objects in this spectrum because light is absorbed by and reflected off matter, which in turn hits our eyes (see figure 1).

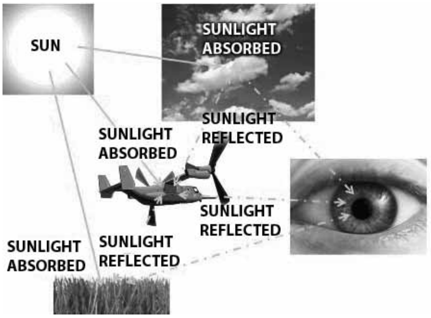


Figure 1. Pathways of light

These waves are absorbed and emitted by the individually charged particles in atoms, molecules, or materials. As light passes through air or matter, its electric field polarizes the medium, and the wave is slowed due to the magnetic field created. In turn, this decrease in speed bends the light more directly into the material. Refraction describes the way light bends when it transits from one medium boundary into another. The factor by which light slows down is known as the material's index of refraction.[13]

By convention, both electrical permittivity (the ability of a material to transmit or permit an electric field) and magnetic permeability (the ability of a material to acquire magnetization) are defined relative to the corresponding qualities of a vacuum, expressed as equal to one.[14] Metamaterials, however, display different EM wave propagation properties. When either of these values is negative or smaller than one, this offers a means of manipulating refraction.[15] In fact, these nanofabricated composite materials use deep subwavelength-scale features to engineer optical constants to the point of reversing the natural direction of light so that it flows against energy. This is in seeming contradiction to what we understand to be normal behavior.[16]

Soviet physicist Victor G. Veselago postulated this phenomenon more than 40 years ago. His theoretical research speculated on a material that was "tuned" using electronic components to manipulate its electric and magnetic properties, thereby producing a negative refraction.[17] Though the concept was in place, researchers lacked the computing power and material engineering techniques to make this a reality.

Over the past decade, however, science has conquered these hurdles and proved that metamaterials can cloak objects. For example, in 2006, Duke University physicists designed and arranged tiny electromagnetic cells to manipulate microwaves and precisely steer them around a four-inch diameter cylinder and then shift them back onto their original path. Imagine this as water flowing around a smooth rock and rejoining downstream. In essence, the concealed volume appeared to have the properties of free space when viewed externally, neither scattering waves nor imparting a shadow in the transmitted field. Neither the cylinder, nor the cloak shell, was ever "seen" by the microwaves. Figure 2 depicts the results of this experiment, showing the relatively unaffected wave fronts and ray lines.[18]

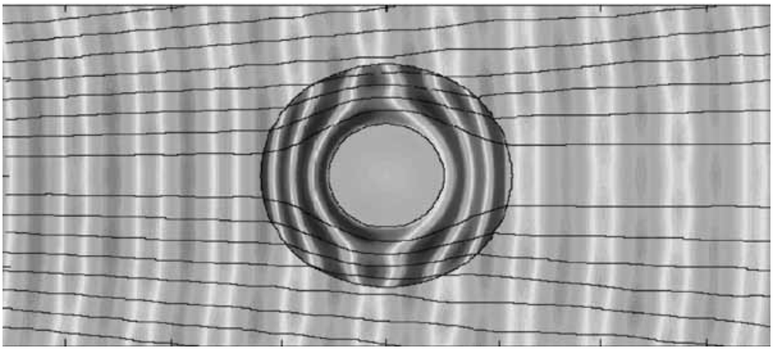


Figure 2. Duke University's 2006 microwave cloak

It is important to differentiate between current low-observable stealth, which minimizes the size and clarity of signatures, making an object difficult but not impossible to detect, and what "cloaking" technology offers: complete invisibility for the designed wavelength.[19] Though these early experiments were performed at microwave frequencies, it was not long before scientists downscaled these structures to tackle optical frequencies.

In August 2008, University of California (UC), Berkeley researchers constructed a "fishnet" material that achieved a negative refraction of light in the near-infrared (IR) range.[20] This was accomplished by creating nanoscale current loops—in essence a series of circuits—which respond together in opposition to that of the magnetic field from the incoming light. Figure 3 depicts two ponds, one exhibiting normal positive refraction and one with negative refraction.[21]

When sunlight travels from air to water in the first pond, it slows and bends toward the direction that is perpendicular to the boundary layer between the media. A practical consequence of this refraction is that the fish appears to be at only 75 percent of its actual depth.[22] In the case of the second pond, a fish swimming under water would instead appear inverted in the air above the water's surface due to negative refraction.

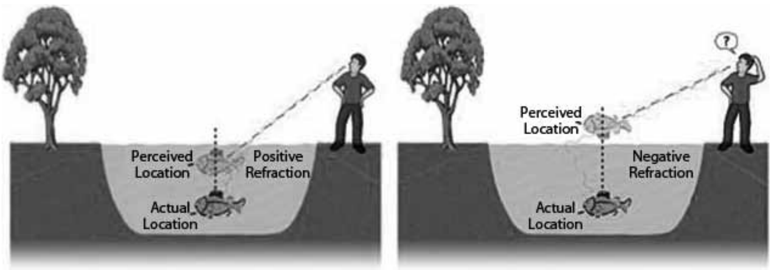


Figure 3. Observing positive and negative refractions

It is important to note that cloaking is not synonymous with negative refraction. Cloaking requires a calculated and designed nonuniform variance in refraction along an object's surface. Light, or any other EM energy desired, must be guided around the shell in curved lines, effectively leaving a void in space. Nonetheless, this paper largely addresses negative index of refraction, as it serves as an observable milestone and a proof of concept in science's ability to steer and otherwise manipulate light, which is essential for achieving a cloaking capability.

Despite recent advances, current metamaterials remain poor at conducting visible light's shorter wavelengths. This means light waves lose energy as they travel around an object, slightly disturbing them, thus preventing unaffected emergence on the other side. In other words, the object would not be cloaked, but rather appear as a spot or shadow. Likewise, the techniques used for fabrication of lab samples are limited to test sizes measured in square inches. Further work delving into mass-producible, active energy material will enable the possibility of completely hiding objects from visible light.[23]

"Why is optical band cloaking relevant today?"[24] Following the dramatic performance of US stealth aircraft during Operation Desert Storm, many nations sought counter-LO technology. Advances in radar, target processing, track correlation, and passive detection all diminish the veil of low observables. As such, it is only a matter of time before current stealth is inadequate protection.[25]

Emergence of Directed Energy Weapons

Defense analysts postulate that China is pursuing novel concepts to defeat American technology with directed energy weapons (DEW).[26] These "new-concept weapons" likely include lasers, microwaves, and particle-beam weapons for both air and space defense missions—all developed to negate anything from low–altitude, unmanned aerial vehicles to high-flying satellites through blinding, degradation, or destruction.

During the last four and a half decades, increases in laser power and suitability have set the foundation for DEWs to enter and eventually dominate battlespace engagements.[27] According to experts at the Air Force Research Laboratory (AFRL), the next two decades will likely bring about additional advancements in beam quality, power, compactness, and magazine depth.[28] Furthermore, DEWs will benefit from more accurate beam steering and tracking, resulting in faster "kills" against operators, sensors, and vehicles at greater distances.[29]

Despite these threats and the added mission difficulty they present, the 2006 Quadrennial Defense Review directed the Air Force to increase its 2025 penetrating component by a factor of five.[30] With stealth's marginalization looming on the horizon, new technology is needed to achieve this goal and assure US access into denied areas. As noted in AFRL's Focused Long Term Challenges (FLTC) for Assured Operations in High Threat Environments, the DOD will require specially designed and/or equipped systems with unique defensive capabilities to go against DE-IADS.[31]

It is in this hostile environment that metamaterial cloaks will prove their worth, as sensors and weapons alike are susceptible to metamaterials' unique characteristics and response functions. Imagine laser beam energy being directed around an aircraft, like water around a stone, neither detecting nor damaging it. Figure 4 depicts the EM spectrum, highlighting current high-power microwave (HPM) and laser weapons ranges for reference.[32] Note that international metamaterials research has exploded over both realms.

DOD senior leadership must maximize metamaterial technology development for two main reasons: first, to maintain airpower relevance in the aforementioned future counteraccess environments and, second, to stay a step ahead of near-peer adversaries. This research will characterize the recent advances in metamaterials and highlight both the benefits and challenges to the US Air Force obtaining an optical stealth capability. Conclusions drawn from this research will help shape DOD investments in metamaterials.

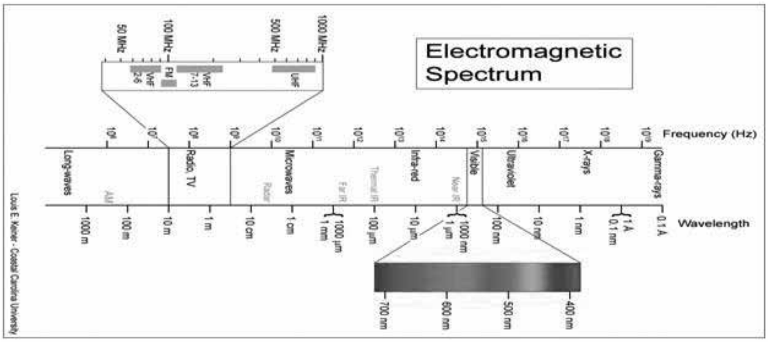


Figure 4. Electromagnetic Spectrum

The Obstacles Ahead: Environmental Scanning

August 2008 was an exciting time for metamaterials research, as scientists at UC Berkeley engineered 3-D materials that reversed the natural direction of near-IR light using optical magnetism. Previous 3-D materials had reported negative refraction but only in the much lower frequency range of microwaves. Similarly, earlier optical frequency materials had been limited to a 2-D, single monolayer of artificial atoms that relied on the physics of resonance to achieve negative refraction. This remarkable development, the creation of "bulk"[33] optical metamaterials with wider spectral ranges and minimized energy loss for all incident angles, was an important step toward the practical application of optical-cloaking technology.[34] To understand where research is heading, one must examine the record of metamaterials, especially the rapid burst of accomplishments made in nanotechnology over the past decade.

