(U) Forecasting of Antenna Technologies

March 2010

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Sandia Systems Assessment and Research Center Document

(U) Forecasting of Antenna Technologies

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(U//~~FOUO~~) In any communication system, the antenna is the "eye to the world." Increasing demands for enhanced capabilities and capacities of wireless devices, whether personal cellular phones or a military UAVs, prove a daunting task for antenna engineers. Antennas, often the last design component to be considered, are at the mercy of the system designer and usually created at the eleventh hour. To enable future technologies, this design paradigm must be reversed; smart antenna characteristics must be considered early in the design process, allowing for the realization of next generation wireless devices. Antenna designs that utilize electrically small characteristics, metamaterials, advanced array architectures, and new material integration approaches are discussed. Leading researchers and their affiliations are referenced in context to the antenna topic. Each topic area provides a discussion on the principle of operation, potential/realized application(s), and a concluding forecasting statement on the technical readiness of the antenna topic.

(U) Forecasting of Antenna Technologies

(U) Introduction

(U//~~FOUO~~) Antennas may represent the most underrated components in telecommunications. Most antenna engineers are likely to believe that antennas are one technology that is more or less impervious to rapidly advancing technologies, for example, semiconductors. As the push for enhanced and functional wireless devices continues at a paramount speed, so does the need for advanced, smart antenna technologies. For example, in a cellular application, the primary requirement for antennas now includes covering multiple bands—GPS, Bluetooth, FM ra dio, WLAN—at minimum cost and low power consumption. Overall, the future of antennas will be driven by that of its end applications.

(U//~~FOUO~~) For this reason, this report attempts to highlight and forecast antennas topics related to:

1. Electrically small antennas
2. Metamaterial-based antennas
3. Advanced array architectures
4. New material integration approaches

(U//~~FOUO~~) This report attempts to address new market technologies, as well as fresh academic ideas that offer new routes in a decades old design discipline.

(U) Report Structure

(U//~~FOUO~~) The organization and methodology in accomplis hing this assessment consists of three main elements: (1) data acquisition, (2) map development and characteristics, and (3) analytical sessions. The data used in this assessment was allocated from Scopus, Web of Science, Inspec, ISI Proceedings, and Google Translate. Web of Science was used in order to cover Technology Readiness Levels (TRL) one to three. Inspec was used in order to cover the higher TRL four and higher. ISI Proceedings were important to include since it covers conference proceedings, which tend to be more recent than peer-reviewed journal manuscripts. Google Translate allowed for viewing titles and abstracts from domestic Chinese journals.

(U//~~FOUO~~) The previously mentioned databases where queried by using a set of terms provided by the subject matter expert (SME). Each technology within the corresponding "antenna technologies" of interest were isolated, queried, and analyzed individually. In most cases, an iterative approach to query enhancement was required in order to identify secondary enabling technologies.

(U//~~FOUO~~) The second element of the assessment consisted of constructing a landscape visualization that enabled analysis of thousands of documents at a time. This visualization was an incredibly dynamic analytical environment that resembled the interactivity of Google Earth. The visualization allows the user to get a high level view of the selected technology related keywords, and allow the flexibility to zoom into a single author/document. As the zoom function is initialized, the clustering of related documents automatically refreshes itself on the basis of establishe d correlation factors. Labeling of each sub-cluster results allowed for identification of prominent keywords. In regards to cluster size, the density of documents is portrayed by height and width. For example, documents within a cluster that are highly correlated (high correlation factor) appear tall and thin as opposed to lower correlation factors topics.

(U) Antenna Topics of Analysis

(U) Electrically Small Antennas

(U//~~FOUO~~) According to the Antenna Engineering Handbook, an electrically small antenna (ESA) is defined as $ka < 0.5$ where $k=2p=\lambda$ and a is the radius of the volume sphere occupied by the radiating element. Electrically small antennas can generally be decomposed as loop, dipole, or slots elements (or some combination thereof).[1]

(U//~~FOUO~~) Many misconceptions exist about the behavior or principles governing ESAs. The MITRE Corp.'s Steven Best, a leading expert on the subject, states: "...the concept of designing the small antenna to match the impedance of free-space is not valid. All small antennas, regardless of size or geometry, are inherently matched to free-space. The only design issues to consider in determining the amount of radiated power are the antennas radiation efficiency and VSWR [voltage standing wave ratio]; the small antenna must be impedance matched to the source."

(U//~~FOUO~~) Best further clarifies that, unlike full featured antennas, the radiation efficiency of dipole does NOT scale with *ka* (frequency). In fact, a high radiation efficiency is possible at small *ka* but this is usually offset by impedance mismatch losses.

(U//~~FOUO~~) A special category of ESAs, known as superdirective antennas, have the characteristic that as size decreases, directivity remains about the same. However radiation resistance and reactance increase. Thus, bandwidth is narrow and efficiency is low.

(U//~~FOUO~~) Future discussions of work in ESAs should first begin with a firm understanding of Q, directivity, gain, and efficiency. Chapter 1 of Robert Hansens book, *Electrically Small, Superdirective, and Superconducting Antennas*, discusses many of the historical definitions used along with their erroneous assumptions.[2] Frequently, the Wheeler-Chu-McLean limit is cited. Rendering the following pertinent questions: "Given certain fundamental limitations of physics, what performance enhancements can be made to improve electrically small antennas? Within volume and power restrictions?"

$$Q = \left(\frac{1}{ka}\right) + \left(\frac{1}{k^3a^3}\right)$$

(U//~~FOUO~~) ESAs are needed/desired for next-generation commercial and military communications. Figure 1 illustrates the attributes and/or areas of research for one particular area—Tag or radio frequency identification (RFID) devices. Aside from the battery, the antenna is usually the largest and size prohibitive component. Figure 2 demonstrates previous Sandia National Laboratories' efforts for the miniaturization and integration of tag electronics behind the antenna. Figure 3 illustrates the Tag/RFID landscape where clear trade-offs have been made between size, range, battery life, and capabilities. Despite popular perception, GPS is not a cure all; cell networks are limited, and many/most RFIDs are a short-range (61 meter) system. Yet, despite their current limitations, a significant investment is being made, as detailed in figure 4.