Metamaterial history began in 1967, when Veselago, a physicist at Moscow's Russian Academy of Sciences, pondered whether matter interacts with the magnetic field of light. The following year, he published a paper postulating the electrodynamics of "left-handed" materials with simultaneously negative dielectric permittivity and magnetic permeability.[35] The theory would go largely unnoticed until 1992, when John Pendry, of Imperial College's Blackett Laboratory in London, while working on radar-absorbing materials for the Marconi Company, came across Veselago's work. Seven years later, he was successful in creating splint-ring resonators (SRR) that exhibited negative magnetic permeability, magnetized in a direction opposite to that of the applied magnetic field, at specific resonance frequencies. The following year, his subsequent article in *Physics Review* ignited major research activities worldwide.

In 2001 Rodger Walser, from the University of Texas, Austin, coined the term "metamaterial" referring to an artificial composite that achieved performance beyond conventional limitations. Shortly thereafter, researchers at the Defense Advanced Research Projects Agency established their own metamaterials research program and expanded the definition as follows:

> Metamaterials are a new class of ordered composites that exhibit exceptional properties not readily observed in nature. These properties arise from qualitatively new response functions that are: (1) not observed in the constituent materials and (2) result from the inclusion of artificially fabricated, extrinsic, low dimensional inhomogeneities.[36]

Later in 2001, David R. Smith, of Duke University's Pratt School of Engineering, combined an array of SRRs and negative electrical permittivity metallic wires, creating a wedge-type structure comprised of a double negative composite metamaterial to experimentally demonstrate negative refraction at microwave frequencies.[37]

By 2003 numerous research groups, including Boeing Phantom Works and the Massachusetts Institute of Technology's Media Laboratory, had confirmed the initial results of Smith's negative refraction.[38] In February 2005, Andrea Alu and Nader Engheta at the University of Pennsylvania announced that plasmons could be used to suppress scattering by resonating at specific wavelengths, thus cancelling out the energy coming from an object.[39] In May 2006,Pendry suggested that, theoretically, metamaterials could make an invisibility cloak.[40] Five months later, Smith demonstrated the first working two-dimensional cloak, which deflected microwave beams around a five-inch wide cylinder. The material, comprised of copper rings and wires patterned into fiberglass, allowed the concealed volume, plus the cloak, to appear as free space when viewed externally.

In January 2007, researchers at the US Department of Energy's Ames Laboratory developed a metamaterial with a negative refraction index at the red end of the visible spectrum.[41] In April 2007, Purdue University engineers announced a theoretical design for an optical cloak. The following month, California Institute of Technology researchers announced obtaining negative refraction in the blue-green portion of visible light.[42] In August 2008, UC Berkeley researchers created a 10-layer fishnet metamaterial structure fabricated on a metal-dielectric stack using focused ion beam milling, achieving a negative index of refraction for IR wavelengths ranging from 1,475 to 1,775 nanometers (nm).[43] This structure is depicted in Figure 5.[44]

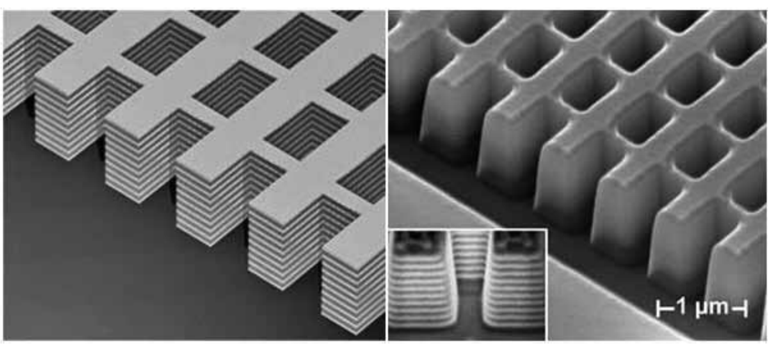


Figure 5. Schematic and scanning electron microscope image of fishnet structure

The researchers also developed a material composed of parallel silver nanowires embedded inside porous aluminum oxide that achieved negative refraction of red light wavelengths as short as 660 nm.[45] This was the first demonstration of bulk media bending visible light backwards.[46] Later that month, Dr. Richard Hammond, a theoretical physicist at the US Army's Research Office, stated that the "proof of principle" regarding the unprecedented level of control of light had been met: "Similar to general relativity . . . the space for light can also be bent in an almost arbitrary way."[47]

In October 2008, Duke researchers covered a small, one-square-inch rounded bump with a metamaterial cloak and shined it with a 13–16 GHz microwave beam. Normal curved material would have scattered the beam, but the metamaterial bump instead reflected the waves back toward the source, just as a flat surface would do, successfully hiding the object from observation.[48] This newest cloak measured four inches in thickness and was made up of more than 10,000 individually arranged pieces. Researchers expect the cloak will function equally as well at frequencies as low as one GHz and as high as 18 GHz.[49]

In a Discovery Channel interview corresponding with this research being published, Smith stated that an invisibility cloak for visible light could be made by June 2009 and that it is only "a matter of coupling the right matter to the right device."[50] Even with the progress made, further exploration of the implementation of metamaterials for DOD applications will require significant improvements in several existing properties. This notion funnels this paper toward its second futures research methodology.

Leading Indicators: Advances and Development

Leading indicators rely on specific factors to announce the approach of an event. As a futures methodology, it has the benefit of correlating results, performance, and proficiency. Specifically, this research focuses on three measurable parameters required to advance metamaterial cloaking capability: operating frequency, bandwidth, and energy loss.[51] The obvious appeal of these leading indicators is that they may signal, or predict, when optical stealth will occur before it actually does.

Metamaterial Frequency Progress

As one should gather from the brief history of metamaterials, progress in this field is rapid, and the scaling of structures from radio to near IR wavelengths, spanning seven orders of magnitude in frequency, occurred in the first seven years.[52] Figure 6 depicts this growth as a solid line. Also shown on the graph, as a dashed line, is the trended expanse of metamaterial research over the next eight years.[53]

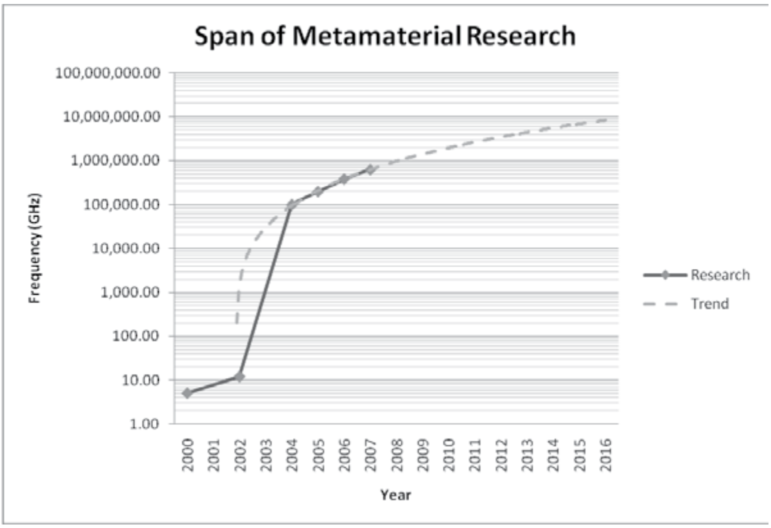


Figure 6. Span of metamaterial frequency research

As with any discovery, one would expect a "leveling off" of the growth curve until some subsequent breakthrough in either theory or technology. If the trend line is accurate, negative refraction of violet light is likely to occur in 2010, with the same happening for ultraviolet (UV) by 2014.[54] Frequency progress alone, however, does not constitute a viable optical cloak capability.

Metamaterial Bandwidth Progress

Bandwidth is equally essential for an operationally significant cloak. Invisibility at a single or narrow frequency is unlikely to be of much value, unless an adversary has only a single sensor or weapon. Unfortunately, current metamaterial capabilities are "narrow" in optical frequency bandwidth. This is understandable, as the majority of metamaterial research has been directed toward achieving negative refraction around a specific frequency and not necessarily a broad-spectrum capability. To date, the widest range has occurred between 780 and 660 nm, expressed as a bandwidth of 70,000 GHz, which occurred in the red portion of light.[55] While this is an impressive feat, a broadband optical cloak would require a far greater accomplishment.

The challenge with bandwidth is that it has a logarithmic relation to frequency. For example, one could blanket all radio and television signals with a one GHz bandwidth. By comparison, to cover the entire IR spectrum from far to near one would require a bandwidth of one million GHz. Tackling the visible spectrum would entail an additional half million GHz bandwidth. Consequently, enveloping the span of the UV spectrum would demand an immense 100 million GHz bandwidth. An optical cloak covering the near-IR through the near-UV would require a 700,000 GHz bandwidth.[56] Further complicating this accomplishment, the cloak's bandwidth would need to be instantaneous, working on all frequencies equally well, all the time.

Unfortunately, sufficient data does not exist to predict when this might occur. As previously mentioned, most research has reported optimal negative index frequencies and not the range over which they occurred. Assuming a relatively constant research effort and a bandwidth growth of 35,000 GHz a year, it will take approximately 17 years to cover the optical spectrum and achieve a broadband cloak.[57] The data points available for analysis are depicted in Figure 7.[58]

Equally discouraging, it is unlikely that a single material will achieve such a broad-spectrum feat any time in the near future. Dynamic control over metamaterial properties is nontrivial, and the desired manipulation of refraction only exists in some finite frequency range, determined by the geometry of the nanostructure.[59] The answer may exist with wavelength tunable structures or "club sandwich" stacking of various materials working on different portions of the EM spectrum. Another solution for tunability in the optical range may involve incorporating electro-optically active materials, such as liquid crystals, into metamaterial

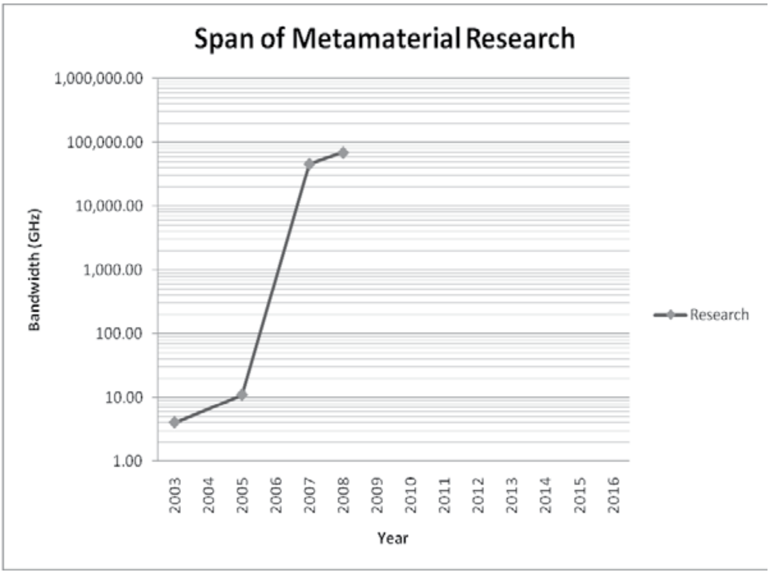


Figure 7. Span of metamaterial bandwidth research

structures.[60] In either case, creating tunable structures in which field intensity is used for dynamic control of transmission properties will require extensive nonlinear studies. Thus, bandwidth may very well present the single greatest hurdle for the operational use of optical cloaking.

Metamaterial Energy Loss

Material energy loss is another significant hurdle that must be overcome to realize a feasible and significant optical stealth capability. In terahertz (THz) or greater frequencies, this loss can contribute significantly to increased scattering. Furthermore, materials themselves have a tendency to absorb portions of EM radiation's power.[61] Obviously, this is important because absorption would degrade cloak performance. Such shortcomings place heavy constraints on the usability of current materials.[62] The UC Berkeley fishnet structure reflected approximately 35 percent of incident radiation per micrometer.[63] By comparison, a standard windowpane reflects only about 4 percent of incident radiation and yet is still considered hardly invisible.

In fact, most researchers are rather guarded when pressed to cite explicit losses for optical metamaterials because such losses are significantly high. Nonetheless, Vlad Shalaev, a professor at Purdue University's Birck Nanotechnology Center, introduced the term "figure of merit" (FOM) to describe them. He defines FOM as the magnitude of the real part of refractive index divided by the imaginary part of refractive index.[64] This means the higher the FOM, the less attenuation per wavelength. To date, reported figures of merit have ranged from 1.3 to 3.5 for IR negative index metamaterial. How does this convert into something more tangible? The reciprocal of FOM is equal to attenuation in units of nepers per radian.[65] Further translated into units of decibels per wavelength, the attenuation of propagation is equal to 54.6637 divided by the FOM.

In other words, an FOM of 3.0 means waves experience a loss of about 18 decibels (dB) per wavelength as they travel though the metamaterial. By comparison, radio frequency (RF) band cloaking materials suffer losses of only 0.5 dB per wavelength.[66] Thus, with present technology, it is difficult to make an optical metamaterial through which waves can travel more than a few microns.

These findings surmise that isotropic 3-D bulk metamaterial designs, with low absorption and high transmission qualities, are required for optical cloaking applications. Any metal-dielectric structure will suffer from an imperfect cloak, however, due to the loss associated with its inclusions. Further research is therefore needed to design metamaterials with lower propagation losses or those that concentrate the electromagnetic fields after refraction has taken place.[67] Likewise, the development of an active medium, one that "pumps" energy toward the surface of the material, is a promising means to compensate for the losses observed in metallic structures.[68] A likely component of such media would be quantum dots or wells.[69] This concept appears both reasonable and feasible within a 20-year horizon.[70]

Backcasting: What are the Metamaterial Hurdles?

Backcasting represents a strategic approach toward developing technology. This method begins with a successful outcome, in this case an operationally significant and feasible optical cloak, and then predicts backwards what milestones must occur to make it a reality. The benefits of backcasting are that it does not limit the range of options, stifle creativity, or project current shortcomings into the future. Backcasting typically involves four main steps. First, define the future goal. Second, analyze the technological and physical characteristics of a path that would lead toward that goal. Third, evaluate the path in terms of physical, technological, and socioeconomic feasibility and policy implications. Fourth, brainstorm ways this desired end-point can be achieved, working backwards to the present.[71] For sake of brevity, this paper uses a minimalist approach to backcasting and focuses more heavily on milestone analysis.

Define the Goal

Assuming metamaterials will span the breadth of the optical band by the year 2014 and that both bandwidth and energy losses will be tackled during following decade, an optical cloaking capability should be available around 2025. For metamaterials to be operationally significant and feasible, they must provide a needed utility—in this case, cloaking—without being overly detrimental toward form factor or aircraft functionality.

Analyze the Technological and Physical Characteristics

Material must be taken from the lab and placed in the hands of the engineers who will marry it to an operational system. For this to occur, the material must be somewhat resilient, and must be able to be cut, bent, molded, or shaped. They must withstand heating and cooling, and otherwise fare well within the environment for which they are intended. The material need not be easily manufactured, but it should be able to be repaired. Weight and thickness cannot be prohibitive to flight, nor can the material interfere with aerodynamics and laminar flow.[72] The material should be strong enough to bear loads and withstand g-forces. It should experience graceful versus rapid degradation and have a multiuse service life. The material should not reduce one signature while raising another. With these factors in mind, the resounding consequence is that metamaterials will need to be comparable in almost every way to contemporary aircraft composites, while at the same time providing the unique EM response function of cloaking.

Evaluate the Path

Socioeconomic feasibility enforces the notion that metamaterials must be resilient and reusable. Furthermore, materials should be safe to handle and disposed of easily. In other words, highly toxic materials are less likely to be pursued due to their environmental-economic impacts.

What about metamaterial research itself? Dispersed, unclassified research conducted in parallel at government laboratories and college universities promotes intellectual sharing while imbuing a sense of competition and reducing costs. At a certain level of technology maturation, however, industry must take the baton and, using its larger budgets and scales of production, present an operational capability.

It is at this systems level that research is driven toward classification, thereby safeguarding cloaking capability and technology. Policy implications also raise an interesting question. Once a cloaking capability is operational, does one announce it, hoping it acts as a deterrent, or keep it a secret, waiting for the opportune time to use it? Both cloaking research and application policy are likely to be shaped by future events and the global political landscape. Perceived need, however, will often trump all other considerations.

Brainstorm to Achieve the Desired End Point

In essence, backcasting asks the question, "What must we consider today to achieve a decisive optical stealth capability in the future?" As summarized by the numerous concerns previously listed, the answer is that one must overcome the challenges of metamaterial durability, suitability, and manufacturability. The next section of this paper addresses and analyzes these issues.

Tackling Limitations within an Operational Context

Because metamaterials research is still in its first decade, all reported findings have taken place in controlled laboratory settings. Therefore, when discussing limitations, one must consider not only the hurdles directly ahead but also the ones farther down the track.

As mentioned previously, the conceptual requirements for a metamaterial cloaking capability lie ahead. Functional requirements lie even farther ahead but must be addressed in the present to better focus research dollars and time. Specifically, this paper addresses the challenges of durability and suitability.

Durability

A convenient definition of durability is the quality of a material to be useful even after an extended period of use. To date, metamaterials are generally characterized as lightweight, thin, fragile, and largely metal. As one moves through microwaves and into the IR and visible light, wavelengths become shorter, and metamaterial structure is forced to the nanoscale. While RF cloaks are upwards of one-tenth of a meter in thickness in the GHz frequency bands, cloaking at visible frequencies dictates materials on the order of one micron, or one millionth of a meter, in thickness.[73] By comparison, the average piece of paper is about 80 microns thick. This is great news for the engineer worried about weight, but bad news for the one worried about material ruggedization. The laws of physics and the desired range of cloaked wavelengths will ultimately dictate metamaterial thickness. Weight and strength, however, may be negotiable design characteristics.

In April 2008, researchers at Los Alamos National Laboratory published their findings citing their success with THz frequency metamaterials fabricated by stacking multiple layers of thin but flexible substrates.[74] For a material to be useful to aircraft, it must be able to withstand vibration, acceleration, and loading. Furthermore, such material must be able to be molded or shaped according to aerodynamic or functional need. Thus, flexible or conformable metamaterials are essential to any cloaking application. Fabrication techniques using rigid or fragile substrates, such as silicon, are clearly unfit.[75] Polyimide fillers, on the other hand, have been utilized in multilayer far-IR frequency metamaterials with promising results.[76] In fact, polyimides have been widely used for photonic and electronic devices for many years because of their high electrical and thermal stability. Their flexibility, durability, and relatively low refractive index and absorption also make them favorable as a THz metamaterial substrate.[77] Los Alamos researchers verified that a substrate stacking fabrication approach could produce an effective bulk 3-D, durable, and conformable metamaterial. This represents an important step in realizing functional optical cloaking devices.

Though further research is needed to create durable optical cloaking metamaterial shells, this eventuality is definitely closer, mostly due to the previously mentioned bulk 3-D designs developed by the UC Berkeley and Los Alamos National Laboratory research teams.[78] True durability, however, will not be measured in the lab but in realistic environmental settings by the maintainers and operators.