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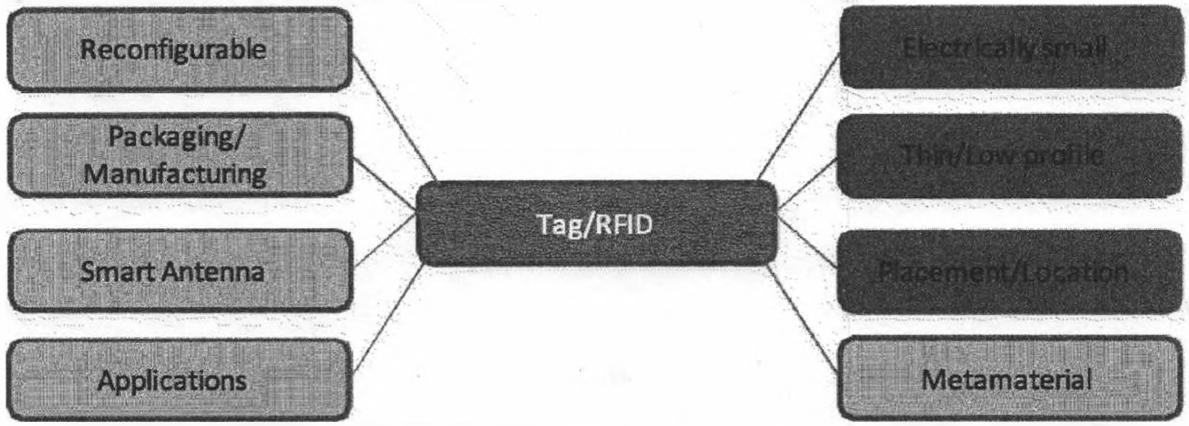

Figure 1. **(U//~~FOUO~~) Technologies and Attributes of RFID Devices**

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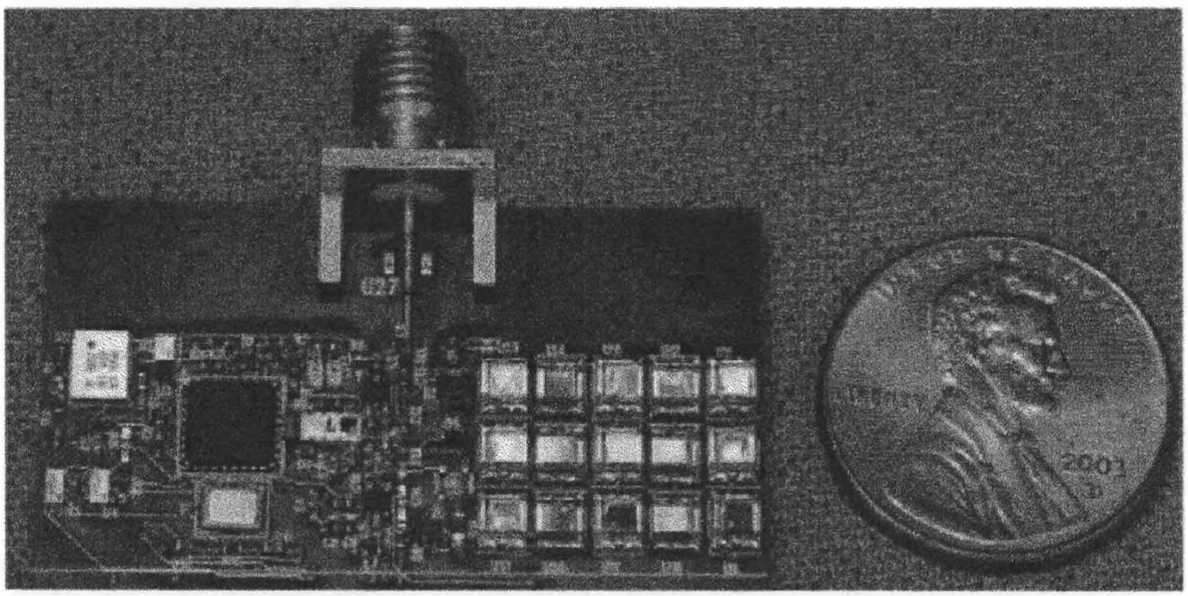

Figure 2. **(U//~~FOUO~~) Miniaturized and Integrated Tag Electronics Behind the Antenna**

(U//~~FOUO~~) The rate of growth in ESA-based publications increased in 2005–2006 and has sustained a continued interest from the global scientific community. Research efforts and applications are widely dispersed.[3] Due to retail/commercial applications, there is a significant amount of work in ultra-high frequency range. Other non-radar applications were medical, transportation, and communications devices.[4] The literature landscape map showed a lot of overlap with research and development in the areas of materials, fabrication techniques, packaging, and batteries (figure 5). The United States dominates the public, unclassified domain in terms of publishing, with Richard Ziolkowski and Stephen Best the leaders on ESA selected topics (table 1).

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Figure 3. **(U//~~FOUO~~) Tag/RFID Landscape**

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Figure 4. **(U//~~FOUO~~) Market Analysis: Summary of Department of Defense Projects Involving Electrically Small Antennas**

Table 1. (U//~~FOUO~~) ESA Publication Comparisons

Year	Total Publications	Country	Publications	Author	Publications
2009 (Aug)	42	United States	397	Ziolkowski	37
2008	71	United Kingdom	73		
2007	86	Japan	36	Best	16
2006	61	Germany	28		
2005	59	Canada	27	Erentok	15
2004	37	South Korea	26		
2003	36	China	25	Ling	14
2002	30				

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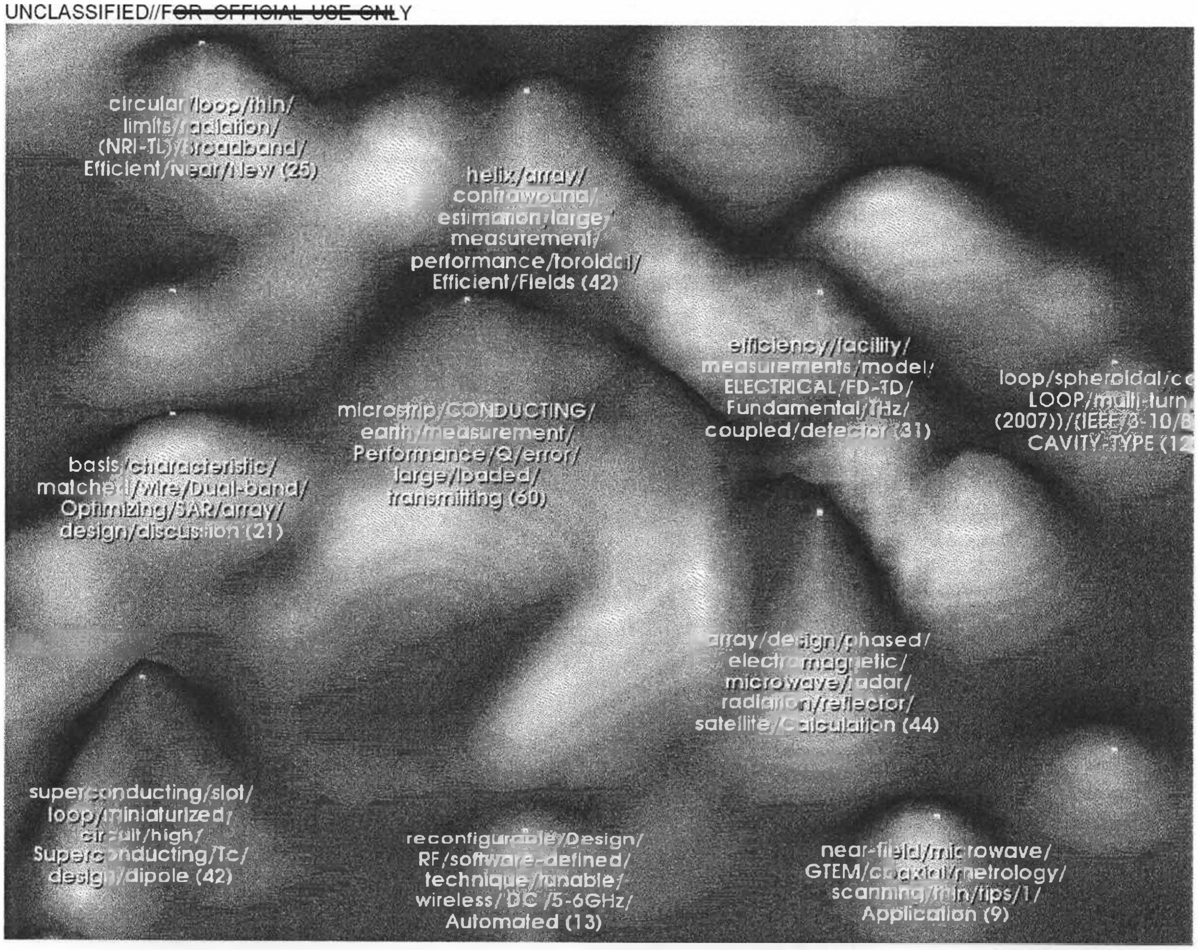