Suitability

This paper defines suitability as the level of adaption required to produce a feasible and operationally significant metamaterial cloak. Specifically, this research investigates the environmental limitations and cloaking shell properties of current metamaterials. The US Air Force test and evaluation community acknowledges that suitability has a large impact on effectiveness, and thus designates an acquisition objective of fielding operationally suitable systems. Furthermore, it dictates that suitability should be assessed from early development through fielding.[79] Thus, when leaving the laboratory and entering the realm of airpower, one has to contend with the conditions of moisture and temperature.

Environmental Limitations. Weather is likely to have a considerable impact on cloak employment for the foreseeable future. Clouds and fog consist of tiny, transparent water droplets suspended in air that scatter light. This is germane to the topic at hand because if droplets were allowed to accumulate on the surface of a cloak, light would be scattered instead of deflected, thereby reducing the cloak's effectiveness. Furthermore, studies indicate that surface perturbations greater than one-tenth of the desired wavelength could be significant to scatter incident waves.[80] This means that any cloak shell would have to be kept immaculately clean or imbued with some selfcleaning or aerosol repelling capability. Though not impossible, this does add another element for consideration.

If one cannot repel water vapor or aerosols,[81] one must avoid them, which dictates flying above the troposphere, a height of about 12 kilometers (km) or 39,000 feet. [82] The water vapor mixing ratio reaches its minimum at around 16 km or 52,000 feet. Maximum cloak effectiveness may require the clear sky conditions of this medium- to high-altitude regime. Furthermore, a cloak-equipped aircraft would need timely and accurate weather information as well as the ability to adjust its flight profiles to avoid cloudy or precipitous conditions. As seen in figure 8, an added benefit of an increase in altitude is a decrease in ambient temperature.[83] Why this is both important and beneficial is not intuitive.

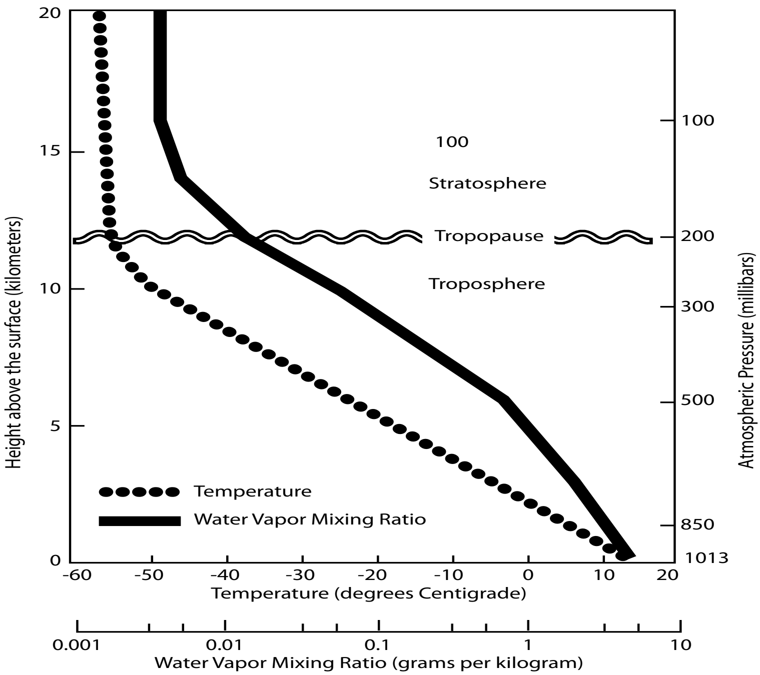


Figure 8. Mean atmospheric temperature and water vapor mixing ratio

Metamaterials are basically nanoscale current loops. In other words, they are a series of circuits and therefore susceptible to thermal noise.[84] Hence, the optical conductivity of metals, and thus cloak efficiency, could increase by a factor of six if ambient temperature is decreased from standard room down into the cryogenic range[85] As seen in the figure above, flying at 16 km, or roughly 52,000 feet, one could decrease the ambient temperature to around -55 degrees Celsius. This is far from the realm of cryogenic temperatures, but it nevertheless has the impact of reducing transmission loss by a factor of four.[86]

These factors illustrate that initial metamaterial cloaking may be relegated to the environmental "sweet spot" between 45,000 and 65,000 feet, where temperature and water vapor are minimized. This does not mean that an optical cloak would not work in weather or at the higher temperatures of lower altitudes. It simply means that in those environments, it might not be perfect and may require further advances in technology. This raises the fundamental question: "Just how well does an optical cloak really need to work?"

Acceptable Level of Performance. When discussing acceptable levels of imperfection, it is important to acknowledge that initial optical cloaks will likely perform at discrete sets of frequencies. Even the next iteration may only work reasonably well, certainly not perfectly, at a wider frequency range.[87] However, contrary to popular belief, a cloak does not have to be perfect. The Air Force test and evaluation community states that for a system to be suitable, it must be reliable enough to accomplish the mission.[88] Thus, perhaps simply reducing one's visual signature is a success. Imagine optically shrinking a KC-135-sized aircraft down to that of an F-16 or smaller!

An imperfect optical cloak may not completely hide an object but instead distort its image or shrink its observed size down to that of a spot. The desired result may be obtained by simply degrading the enemy's capability or shaking trust and confidence in their systems. In this regard, initial optical metamaterials will be much like current-day stealth. Furthermore, cloaks may intentionally be designed with some level of imperfection to facilitate the integration of aircraft sensors, communication, and navigation systems.[89]

Likewise, unless one is only concerned about cloaking gliders or dirigibles, breaks in the shell will be required for inlets and exhausts. Interestingly enough, complete cloak coverage is, in fact, not necessary. Even a partial cloak can still reduce the overall scattering to a wide angle of observation. Similarly, an increase in the physical/electrical size of an object does not lead to an increase in the cloak's overall scattering cross-section. It is the percentage, and not the actual amount, of surface area covered that determines effectiveness. Research indicates that with only 50 percent coverage, about a 90 percent reduction in observed spherical surface could be accomplished.[90]

Cloak design is also not restricted to symmetry or shape.[91] Thus, a cloak may only need to work well enough to deny the enemy the opportunity to establish a targetable first look. With this in mind, the linchpin of cloak effectiveness may well be determined by the feasibility and cost of manufacturing.

Manufacturability

Optical band metamaterials, as a whole, are challenging to make. One must ask, then, "What is the feasibility of mass-producing 3-D metamaterials?" Clearly, the challenge exists to develop a means to overcome fabrication challenges and allow manufacturing on a large scale. To get an idea of the scale of this task, in mid-2006 a lab's typical metamaterial output, in a single batch, might only fill a coffee cup.[92]

Output rate is largely determined by the complexities of material being created. Unfortunately, optical metamaterials are extremely intricate. These materials rely on nanoscale technology—in essence, designing and building electronics in which every atom and chemical bond is specified precisely.[93] With tolerances less than 10 nm when approaching the UV, fabrication of optical band materials requires strict synthesis, patterning, and/or direct assembly.

Nevertheless, some progress has been made in metamaterial manufacturing. Direct laser writing through chemical vapor deposition is a promising technique for fabricating large-scale materials.[94] Other successful techniques include electron beam nanolithography and monolithically growing materials on a single substrate using multilayer processing.[95] Further studies on advantageous bottom-up, "self-assembly" fabrication need to be conducted.[96]

Contrary to the economics of high technology, however, metamaterials need not be expensive or time consuming to manufacture. Duke University's October 2008 microwave cloak was cheap and easily producible. Using a transformation optics approach, researchers developed a systematic algorithm that "vastly speeds the metamaterial cloak-design process and makes the design of complex media possible."[97] The researchers used hobby-level circuit boards at a cost of about one dollar per square inch to cloak a bump. At an equivalent rate, one could cloak both the top and bottom sides of an F-16's wings for $86,400.[98] According to Smith, "If you were to commercialize this technology, it would cost next to nothing."[99] Even more impressive, it took Smith and his colleagues only about nine days to design and implement the experiment.[100]

With the investigation of challenges complete, one must analyze the information at hand to better understand the time frames and applications of optical metamaterials.

Analysis

Technology is created from existing knowledge and often through measured iterations, with each intermediate step conferring an advantage of its own. For these reasons, the next two decades are likely to see three distinct generations of optical metamaterials.

The next four years, 2010–14, will be categorized as Generation One: specific use and narrow frequency bandwidth, on the order of 250,000 GHz. This iteration will be centered around the near-IR radiation band and able to cover about a quarter of the IR spectrum. Cloaking will be imperfect and require maximized flight profiles. Generation One, in point of fact, will be more of a shield than a cloak, designed to protect an aircraft's critical systems against a weapon, such as IR lasers, or degrade an enemy sensor, such as an IR laser rangefinder. Generation One will also be appliqué in nature, a metamaterial armor with the ability to be married to a wide range of systems, though cost and weight may be prohibitive.[101]

The subsequent five to 15 years, 2015–24, will be categorized as Generation Two: limited use but with a bandwidth approaching the entire optical frequency range, roughly 300 to 3,000 THz. This will require several tunable materials working in concert. Cloaking will still be imperfect but more effective over a wider environmental range. Generation Two will be an improved shield, designed to reduce optical signature and provide protection from numerous laser frequencies. Materials will be a mix of appliqué and those imbedded within an aircraft's skin/structure. "Shield Plus" will be found on a wide range of systems, though weight may still be prohibitive in some cases.

The last 15- to 25-year period, 2025–34, will be categorized as Generation Three: wide use and broadband frequency range from IR to UV provided by a single, though layered, active material. Cloaking will be perfected, thus achieving optical stealth as well as DE protection in most environments. These materials will be integral to aircraft design and function as both skin and structure. Weight is no longer prohibitive, but cost may drive production to relatively few numbers of such aircraft.

Implications

> *Would you tell me, please, which way I ought to go from here? That depends a good deal on where you want to get to, said the Cat.*
>
> —Lewis Carroll
> *Alice's Adventures in Wonderland*

Laboratory research has melded physics with materials science and designed matter with unique EM characteristics and response functions. Metamaterials exhibit exceptional, unnatural properties; namely, the ability to manipulate EM waves in ways previously only dreamed about. Cloaking is a proven phenomenon with broad applications. Thus, metamaterials promise significant technological advances in stealth and survivability across the EM spectrum, from radio through UV frequencies. The Air Force will require this capability against a counter-LO, DE-equipped IADS.

The near-term reality is that optical band cloaks/shields will be designed for specific purposes and possess relatively narrow capabilities. Ironically, this may serve to defeat many sensors and weapons. Because of atmospheric windows and the availability of suitable components, laser and IR systems are built at specific wavelengths. The following table depicts several such systems and their operating parameters.[102]

Table 1. Sampling of active IR and laser devices

PURPOSE	WAVELENGTH (nm)	FREQUENCY (THz)	BAND
Laser Dazzler	532	563.9	Visible (Green)
Aiming Laser (Sight)	633	473.9	Visible (Red)
Laser Illuminator	830	361.4	Near-IR
Laser Target Designator	1,064	282.0	Near-IR
High-energy, Chemical Oxygen Iodine Laser	1,316	228.0	Near-IR
Laser Range Finder	1,540	194.8	Near-IR
Laser Detection and Ranging	10,600	28.3	IR
Infrared Line Scan	12,000	25.0	IR

Adapted from Guercio, Sabatini, and Vignola, "Eye-Safety Analysis;" Crane, "New Laser Technologies;" Jane's Electro-Optic Systems 2008-2009; and http://www.optotronics.com/laser-dazzlers.php.

Today, albeit under laboratory conditions, any one of these devices could be degraded or defeated by a metamaterial. Furthermore, technology is advanced enough that a single material is close to being able to work against three out of four near-IR devices simultaneously. With further research, resources, and time, a single metamaterial cloak may very well be able to elude or defeat all of these and countless other sensors and weapons.

Relevance in Low-Technology Scenarios

This paper has addressed the benefits of optical band cloaking in a high-tech DE-IADS environment. But what about the other end of the conflict spectrum? Does cloaking promise any advantages in low-intensity, counterinsurgency engagements? The answer is a resounding yes.

A modern military, one heavily dependent on technology, is quick to forget that the most prolific battlespace threat, and in many ways the toughest to beat, is still the human eye. Likewise, the US military has yet to fully recognize the increasing threat of aircraft being tracked and engaged by electro-optical and IR means; namely, laser-beam riding or IR-guided missiles and visually aimed weapons such as antiaircraft artillery, rocket-propelled grenades (RPG), and small arms. During operations in both Somalia and more recently in Iraq, an alarming number of rotary wing aircraft were damaged or downed by RPGs and small arms.

Similarly, both the lethality and proliferation of nonradar-guided surface-to-air missiles (SAM) have been on the rise. During the course of Operation Desert Storm, approximately 80 percent of US fixed-wing aircraft losses were attributed to IR SAMs. Moreover, they account for a staggering 90 percent of all aircraft lost in combat in the past 15 years.[103] Equally sobering is that IR seekers have ever-improving counter-countermeasure capabilities that seriously degrade the effectiveness of flares and jammers. Reducing optical signature through metamaterials may present the single best means of combating the low end of the threat spectrum.[104] In fact, metamaterial cloaking in the IR and visible bands will allow persistent intelligence, surveillance, and reconnaissance (ISR) and rapid attack operations against a wide range of air defense forces.

Disruptive Capability in the Hands of the Enemy

US Joint Forces Command's *Joint Operating Environment 2008* sets the stage for a grim possibility. "Advances in technology will continue at an exponential pace as they have over the past several decades. Some pundits have voiced worries the United States will lose its lead as the global innovator in technology or that an enemy could make technological leaps that would give it significant advantages militarily."[105] With this in mind, this paper would be remiss if it did not ask the question, "What could an enemy do with this technology?"

Invisibility, much like stealth, has the unique ability to convey a sense of invulnerability or invincibility, highly desirable for both striking first and creating fear. Imagine an enemy that can frustrate our ISR efforts by not just camouflaging by cloaking their high-value targets. An adversary that we cannot find, fix, or track presents quite a dilemma. Imagine the panic of finding an enemy we cannot engage because it can defeat our laser designators/ range finders.

Recommendations

Is optical invisibility just a gimmick, or does it offer a highly desirable and essential warfighting capability? Even skeptics are apt to offer a nod of support. This author concedes the point that invisibility is an advantage only when your adversary is not expecting you. Furthermore, it is "only of fleeting value at best if your adversary knows that you are there."[106] Thus, optical stealth does not diminish the value of radar or acoustic stealth. As a result, optical cloaking may only be seen as a more perfected form of camouflage.

Future aircraft, however, will need special capabilities, beyond current stealth properties, to survive in a DE-IADS environment. Furthermore, the future may not be as far off as one would hope. In December 2008, Boeing successfully acquired, tracked, and shot down an unmanned aerial vehicle with a truck mounted laser.[107] Fortunately, metamaterials are a promising avenue to shield systems from disruptive radio waves, electric and magnetic fields, and laser weapons.[108]

This paper sought to answer the question, "Will metamaterials facilitate an operationally feasible and significant optical stealth capability for the US Air Force?" The answer is a qualified yes, assuming the United States establishes itself at the forefront of this science and funds and conducts further research that eventually proves its worth during operational testing. As a senior advisor at the National Science Foundation so aptly stated, "A keystone of US defense posture includes maintaining a strong science and technology R&D [research and development] program in order to have leading edge technologies available for timely weapons development as required."[109]

Areas for continued DOD research in the pursuit of metamaterial cloaking technology were highlighted in this paper. Specifically, the near-term objective should focus on developing laser protection and reducing the optical signature of currently fielded systems.

Metamaterials represent an emerging technology with far-reaching and broad potential that may well usher in an era of "EM dominance." Just as Perseus used an enchanted helmet to sneak up on and slay Medusa, metamaterials represent a practical way to defeat the DE-IADS monster by negating its deadly gaze. Based on frequency trends and assumptions made about bandwidth and material energy loss, this paper predicts a broadband optical cloaking capability, in the laboratory at least, by the year 2025.

1 October 2029 Continued

Having delivered a devastating blow to the enemy's operations center and DE defense sites, the sole aircraft created an opportunity for the lesser capable follow-on forces to mass and prosecute the remaining bulk of the attack plan. The lethal first strike would wreak havoc on the IADS for several hours, a duration estimated to span the entire succinct but brutal conflict. The aircraft had only been visible for a brief instant, when the weapons bay doors opened to dispatch its deadly payload. Aircrew morbidly referred to this as "seeing the Cheshire's smile."

Safely back over the East China Sea, the optical cloak was disengaged. The now visible aircraft gave a slight wing roll to correct to course, revealing the subdued roundel of the People's Liberation Army Air Force. The United States and its Taiwanese allies had just been introduced to the devastating capability of the next revolution in military affairs—metamaterial cloaking.[110]

Conclusion

Metamaterial cloaking represents the pinnacle of electronic protection and the next generation of stealth.[111] This technology has a broad and demonstrated application of concept that stretches from radio to UV frequencies. Hence, it should be an integral element of future Air Force systems. Though it might be two decades before invisibility becomes a reality, it would be in the DOD's best interest to further metamaterial research and consider safeguards against possible misuse. Cloak-endowed aircraft will possess improved covertness and survivability against optical-based defense systems and contribute to a much-needed daylight stealth attack capability. Hence, optical cloaking represents a clear combat advantage.

Initially equipping small numbers of various weapon systems with metamaterial will represent a significant and viable "Silver Bullet Force," protected against, and capable of engaging and destroying long-range advanced DE-IADS. In doing so, the Air Force will be able to penetrate and reign uncontested in the battlespace. Should laser weapons become the IADS long-range "shooters" of choice, the Air Force may very well find that survival requires a majority of its air- and space-based assets to possess an optical-cloaking capability.

As with any disruptive technology, the fundamental issue will be how affordably, quickly, and effectively one can incorporate metamaterials not only into concepts, doctrine, and approach to war but into the actual units and commands that will require those technologies.[110] In the future, someone will develop a suitable broad-spectrum cloak. Merely hoping that it will belong to the United States is not a prudent strategy.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. Once a beautiful maiden, Medusa enraged the goddess Athena, who transformed her hair into serpents and made her face so terrible to behold that the mere sight of it would turn a man to stone. http://www.greekmythology.com/Myths/Creatures/Medusa/medusa.html.

2. Carroll, *Alice's Adventures in Wonderland*.

3. Smith, "What are Electromagnetic Metamaterials?"

4. Liu et al., "Broadband Ground-Plane Cloak," 366.

5. Joint Publication (JP) 3-13.1, *Electronic Warfare*, I-8. *Directed energy* (DE) is an umbrella term covering technologies that produce a beam of concentrated *electromagnetic* (EM) energy or atomic or subatomic particles. A DE weapon is a system using such technology as a direct means to damage or destroy adversary equipment, facilities, and personnel. DE applica-

tions easily fit into traditional energy weapons (EW) roles. For example, a laser designed to blind or disrupt optical sensors are, in EW terms, electronic attack. A visor or goggle designed to filter out the harmful wavelength or laser light is electronic protection.

6. Smith, "Weapons of the Future Are Here." Isoluminosity is the phenomenon that occurs when different objects displaying the same brightness seem indistinguishable from each other. In the 1940s, the US Navy developed operation "Yahootie," the first practical attempt to create an invisible aircraft. A string of bright lights was placed on the wings and propeller hubs and crews adjusted the lights to match the natural background light behind the aircraft, masking it against the sky.