Figure 5. **(U//~~FOUO~~) ESA Landscape**

(U//~~FOUO~~) One ESA-based topic in its infancy that should be highlighted in this forecasting report is the use of non-Fostering matching networks.[5,6,7] As mentioned above, any gain an ESA exhibits in radiation efficiency is offset by impedance mismatch and/or associated matching network. Non-Foster impedance matching is an active device technique to mitigate these losses (figure 6).

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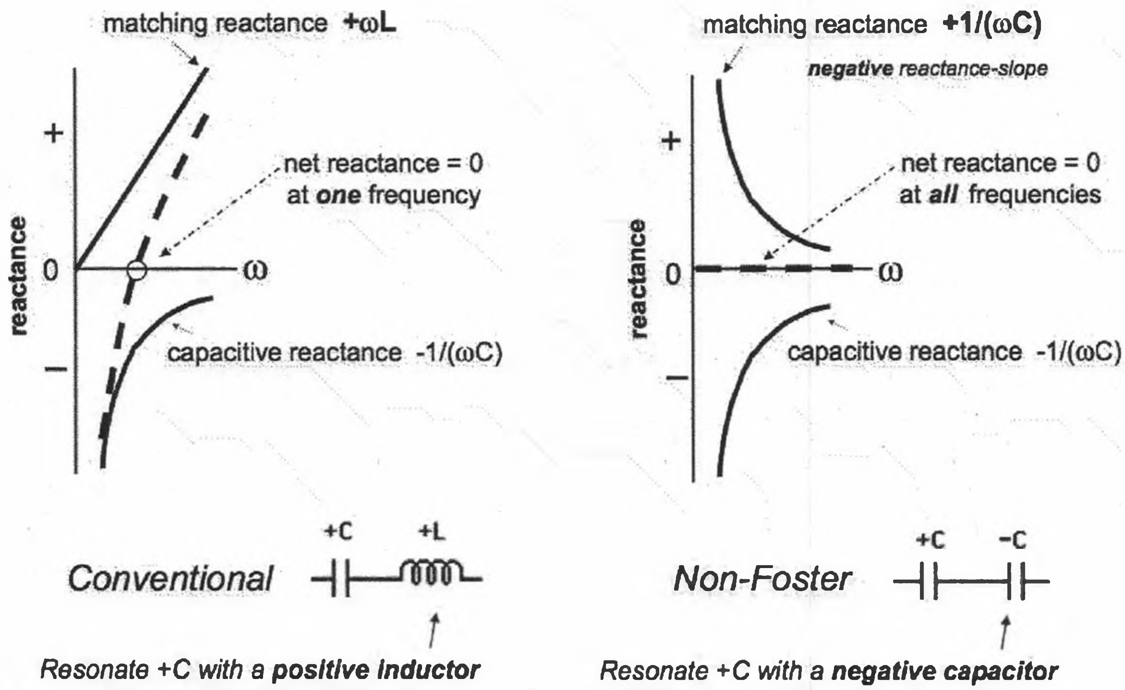

Figure 6. **(U//~~FOUO~~) Conventional Versus Non-Foster Resonance of a Positive Capacitor**

(U//~~FOUO~~) Electrically small antennas, regardless of their shape and type, have high Q, and consequently are difficult to match. The technique of non-Foster impedance matching, which employs active networks of negative inductors and capacitors (negative impedance converters [NIC]), bypasses the restrictions of gain-bandwidth theory. The idea is to construct a negative-image model of an antenna, which cancels the antennas parasitic reactance and transforms its frequency-dependent radiation resistance to a constant value. The book by Aberle and Loepsinger-Romak states the following corollaries.[5]

1. The immittance function can be written as the ratio of two polynomial functions of the Laplace variable $s=\sigma + j\omega$:

$$Z(s) = \frac{N(s)}{D(s)}$$

2. The coefficients of the polynomials $N(s)$ and $D(s)$ are positive and real.
3. The difference in the orders of $N(s)$ and $D(s)$ is either zero or 1.

(U//~~FOUO~~) Aberle and Loepsinger-Romak clarify: Thus, "If a two-terminal device has an immittance function that does not obey any of the three consequences of Fosters reactance theorem listed above, then it is called a 'non-Foster' element."

(U//~~FOUO~~) Through simulation and initial experimental demonstration, it has been realized that a wide assortment of active devices (for example, op-amp, current-fed amplifiers, and floating negative resistors) can potentially provide larger properties while maintaining modest efficiencies. The two major problems associated with the technique currently include development of a stable network over the frequency range of interest, and development of higher quality active components. For example, the use of op-amp NIC at higher frequencies (greater than HF) must await the development of opamps with significantly higher unity-gain bandwidths than are currently available. Additionally, the parasitics of the device and circuit board will have to be minimized as much as possible.[5-7]

(U) Metamaterials

(U//~~FOUO~~) Metamaterials, the so-called man-made electromagnetically designed materials, offer new possibilities to design materials tailored for specific application purposes. Due to the fact that an engineer is not restricted by the materials' electromagnetic constitutive parameters that are readily available in nature, he or she is free to design conventional devices in a new and possibly more advantageous way. This mind-set has resulted in an enormous amount of claims, decreeing not only improvement of conventional devices, but in the creation of whole new classes of devices for a wide range of applications. This portion of the document highlights some of the "advances" (or marketing schemes) of metamaterials in the last decade.