7. Visual light plus elements of the near-infrared (IR) and near-ultraviolet (UV) spectrum, expressed as wavelengths from roughly 1,000 to 100 nanometers.

8. Hebert, "Great Expectations," 32.

9. DOD, *Capstone Concept for Joint Operations*, 15 January 2009, iv.

10. National Research Council, *Future Air Force Needs for Survivability*, 52.

11. DOD, *Capstone Concept*, 4.

12. Hebert, "Great Expectations," 33.

13. Bloomfield, *How Things Work*, 524–25, 527. Index of refraction is defined as the ratio of the speed of light in a vacuum to that in a material. It also quantifies how strongly a material reflects light on its surface.

14. Hecht, "Photonic Frontiers: Negative-Index-Materials."

15. Fang to the author, e-mail.

16. Krowne, The "Electronics and Physics."

17. Shalaev, "Optical negative-index metamaterials," 41.

18. Schuring et al., "Metamaterial Electromagnetic Cloak," 977–79.

19. Duke University, "David Smith."

20. Goshen, "Invisibility cloak moves from fantasy."

21. Yang, "Invisibility shields one step closer."

22. Voland, " 'Invisible' materials bend light."

23. Duke University, "David Smith."

24. The science behind cloaking can be applied to the entire EM spectrum. However, the scope of this paper is merely to discuss the benefits of doing so in what the author refers to as the "optical" bands, roughly 300 to 3,000 terahertz (THz), which includes near-IR and near-UV radiation.

25. Thill, "Penetrating the Ion Curtain," 12.

26. Fitzgerald, "China Plans to Control Space;" Pillsbury, *An Assessment of China's Anti-Satellite*, 12; and Thomas, *Cyber Silhouettes*, 235.

27. Thill, "Penetrating the Ion Curtain," ix.

28. Air Force Research Laboratory (AFRL), "Focused Long Term Challenges (FLTC)," 3.5, 3.6, 4.1, and 5.2.

29. Thill, "Penetrating the Ion Curtain," 11.

30. Hebert, "Great Expectations," 34.

31. AFRL, "FLTC," 5, states the capability vision for achieving mission objectives with impunity against full-spectrum threats, from antiaccess integrated air defense system to cyber: anticipate threats and avoid through stealth and deception, detect and defeat through defenses, survive the attack through adaptive and passive protection, and recover from threat effects.

32. Wikipedia, “Electromagnetic Spectrum;” high-power microwave and laser weapons highlights added by Thill, “Penetrating the Ion Curtain,” 5; and metamaterial research material added by author.

33. Material thickness greater than 10 times the size of a wavelength of light.

34. Yao et al., “Optical Negative Refraction,” 930.

35. Defense Advanced Research Projects Agency (DARPA), “Negative Index Materials.”

36. Smith, “What are Electromagnetic Metamaterials,” 1.

37. Ozbay, “The Magical World of Photonic Metamaterials,” 23.

38. Padilla, Basov, and Smith, “Negative refractive index materials,” 32.

39. Alu and Engheta, “Achieving transparency with plasmonic coatings;” and Dawson, “More information on Surface Plasmons.” Quanta of waves are produced by collective effects of large numbers of electrons in matter when the electrons are disturbed from equilibrium.

40. Sanderson, “Unexpected tricks of light,” 364.

41. Ames Laboratory, “Metamaterials found to work for visible light.”A wavelength of 780 nanometers (nm), or expressed as a frequency, 385 THz.

42. Lezec, Dionne, and Atwater, “Negative Refraction at Visible Frequencies,” 430 (wavelengths of 476 to 514 nm expressed as a frequency of 630 THz); and Yang, “Invisibility shields one step closer,” alternating layers of silver and magnesium fluoride.

43. Ozbay, “The Magical World of Photonic Metamaterials,” 25.

44. Yang, “Invisibility shields one step closer.”

45. Expressed as a frequency of 454 THz.

46. Yang, “Invisibility shields one step closer.”

47. Kyzer, “Army research on invisibility,” blogger’s roundtable discussion on the development of metamaterials.

48. Liu et al., “Broadband Ground-Plane Cloak,” 366.

49. Ibid., 366, 368.

50. Bland, “Invisibility Cloak Closer than Ever.”

51. DARPA, “Negative Index Materials.”

52. Padilla, Basov, and Smith, “Negative refractive index materials,” 28–29.

53. In order to predict metamaterial development, the author chose a polynomial trendline, as it best relates the process to an engineering and manufacturing endeavor. New scientific discovery, however, would likely produce logarithmic growth. Omitted from the graph was data lower than one GHz frequency. Data points obtained from numerous sources, but largely from Padilla, Basov, and Smith, “Negative refractive index materials;” and Shalaev, “Optical negative-index metamaterials.”

54. Bohren and Huffman, *Absorption and Scattering of Light by Small Particles*, 256–57. This prediction was based upon the assumption that any and all metamaterial research, such as negative index of refraction, can leverage cloaking applicability. In effect, any knowledge is knowledge for the cause. Progression below 330 nm wavelengths promises to be difficult as all free-electron metals exhibit transparency near this plasma frequency. Light in UV region is strongly absorbed because the photon energy matches energy differences between filled and empty electron energy levels.

55. University of California, Berkeley, August 2008.

56. Wavelengths from 1,000 nm to 330 nm, respectively.

57. Between 2007 and 2008, the bandwidth growth appears to have been about 24,000 GHz. The assumption is that at some point in the near future, increasing bandwidth will become the aim of research efforts and that technology and science will drive added material functionality.

58. Data points from numerous sources, but largely from Padilla, Basov, and Smith, “Negative refractive index materials;” and Shalaev, “Optical negative-index metamaterials.”

59. Shadrivov and Kivshar, “Nonlinear Effects in Left-Handed Metamaterials,” 331, 332.

60. Shalaev, “Optical negative-index metamaterials,” 46.

61. Cummer et al., “Full-wave simulation of electromagnetic cloaking structures,” 4.

62. Fang to the author, e-mail.

63. Valentine et al., “Three-Dimesional optical metamaterials,” 378–79.

64. Cummer to the author, e-mail. The imaginary part of the index controls the exponential field decay rate in relation to distance, while the real part of the index controls wavelength. Thus the ratio of the two, expressed as field decay per wavelength, is inversely proportional to figure of merit.

65. A neper is a logarithmic unit of ratio, used to express gain, loss, and relative values. Like a decibel, it is a logarithmic scale unit, the difference being that instead of using base-10 logarithms, the neper uses base e (~2.71828). The neper is often used to express ratios of voltage and current amplitudes in electrical circuits, whereas the decibel is used to express power ratios. http://www.microwaves101.com/encyclopedia/neper.cfm.

66. Cummer to the author, e-mail. This translates into a FOM of 108.

67. Plumridge, Steed, and Philips, “Negative refraction in anisotropic waveguides,” 20,548–55.

68. Ozbay, “The Magical World of Photonic Metamaterials,” 27.

69. Paschotta, *Encyclopedia of Laser Physics and Technology*. A *quantum well* is a thin material structure which confines electrons in the dimension perpendicular to the layer surface, whereas the movement in the other dimensions is not restricted. The confinement has profound effects on the density of states for the confined particles. Similarly, *quantum dots* are small structures that confine particles in all three dimensions and are considered a kind of artificial atom where the energy levels can be adjusted by design (e.g., by controlling the quantum dot dimensions or the material composition).

70. Cummer to the author, e-mail.

71. Victoria Department of Sustainability, “Backcasting.”

72. Both considerations are largely dependent on what one wants to cloak and at what frequencies. Regarding the optical band, this is unlikely to be a cause for concern. Frequency has an inverse relation to material thickness; the higher the desired frequency, the thinner the cloak material. As such, optical band metamaterials will be no thicker than a piece of paper. Furthermore, metamaterials could replace aircraft paint. Thus, the issue of weight is null.

73. Cummer et al., “Full-wave simulations,” 3.

74. Azad et al., “Flexible Quasi-Three-Dimensional Terahertz Metamaterials,” 1.

75. Ibid.

76. A *polyimide* is a polymer of carbon-nitrogen monomers. Known for thermal stability, good chemical resistance, and excellent mechanical properties, it can be combined with graphite or fiberglass for increased flexural strength. Polyimides also exhibit high tensile strength and very low tendency to deform permanently during continuous use at temperatures of 450°F (232°C) and for short excursions as high as 900°F (482°C). Furthermore, polyimides are not affected by commonly used solvents and oils and resist weak acids. Such polymers are often used for flexible cables, high temperature adhesives, and mechanical stress buffers. From various sources, including http://www2.dupont.com/Kapton/en_US/index.html; http://www.professionalplastics.com/POLYIMIDE; and http://www.nasa.gov/home/hqnews/2008/dec/HQ_08333_Commercial_Invention.html.

77. Azad et al., "Flexible Quasi-Three-Dimensional Terahertz Metamaterials," 1.

78. Voland, "'Invisible' materials bend light."

79. Hamilton, address.

80. Fang to the author, e-mail; and Cummer et al., "Full-wave simulation," 4. For sunlight, this means a surface irregularity of greater than 56 nm could cause scattering. By comparison, the average thickness of a human hair is 90,000 nm.

81. Bohren and Huffman, *Absorption and Scattering of Light*, 434 and 436. Atmospheric aerosols refer to the solid and liquid particles in the earth's atmosphere, excluding those of water in clouds, fog, and rain. Sizes range from 0.1 to 10 micrometers and include surface dust, sea spray, and sulfur compounds. Although very tenuous and highly variable, they act as condensation nuclei and alter the optical properties of clouds. Aerosols are of military importance, especially in the applications of space-based visible and IR surveillance and laser-guided weapons.

82. The troposphere is the lowest portion of Earth's atmosphere, containing approximately 75 percent of its mass and nearly all the water vapor and aerosols. The average height of the troposphere is about six nm in the middle latitudes, deeper at the equator (11 nm), and shallower near the poles (4 nm). http://www.metoffice.gov.uk/education/secondary/teachers/atmosphere.html.

83. American Geophysical Union, "Water Vapor in the Climate System."

84. Also referred to as Johnson noise, it is the random white noise generated by thermal agitation of electrons in a conductor or electronic device and is proportional to the absolute temperature of the conductor. The thermal noise level is the limiting minimum noise any circuit can attain at a given temperature. http://www.sengpielaudio.com/calculator-noise.htm. This corresponds to 20 and -150 degrees Celsius, respectively.

85. Fang to the author, e-mail.

86. The formula for calculating noise voltage is $\sqrt{4k_B T \Delta f R}$, where κ_B is the Boltzmann constant, T is the absolute temperature in Kelvin, Δf is the bandwidth, and R is the resistance of the circuit element.

87. Cummer to the author, e-mail.

88. Hamilton, address.

89. Interestingly enough, cloaking theory suggests that EM energy should be able to penetrate cloaks from the inside out while redirecting that same energy from coming in. This would suggest that cloaks may

need some blanking capability or that any sensors and communications will have to operate out of cloak band.

90. Fang to the author, e-mail.

91. Rahm et al., "Design of Electromagnetic Cloaks," 91.

92. Markey, "Invisibility Cloak Possible," 2.

93. Hall, *Nanofuture*, 21.

94. Ozbay, "The Magical World of Photonic Metamaterials," 25 and 26.

95. Ibid., 23; and Azad, "Flexible Quasi-Three-Dimensional Terahertz Metamaterials," 1.

96. Park and Kim, "Negative-Index Materials," 910.

97. Liu et al., "Broadband Ground-Plane Cloak," 366.

98. An F-16 has a wing area of 300 square feet, or total surface area of roughly double that.

99. Smith, quoted in Bland, "Invisibility Cloak Closer than Ever."

100. Bland, "Invisibility Cloak Closer than Ever."

101. As stated previously, the thickness of a cloak has no relation to the size of the object being hidden. Thickness only depends upon the frequency of the EM energy that is to be negated. As such, an optical band cloak would be paper-thin for both a Boeing 747 and a hummingbird. The added weight might be negligible for the jumbo jet while disastrous for the bird.

102. From various sources, including http://www.optotronics.com/laser-dazzlers.php; Guercio, Sabatini, and Vignola, "Eye-Safety Analysis," 1; Crane, "New Laser Technologies;" and Jane's Electro-Optic Systems 2008–2009.

103. http://www.globalsecurity.org/military/systems/aircraft/systems/ircm.htm; Erwin, "U.S. warplanes vulnerable," 26; and Puttré, "Facing the Shoulder-Fired Threat," 39.

104. As an aircraft travels through air, the very molecules that comprise the atmosphere "rub" against its skin, generating friction, and ultimately heat and IR radiation. A cloaking shell would also be susceptible to this phenomenon. Specifically designed metamaterials, however, could redirect or greatly absorb this radiation, to avoid the watchful eyes of passive detectors.

105. US Joint Forces Command (USJFCOM), *Joint Operating Environment 2008*, 37.

106. Smith, "Blueprint for Invisibility," 6.

107. "The Monitor News," *Journal of Electronic Defense*, 24.

108. Cho, "High-Tech Materials," 1,120.

109. Dr. Mihail C. Roco, senior advisor for nanotechnology, National Science Foundation, quoted in Berbube, *Nano-Hype*, 105.

110. How realistic is this "surprise" ending? Though the probability of such an aggressive Chinese action may be low, the technical aspects of such a feat is possible based upon two facts. First, China has been on the leading edge of metamaterial research. Duke University's January 2009 cloaking research was supported by InnovateHan Technology, the National Science Foundation of China, the National Basic Research Program of China, and the National Science Foundation of Jiangsu Province, China. Second, if the gross domestic product alone directly translates into military power, in the 2030s China would have the capacity to afford military forces equal or superior to current US capabilities. Latter point is from USJFCOM, *Joint Operating Environment 2008*, 28.

111. JP 3-13.1, *Electronic Warfare*, I–4; and USJFCOM, *Joint Operating Environment 2008*, 50. Electronic protection is the subdivision of electronic warfare involving actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy use of the electromagnetic spectrum that degrades; neutralizes, or destroys friendly combat capability. Examples include spectrum management, electromagnetic hardening, emission control, and use of wartime reserve modes.

Abbreviations

ABL	airborne laser
AFRL	Air Force Research Laboratory
COIL	chemical oxygen iodine laser
dB	decibel
DE	directed energy
DEW	directed energy weapon
EM	electromagnetic
FLTC	Focused Long Term Challenges
FOM	figure of merit
GHz	gigahertz
HPM	high power microwave
IADS	integrated air defense system
IR	infrared radiation
ISR	intelligence, surveillance, and reconnaissance
km	kilometer
LO	low observable
nm	nanometer
R&D	research and development
RF	radio frequency
RPG	rocket-propelled grenade
SAM	surface-to-air missile
SRR	splint-ring resonator
THz	terahertz
UC	University of California
UV	ultraviolet

Bibliography

Air Force Research Laboratory. "Focused Long Term Challenges (FLTCs) Capability Visions and Problem Statement Description Handout," 30 August 2008.

Alù, Andrea, and Nader Engheta. "Achieving transparency with plasmonic coatings." *Physical Review E* 72 (2005): 16,623–31.

American Geophysical Union (AGU). "Water Vapor in the Climate System Special Report." Washington, DC: AGU, December 1995. http://www.agu.org/sci_soc/mockler.html.

Ames Laboratory. "Metamaterials found to work for visible light." Office of Public Affairs press release, 4 January 2007.

Associated Press. "Cloak of Invisibility: Fact or Fiction?" *MSNBC.com*, 19 October 2006. http://www.msnbc.msn.com/id/15329396/.

Azad, Abul K., Hou-Tong Chen, Antoinette J. Taylor, Elshan Akhadov, Nina R. Weisse-Bernstein, and John F. O'Hara. "Flexible Quasi-Three-Dimensional Terahertz Metamaterials." Los Alamos National Laboratory, NM: 30 April 2008. http://arxiv.org/PS_cache/arxiv/pdf/0804/0804.4880v1.pdf.

BBC. "Invisibility cloak 'step closer.'" *BBC News*, 11 August 2008. http://news.bbc.co.uk/2/hi/science/nature/7553061.stm.

Berbube, David M. *Nano-Hype: The Truth behind the Nanotechnology Buzz*. Amherst, NY: Prometheus Books, 2006.

Bland, Eric. "Invisibility Cloak Closer than Ever to Reality." *Discovery News*, 15 January 2009. http://dsc.discovery.com/news/2009/01/15/invisibility-cloak.html.

Bloomfield, Louis A. *How Things Work: The Physics of Everyday Life*. Hoboken, NJ: John Wiley & Sons, Inc., 2006.

Bohren, Craig, and Donald R. Huffman. *Absorption and Scattering of Light by Small Particles*. New York, NY: John Wiley & Sons, Inc., 1983.

Britt, Robert Roy. "New Theory: How to Make Objects Invisible." *Live Science*, 2005. http://www.livescience.com/technology/050228_invisible_shield.html.

Chang, Kenneth. “Light Fantastic: Flirting With Invisibility.” *New York Times*, 12 June 2007.

Cho, Adrian. “High-Tech Materials Could Render Objects Invisible.” *Science* 312, no. 5777 (2006): 1,120.

Colton, David, and Rainer Kress. *Inverse Acoustic and Electromagnetic Scattering Theory*. New York, NY: Springer-Verlag, 1998.

Crane, David. “New Laser Technology for Infantry Warfare, Counterinsurgency Ops, and LE Apps.” *Defense News*, 17 January 2005. http://www.defensereview.com/modules.php?name=News&file=article&sid=683.

Cubukcu, Ertugrul, Koray Aydin, Ekmel Ozbay, Stravroula Foteinopoulu, and Costas M. Soukoulis. “Electromagnetic waves: Negative refraction by photonic crystals.” *Nature* 423, no. 6940 (2003): 604–05.

Cummer, Steven A., Bogdan-Ioan Popa, David Schurig, David R. Smith, and John B. Pendry. “Full-wave simulations of electromagnetic cloaking structures.” *Physical Review E* 74, no. 036621 (2006): 1–5.

———. To the author. E-mail, 28 March 2009.

Dawson, Paul. “More information on Surface Plasmons.” Queen’s University Belfast, 17 May 1996. http://www.qub.ac.uk/schools/SchoolofMathematicsandPhysics/con/plasmon/sp1.html.

Defense Advanced Research Projects Agency (DARPA). “Negative Index Materials.” Defense Sciences Office. http://www.darpa.mil/dso/thrusts/materials/novelmat/nim/index.htm.

Department of Defense. *Capstone Concept for Joint Operations Version 3.0*, 15 January 2009. http://www.jcs.mil/090115CAPSTONEConceptJointOps.pdf.

Duke University. “David Smith: Creating New Materials that Go Beyond Nature.” Duke Engineering, 15 October 2008. http://www.pratt.duke.edu/news/?id=1520.

Erwin, Sandra I. “U.S. warplanes vulnerable to shoulder-fired missiles.” *National Defense* 86, no. 577 (2001): 26–27.

Fang, Nicholas X., assistant professor, University of Illinois, Department of Mechanical Science and Engineering and the Center for Nanoscale Chemical Electrical Mechanical Systems. To the author. E-mail, 28 March 2009.