(U//~~FOUO~~) Electromagnetically engineered composites or metamaterials are broadly defined as an array of sub-wavelength components with effective homogenous structures that result in unusual properties, not readily available in nature.[8] An effectively homogenous structure is a structure whose structural average cell size, p, is much smaller than the guided wavelength, λ_g. Therefore, the average cell size should be at least smaller than a quarter of wavelength, $p < \lambda_g/4$ –the effective homogeneity condition – to ensure that refractive phenomena will dominate over scattering/diffr action phenomena. If the condition of effective-homogeneity is satisfied, the structure behaves as a real material in the sense that electromagnetic waves are essentially myopic to the lattice and only experience the average, or effective, macroscopic well-defined constitutive parameters, which depend on the nature of the unit cell.

(U//~~FOUO~~) In 1964, Viktor Veselago published a manuscript asking a fundamental question, "What happens when both μ_r and ε_r are negative?"[9] While exploring the theoretical notion that such an experimental material could exist, the general premise remained dormant until 2000. At the University of California-San Diego, David Smith and colleagues experimentally demonstrated a negative index composite at microwave frequencies.[10] By utilizing a two-component metallic composite—the split ring resonators and posts— μ_r and ε_r could be simultaneously negative within a narrowband frequency range. This lossy, directionally-dependent demonstration initiated an avalanche of research, funding, and, of course, controversy in the last decade.[8,11,12,13]

(U//~~FOUO~~) Figure 7 highlights the publications by country for metamaterials-related research. Not included on the figure are countries with fewer than 100 papers from 2004–2008, including Italy (97) and Japan (88). Rapid and sustained growth is observed, as seen in publications levels. With respect to metamaterials-related funding, allocation is diffuse and unfocused—that is, many small awards with respect to basic research topics. From public domain data, $140 million of government-based metamaterial funding has been identified internationally, and this is believed to account for about half of the total funding. With respect to specific countries, it is difficult to identify funding specifics for metamaterials research and development in China, but several reports indicate major investments initiated in 2000 and continued to date. Specifically, between 2000–2005 some $456 million was applied to materials research in China by two agencies—the National Natural Science Foundation of China (NSFC) and the Ministry of Science and Technology (MOST)—and metamaterials were identified as a priority for materials science research. As stated by William Berry and Cheryl Loeb of the National Defense University in the March 2008 publication "China's S&T Emergence: A proposal for U.S. DoD-China Collaboration in Fundamental Research":

> "... it is very likely that in the next 15 years [China] will be world class in many areas of the life and physical sciences. In some key technology areas of high importance to DoD, they will most likely surpass the United States. Some areas in which China is advancing rapidly are ... materials science, such as metamaterials and catalysis." [14]

(U//~~FOUO~~) Additionally, Japan is an interesting case in that there is a fair amount of Japanese commercial activity, but only a relative handful of publications.

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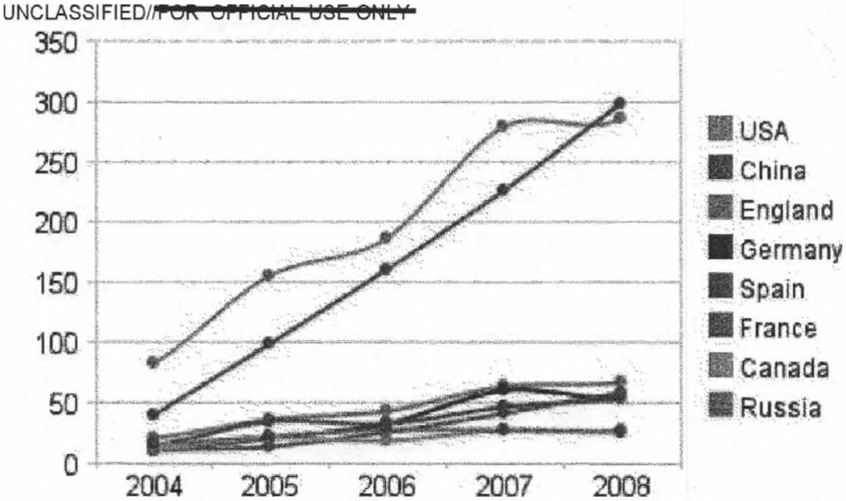

Figure 7. **(U//~~FOUO~~) Publications by Country for Metamaterials-Related Research**

(U) Metamaterial-Based Antennas

(U//~~FOUO~~) Metamaterial-based antennas have offered salivating promises of breaking the Wheeler-Chu-McLean limit, enabling high directivity and isolation in confined spaces, and tunable operational frequencies, to name a few (mostly in simulations). However, fundamental physical phenomena and decades-old antenna design techniques serve as robust principles and solid foundations that are so often re-packaged under new marketing/terminology schemes. Table 2 highlights the research efforts in terms of metamaterials related antenna topics. The United States represents the majority of publishing, but in recent years, China and Russia have been increasing their contributions to the topic area. It should be noted that when discussing metamaterial-based antennas, there are generally three research focus points: (1) metamaterial substrates, (2) electrically small metamaterial antennas, and (3) generalized transmission line approaches. The first topic area on metamaterial substrates is often referred to as Sievenpiper structures, high impedance surfaces (HIS), electromagnetic bandgap (EBG) structures, or artificial magnetic conductors (AMC). While these structures allow for low-profile antennas (reduction in zdimension) over a narrowband, they require large x-y dimensions, such that the ground plane does not act as a radiator. It is not the intent of this document to review this topical area.[15]

Table 2. (U//~~FOUO~~) Metamaterial Antenna Publication Comparison

Year	Total Publications	Chinese Publications	Russian Publications
2009 (Aug)	165	35	14
2008	310	84	26
2007	301	49	24
2006	187	23	21
2005	126	14	12
2004	56	6	7
2003	35	0	6
2002	11	0	2

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(U//~~FOUO~~) Ziolkowski and colleagues at the University of Arizona were (and continue to be) one of the original groups to advocate for electrically-small antennas inspired by metamaterials.[16,17] Through the application of double negative metamaterials (DNG), the power radiated by electrically-small dipole antennas can be notably increased. This increase could be accomplished by surrounding an antenna with a shell of DNG material. At the time (late 2003) this phenomenon was investigated both analytically and numerically. When the electric dipole is embedded in a non-dispersive homogeneous DNG medium, the analysis shows that the antenna acts inductively rather than capacitively, as it would in free space without the interaction of the DNG material. In addition, the dipole-DNG shell combination increases the real power radiated by more than an order of magnitude over a free space antenna. A notable decrease in the reactance of the dipole antenna corresponds to the increase in radiated power.

(U//~~FOUO~~) More recently, Ziolkowski and co-workers have simulated and experimentally demonstrated electrically small Z antenna configurations for 570 and 300 megahertz (with respect to radiated power values).[18,19,20] It was shown that nearly complete matching with no external circuit was achieved. Thus, the metamaterial-inspired, near-field resonant parasitic component acts as an internal matching network, which produces nearly complete matching to the source, and enhances the total radiated power by acting as a transducer, which changes the reactive field of the driven element into a propagating field. However, Pekka Ikonen from Nokia asks a simple question in a recent publication from an industrial point of view, "Have we seen any real practical benefits from electrically small metamaterial-based antennas?"[21] With respect to mobile phones, despite the interesting theoretical findings, the commercial acceptability of metamaterial-based ESAs is low. Discussion topics include challenging application environment for artificial composite materials, complex interactions of finite-sized ground planes, lack of self-driven constructive criticism, and inadequate acknowledgment of prior work.

(U//~~FOUO~~) While the design approach is marketed as metamaterial-based ESA, in reality, this technique has been around for decades, but referred to as near-field impedance matching. Again, the definition of a metamaterial is brought into question. As described in the opening paragraphs of this section, metamaterials are arrays of sub-wavelength components that produce an effective medium behavior. However, in Ziolkowski's metamaterial-based ESA designs, one single "metamaterial" element is often coupled with a monopole antenna (figure 8). Upon discussion within the ESA community, a change in terminology resulted on Ziolkowski's behalf— metamaterial-inspired ESAs. Furthermore, one should ask what "real power radiated" means in context to benchmarking with traditional reference antenna designs. Often, these metamaterial-based designs are simulation only, where full experimental characterization in the real application environment should be completed in cases where metamaterial-inspired designs are fully benchmarked against reference antennas. It is our opinion that further study of metamaterial-inspired antennas is warranted, but an "apples to apples comparison" is required. However metamaterial antennas are employed, the design is still bound by fundamental physics; thus, one can approach the Wheeler-Chu-McLean limit, but any claim of breaking the limit is invalid.

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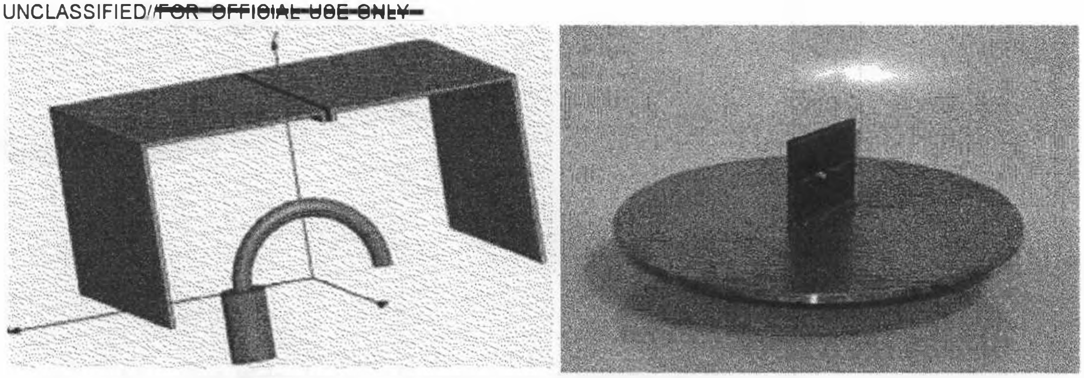

Figure 8. **(U//~~FOUO~~) Metamaterial-Inspired ESA Design from the University of Arizona**

(U//~~FOUO~~) Alternatively, during the early metamaterial years, the vast majority of the groups involved in research focused on investigating the phenomena from a physics point of view, verifying the fundamental properties of left-handed media (LHM) as predicted by Veselago predicted in 1964. Alternatively, several authors adopted an engineering approach, based on a generalized transmission line theory.[8,22,23] A left-handed-material-loaded transmission line could be integrated with traditional right-handed transmission lines to produce unique, printed circuit board antenna feed designs. The advertised advantages of metamaterial-loaded transmission lines included more compact size, positive or negative phase abilities while occupying the same physical length, and exhibiting a linear, flat-phase response with frequency, resulting in shorter group delays. Due to high series distributed capacitance values, designs were shown to work at lower frequency ranges. This effort resulted in the development of a suite of novel, guided-wave, radiated wave, and refracted wave devices and structures. A San Diego-based company, Rayspan, has licensed several patents based on these techniques to commercialize and market electrically small, metamaterial antennas based on research efforts lead by UCLA's Tatsuo Itoh. To date, the company has reportedly raised $25 million, and secured high-production contracts with Netgear and LG for wireless routers (WNDR3700) and cellular phones (Chocolate BL40), both shown in figure 9.[24]

(U//~~FOUO~~) Underlying this metamaterial enhanced transmission line approach is a continued controversy that challenges the proposed LHM fundamentals. Traditionally, the telegrapher's equation is a differential equation based on the representation of a transmission line as an infinite set of periodically repeating, infinitesimally sized series inductance and shunt capacitance elements. This low-pass network is a representation of 1-D transmission lines, and it forms the basis of transmission line theory. The metamaterial-transmission line approach replaces the series inductances and shunt capacitances with series capacitances and shunt inductances, respectively, achieving a high-pass filter. Thus, the technologies developed by Rayspan are more appropriately labeled as a filter theory technique, whereby utilizing circuit/filter designs with that of capacitively feed antenna structures, produces the as-advertised Rayspan "metamaterial" capabilities. For a more in-depth discussion on LHM-transmission line design versus filter theory, a recent series of letters were published in the IEEE APS between pro-metamaterial and pro-filter theory representatives.[25]

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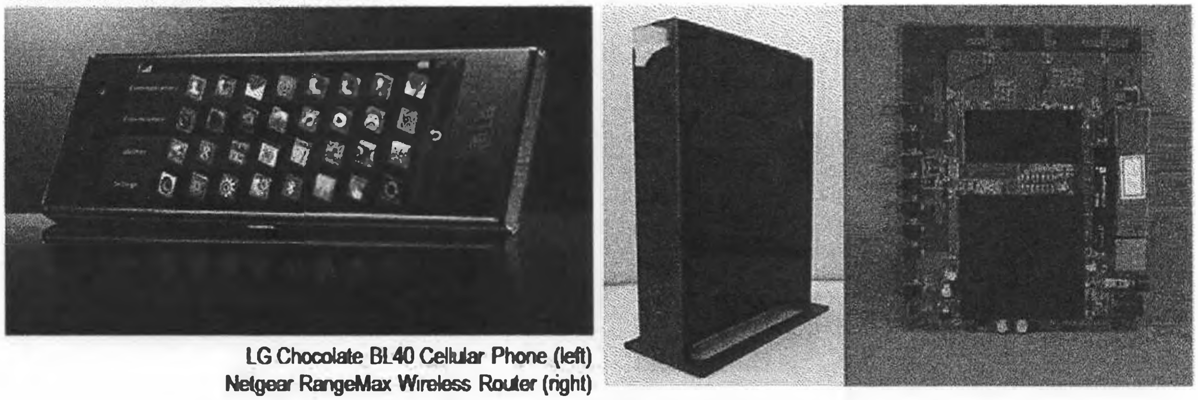