Fitzgerald, Mary C. "China Plans to Control Space and Win the Coming Information War." *Armed Forces Journal*, November 2005. http://www.afji.com/2005/11/1005734.

Freudenrich, Craig. "How Laser Weapons Work." http://science.howstuffworks.com/laser-weapon.htm.

Frogley, Mark D., and Chris Phillips. "Invisibility at the flick of a switch." *The Royal Society*, 2006. http://royalsociety.org/exhibit.asp?id=4659.

Frogley, Mark D., J. F. Dynes, M. Beck, J. Faist, and Chris Phillips. "Gain without inversion in semiconductor nanostructures." *Nature Materials* 5, no. 3 (2006): 175–78.

Gething, Michael J. *Jane's Electro-Optic Systems 2008–2009*. Alexandria, VA: Jane's Information Group, 2009.

Goshen, Hadas. "Invisibility cloak moves from fantasy to potential reality at UC Berkeley." *Llama Ledger*, 15 October 2008.

Guercio, Flavio, Roberto Sabatini, and Salvatore Vignola. *Eye-Safety Analysis of Tactical Laser Systems*. Rome, Italy: Italian Air Force Research and Flight Test Division, 1999.

Hall, J. Storrs. *Nanofuture*. Amherst, NY: Prometheus Books, 2005.

Hamilton, Dave. Address. 23rd Annual National Test and Evaluation Conference, Hilton Head Island, SC, 15 March 2007. http://www.dtic.mil/ndia/2007test/Hamilton_TEexecs .pdf.

Hebert, Adam J. "Great Expectations." *Air Force Magazine* 90, no. 8 (2007): 32–35.

Hecht, Jeff. "Photonic Frontiers: Negative-Index-Material: Negative-index materials are on positive track." *Laser Focus World* 44, no. 11 (2008).

Joint Publication 3-13.1. *Electronic Warfare*, 25 January 2007.

Jülich Research Centre, Institute of Bio- and Nanosystems. "Novel 3-dimensional Ge dot crystals grown on templated Si substrates," 26 July 2008, http://www.fz-juelich.de/ibn/index.php?index=989.

Justice, Bryan J., Jack J. Mock, Liheng Guo, Aloyse Degiron, David Schurig, and David R. Smith. "Spatial mapping of the internal and external electromagnetic fields of negative index metamaterials." *Optics Express* 15, no. 19 (2006): 8,694–8,705.

Krowne, Clifford M. "Anisotropy of electromagnetically induced left-handedness in atomic three-level media based upon bianisotropic polarizabilities and tensor character." *Physics Letters A* 372, no. 21 (2008): 3,926–33.

———. "Electronics and Physics of Left-Handed Materials and Circuits." *Naval Research Laboratory Review*, 2004.

———. "Multi-species two-level atomic media displaying electromagnetic left handedness." *Physics Letters A* 372, no. 13 (2008): 2,304–10.

Kyser, Lindy. "Army research on invisibility not science fiction." *Army News Service*, 21 August 2008.

Lezec, Henri J., Jennifer A. Dionne, and Harry A. Atwater. "Negative Refraction at Visible Frequencies." *Science* 316, no. 5823 (2007): 430–32.

Liu, R., C. Ji, J. J. Mock, J. Y. Chin, T. J. Cui, and D. R. Smith. "Broadband Ground-Plane Cloak." *Science* 323, no. 5912 (2009): 366–69.

Markey, Sean. "Invisibility Cloak Possible, Study Says." *National Geographic News*, 25 May 2006.

———. "First Invisibility Cloak Tested Successfully, Scientists Say." *National Geographic News*, 19 October 2006.

Miller, Steve. "Lighter, Stronger, More Affordable: DARPA's Quests in the Realm of Materials Science." *DARPA: 50 Years of Bridging the Gap*, 2008, 128–33.

National Research Council. *Future Air Force Needs for Survivability*. Washington, DC: National Academies Press, 2006.

Owen, James. "Invisibility Shield Planned by Engineers." *National Geographic News*, 28 February 2005.

Ozbay, Ekmel. "The Magic World of Photonic Metamaterials." *Optics and Photonics News* 19, no. 11 (2008): 22–27.

Padilla, Willie J., Dimitri N. Basov, and David R. Smith. "Negative refractive index materials." *Materials Today* 9, no. 7–8 (2006): 28–35.

Parimi, Patanjali V., Wentao T. Lu, Plarenta Vodo, and Srinivas Sridhar. "Photonic crystals: Imaging by flat lens using negative refraction." *Nature* 426, no. 6965 (2003): 404.

Park, Wounjhang, and Jinsang Kim. "Negative-Index Materials: Optics by Design." *Materials Research Society Bulletin* 33, no. 10 (2008): 907–14.

Paschotta, Rudiger. "Quantum Dots" and "Quantum Wells." *Encyclopedia of Laser Physics and Technology*, August–September 2008. http://www.rp-photonics.com.

Pendry, John B., D. Schurig, and David R. Smith. "Controlling Electromagnetic Fields." *Science* 312, no. 5781 (2006): 1,780–82.

Phillips, Chris. "Quantum Optics with Semiconductor Nanostructures." Imperial College London, 2008. http://www3.imperial.ac.uk/people/chris.phillips/research/quantumoptics.

Pillsbury, Michael P. *An Assessment of China's Anti-Satellite and Space Warfare Programs, Policies and Doctrines.* Washington, DC: US–China Economic and Security Review Commission, 19 January 2007, 12. http://www.uscc.gov/researchpapers/2007/FINAL_REPORT_1-19-2007_REVISED_BY_MPP.pdf.

Plumridge, Jonathan R., Robert J. Steed, and Chris Phillips. "Negative refraction in anisotropic waveguides made from quantum metamaterials." *Physical Review B* 77, no. 20 (2008): 20,548–51.

Puttré, Michael. "Facing the shoulder-fired threat: The air superiority myth hits the MANPADS mountain." *Journal of Electronic Defense* 24 no. 4 (2001): 38–45.

Rahm, Marco, David Schurig, Daniel A. Roberts, Steven A. Cummer, David R. Smith, and John B. Pendry. "Design of Electromagnetic Cloaks and Concentrators Using Form-Invariant Coordinate Transformations of Maxwell's Equations." *Photonics and Nanostructures–Fundamentals and Applications* 6, no. 1 (2008): 87–95.

Sanderson, Katherine. "Unexpected tricks of the light." *Nature* 446, no. 7134 (2007): 364–65.

Savage, Michele. "Invisible Soldiers?" *Defense News* 23, no. 34 (2008): 16.

———. "Next-gen Cloaking Device." *Defense News* 24, no. 4 (2009): 16.

Schuring, D., J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith. "Metamaterial Electromagnetic Cloak at Microwave Frequencies." *Science* 314, no. 5801 (2008): 977–79.

Shadrivov, Ilya V., and Yuri S. Kivshar. "Nonlinear Effects in Left-Handed Metamaterials." *Physics of Negative Refrac-*

tion and Negative Index Materials. New York, NY: Springer, 2007.
Shalaev, Vladimir M. "Optical negative-index metamaterials." *Nature Photonics* 1, no. 1 (2007): 41–48.
Smith, Charles R. "Weapons of the Future Are Here." *Newsmax*, 11 February 2005. http://archive.newsmax.com/archives/articles/2005/2/10/202311.shtml.
Smith, David R. "The Science Fact and Fiction of Invisibility." Duke University, 28 May 2006. http://people.ee.duke.edu/~drsmith/cloaking.html.
———. "An introduction to negative refraction." Duke University, 19 November 2005. http://people.ee.duke.edu/~drsmith/negative_index_about.htm.
———. "What are Electromagnetic Metamaterials?" Duke University, 10 June 2006. http://people.ee.duke.edu/~drsmith/about_metamaterials.html.
Spotts, Peter N. "Disappear into thin air? Scientists take step toward invisibility." *Christian Science Monitor*, 20 October 2006.
"The Monitor News." *Journal of Electronic Defense* 32, no. 3 (2009): 24.
Thill, Joseph A. "Penetrating the Ion Curtain: Implications of Directed Energy Integrated Air Defense Systems in 2030." Maxwell AFB, AL: Air Command and Staff College, April 2008.
Thomas, Timothy L. *Cyber Silhouettes: Shadows over Information Operations*. Fort Leavenworth, KS: Foreign Military Studies Office, 2005.
US Joint Forces Command. *The Joint Operating Environment 2008: Challenges and Implications for the Future Joint Force*. Norfolk, VA: Center for Joint Futures, 25 November 2008.
Valentine, Jason, Shuang Zhang, Thomas Zentgraf, Erick Ulin-Avila, Dentcho A. Genov, Guy Bartal, and Xiang Zhang. "Three-dimensional optical metamaterial with a negative refractive index." *Nature* 455, no. 7211 (2008): 376–79.
Victoria Department of Sustainability and Environment. "Backcasting," 11 July 2007. http://www.dse.vic.gov.au/DSE/wcmn203.nsf/LinkView2879E72156CA84CA2570340024AD8AF0262F6E20F33AE3CA2570910006165A.

Voland, Gerlad. "'Invisible' materials bend light to hide from sight." *Journal Gazette*, 8 September 2008. http://www.journalgazette.net/apps/pbcs.dll/article?AID=/20080908/FEAT0113/809080356.

Yang, Sarah. "Invisibility shields one step closer with new materials that bend light backwards." UC Berkeley press release, 11 August 2008. http://berkeley.edu/news/media/releases/2008/08/11_light.shtml.

Yao, Jie, Zhaowei Liu, Yongmin Liu, Yuan Wang, Cheng Sun, Guy Bartal, Angelica M. Stacy, and Xiang Zhang. "Optical Negative Refraction in Bulk Metamaterials of Nanowires." *Science* 321, no. 5891 (2008): 930.