Figure 9. **(U//~~FOUO~~) Commercially Available Metamaterial Devices**

(U//~~FOUO~~) While it is not the intent of this document to describe all the potential applications, three topics should be highlighted for future forecasting awareness: transformational optics for negative index metamaterial (NIM) lenses, cloaking, and dispersion engineering. [12,26,27,28,29,30,31]

(U//~~FOUO~~) Transformation optics is a novel method for the design of complex electromagnetic media that offers new opportunities for the control of electromagnetic waves. The transformation optical approach is conceptually simple. One imagines warping space so as to control the trajectories of light in a desired manner. In academic-industrial joint collaboration, funded by DARPA, leading metamaterial advocates, such as David Smith and Sir John Pendry, and then Boeing Phantom Works, utilized a conformal transformation technique to design a NI M lens for the enhancement of scanning angle of phased-array antennas (PAA). A major limitation of PAAs is the inability to scan the beam close to the horizon. Most available PAA systems have a maximum usable scanning angle of about 60 degrees from the vertical axis. One method of increasing, the scanning angle is the utilization of mechanical augmentations, such as gimbaled systems. However, mechanical augmentations sacrifice the main benefit of a PAA, which is the ability to electronically scan without mechanical time delay and overshoot. Mechanical augmentation also increases the system size and weight making it undesirable for aerial and satellite platforms. The work was successful in designing, simulating and experimentally verifying the use of transformational optics based on NIM lenses (figure 10), but also highlighted the future need for low loss, isotropic NIM designs. As stated, "It is challenging to build a fully, isotropic material from SRRs and wires alone," coupling these limitation with lossy metallic properties requires future alternative approaches. [32]

(U//~~FOUO~~) While the notation of electromagnetic cloaking typically results in rolling eyes and deep sighs because of the over-marketing of *Harry Potter* cloaks seen on the internet, but one international group's advances on the topic requires attention. Sergei Tretyakov, a leading proponent for metamaterials and long-time respected name of the electromagnetic community, and his research group at the Helsinki University Technology in Finland have designed, simulated, and experimentally demonstrated cloaking structures based on simple, multi-layer metallic structures (figure 11). Generalizing one- and two-dimensional periodically loaded transmission line networks, the group has designed volumetric transmission line networks that reduce the scattering and absorption of impinging electromagnetic waves—that is, structures capable of electromagnetic cloaking. Their approach advertises advantages in comparison to alternative cloaking techniques, for example, simplicity of design and manufacturing and wide operational bandwidth. Several papers are highlighted: [28-30]

1. "Broadband electromagnetic cloaking of long cylindrical objects," S. Tretyakov, P. Alitalo, O. Luukkonen, and C. Simovski. *Physical Review Letters*, 103, 103905, Sept 4. 2009.
2. "Electromagnetic cloaking with metamaterials," S. Tretyakov, P. Alitalo, O. Luukkonen, and C. Simovski. *Materials Today*, Vol. 12[3], March 2009.
3. "Experimental verification of broadband cloaking using a volumetric cloak composed of periodically stacked cylindrical transmission line networks," S. Tretyakov, P. Alitalo, O. Luukkonen, and C. Simovski. *Applied Physics Letters*, 94, 014109, 2009.

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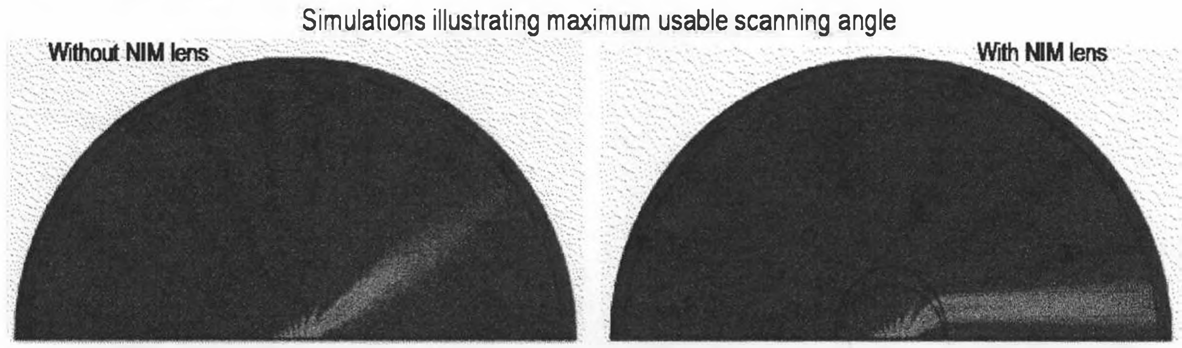

Figure 10. **(U//~~FOUO~~) Scan Angle Enhancement of Phased Array Antennas Using a NIM Lens**

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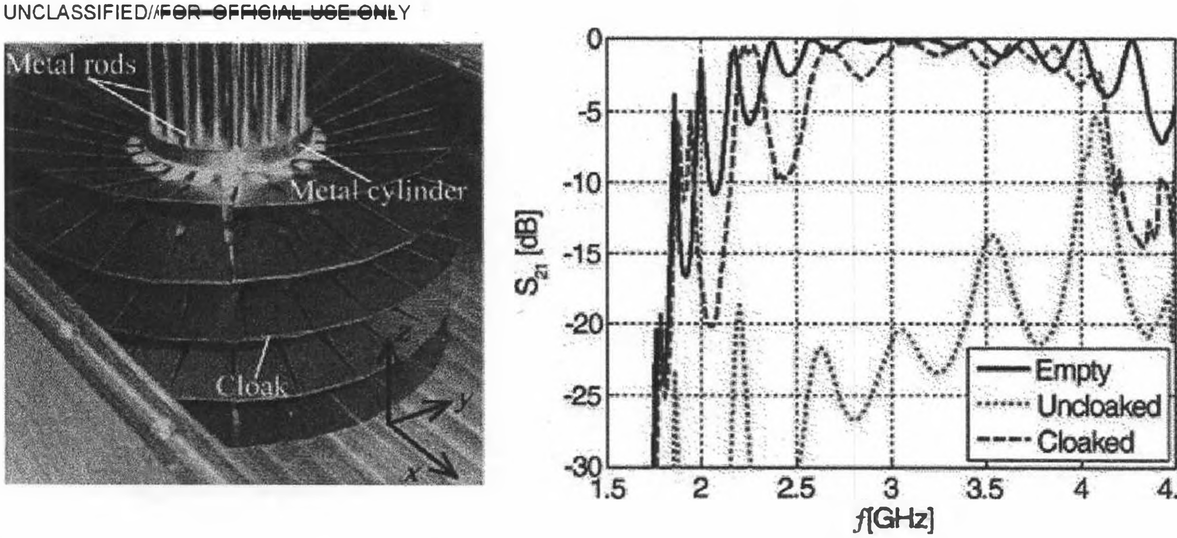

Figure 11. **(U//~~FOUO~~) Broadband, Volumetric Electromagnetic Cloaking Via Periodically Stacked Cylindrical Transmission Line Networks**

(U//~~FOUO~~) As the sophistication of electromagnetic cloaking advances via several techniques, it is not a question of whether long cylindrical objects can be removed from detection; the pertinent question now is "Can we develop techniques to identify cloaked objects in the field?"

(U//~~FOUO~~) The fact that any physically realizable medium must be dispersive is the consequence of the principle of causality, which demands no effect precedes its cause.[33,34] Dispersion engineering makes reference to the possibility of controlling the dispersion relationships in a transmitting medium. With such an ability to control dispersion, a key science and technology obstacle could be overcome with respect to broadband true time delay (TTD) devices, for example, in electronically scanning, phase-array antennas. Metamaterial transmission lines offer the potential degrees of freedom to tailor dispersion diagrams by tuning group and phase velocities. Again, the discussion of metamaterial versus filter theory arises, but other potential routes for dispersion engineering have been proposed. For example, the ability to design and synthesize dispersion-engineered materials and waveguides offers a challenging, but alternative route where compensating material dispersion offsets the dispersion of a designed waveguide.

(U//FOUO) Electronically scanning, phased-array antennas play a critical role in many national security related applications. Time delay of a broad-band signal may be accomplished by increasing its propagation distance or by slowing its propagation velocity. Increasing propagation distance by adding extra lengths of the same guiding medium produces time delay but not necessarily TTD unless all in-band frequencies propagate through the medium at the same phase velocity (that is, the medium has no dispersion). Existing TTD devices use electromechanical switches to add discrete lengths of quasi-none-dispersive transmission lines to each of the radiating elements. This approach has several drawbacks:

- The delay is discrete, which means the beam may not be continuously steered.
- Adding more switch states to increase steering resolution adversely affects insertion loss stability and beam shaping.
- Because light propagates in vacuum at approximately 1 foot per nanosecond, large delays using switched TTD devices require high index-of-refraction substrates to be compact. Dispersion engineered transmission lines and waveguides offer unique and high quality routes for future TTD implementations.

(U) Advanced Antenna Array Architectures

(U//FOUO) In any communication system, the antenna is the eye to the world. The antenna's radiation characteristics are designed specific to the system it supports. An antenna can consist of a single radiator or of many radiators acting in concert to form a phased array. Smart and phased array antennas provide adept functionality such as increased gain, conformality, sidelobe level control, and electronic steering.

(U) Smart Antennas

(U//FOUO) The term "smart antennas" is often used in reference to cellular technologies for adaptive control of radiation patterns for communication links between base stations and the user. While the primary focus of this section is devoted to phased array design considerations, it should be noted the future cellular industries growth will be driven by evolving smart antenna technologies. This past July, Christopher Taylor, director of the RF and wireless components service at Strategy Analytics, released a new report detailing emerging antenna technologies and the primary companies in the cellular industry in *Antennas for Mobile Devices: New Technologies, New Opportunities*. Explicitly stating that future devices will require at least seven, if not more, cellular bands to maintain technological demands, placing a large burden on antenna designers. In order to avoid a downturn in the cellular antenna market, several device manufacturers have teamed up with leading antenna design experts, for example, Laird, Tyco, Pulse, Ethertronics, and Skycross, hoping to identify antennas solutions hoping to breach the five billion unit mark for antennas in wireless mobile equipment by 2014.[35]

(U) Phased Array Antennas

(U//FOUO) This portion of the report describes some of the current antenna array research and development efforts taking place in various countries around the world, especially China's recent surge in publications. The papers scrutinized for this report focus on advanced array architectures that accomplish specific performance needs such as sidelobe level (SLL) control, monopulse, electronically steered arrays, and synthetic aperture radar (SAR).

(U/~~FOUO~~) The first area of study is SLL control. SLL's suppression is important when one wants the antenna to focus its energy in a particular direction without radiating energy in other undesirable directions. One of the easiest ways to suppress SLLs is to weight the aperture with a Taylor-shaped aperture distribution. Figure 12 shows four different weighting schemes applied to a 16-element linear array, having $\lambda_o/2$ element spacing. The green curve represents an equal amplitude aperture where all 16 elements have the same power. The light blue curve represents a 16-element linear array that is subdivided into four element subarrays, each having an individual weight. Similarly, the dark blue curve represents two element subarrays. The red curve illustrates the 40 decibel (dB) Taylor weighted aperture.

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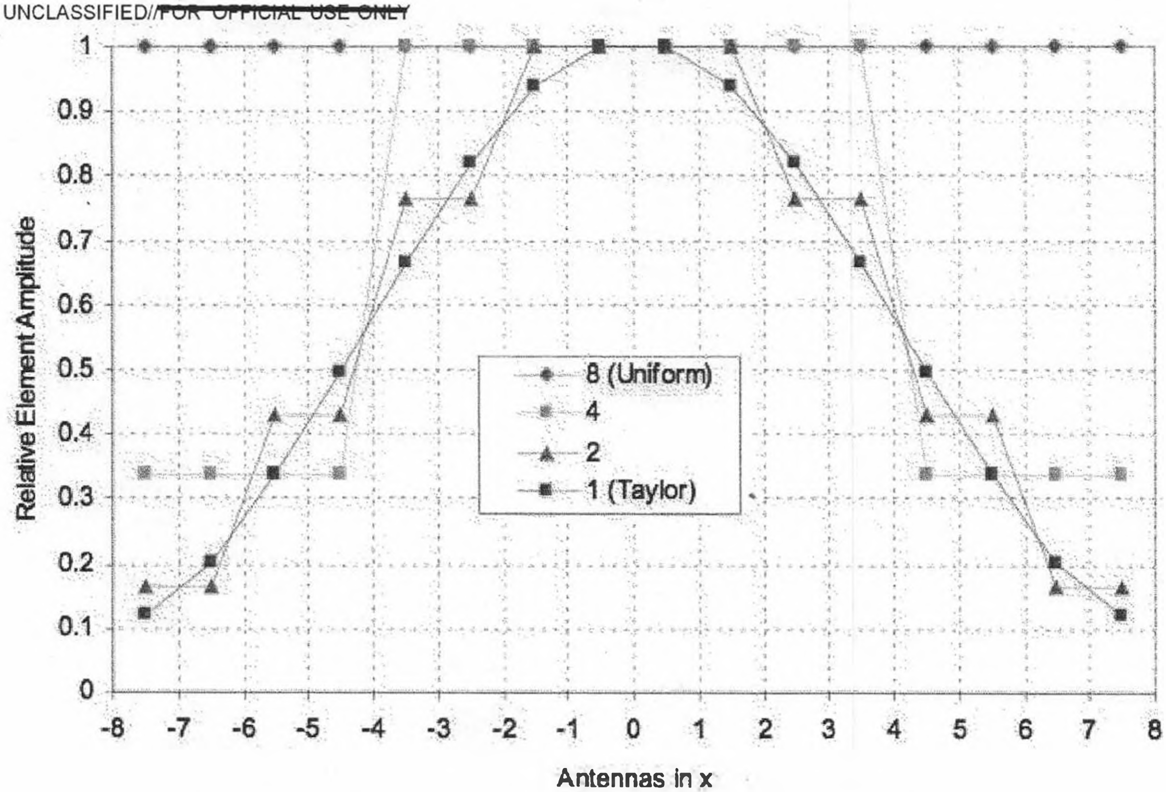

Figure 12. **(U//~~FOUO~~) Amplitude Weights for a 16-Element Linear Array**

(U/~~FOUO~~) These four weighting schemes are then spatially Fourier transformed to yield far-field array factors for the 16-element linear array. These patterns are presented in figure 13. The uniform aperture produces SLLs on the order of 13 dB, whereas the Taylor distribution produces 40 dB SLLs worst case. The other descretized apertures produce SLLs somewhere in-between the extreme cases. Thus, the Taylor weighting is desired in situations where an array's energy needs to be focused in only one direction and suppressed in all other directions.

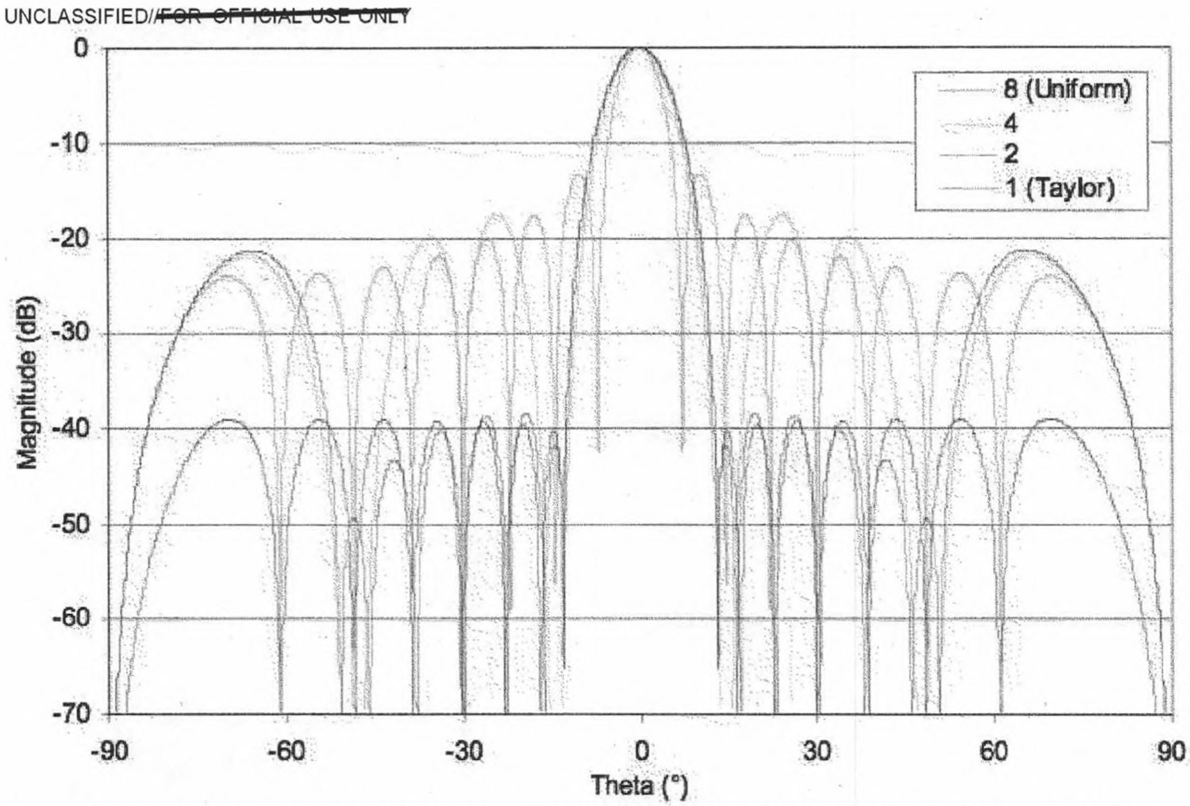

Figure 13. **(U//~~FOUO~~) 16-Element Linear Array Patterns for Different Weighting Schemes**

(U//~~FOUO~~) A large volume of literature can be found on the topic of weighting apertures. Much of this work originates from the United States, Europe, The Soviet Union/Russia, and Japan and applies not only to linear or planar arrays but conformal ones as well. However, in the last several years, several other nations have published a considerable amount of work in reputable journals. These nations include many in Asia, such as Taiwan, China, and Singapore. Even some countries in the Middle East have contributed. China and Singapore have been especially active since 2007, even devoting some of their attention to conformal surfaces. Two such papers that caught our attention are:[36,37]

1. "Low-sidelobe pattern synthesis of spherical array using the hybrid genetic algorithm," Wentao Li, Shufang Liu, Xiaowei Shi, and Yongqiang Hei. Xidian University, Xian, Shaanxi 710071, China.
2. "Pattern synthesis of conformal array antenna in the presence of platform using differential evolution algorithm," Jing-Li Guo ad Jian-Ying Li. Temasek Laboratories, National University of Singapore.

(U//~~FOUO~~) Most of the work coming out of China on this topic is mathematically based. However, the math is fairly rigorous, showing considerable competence in this area of weighted apertures.

(U//~~FOUO~~) The second area of interest here is on monopulse advancements and research. The story here is very similar. Outside the western states (that is, the United States, Europe, Canada, and Australia) monopulse work has been done, albeit mostly theoretical pattern synthesis. Legacy monopulse design and manufacturing has been accomplished in the Soviet Union/Russia, but most recent work has been carried out in the Far East, particularly Japan and China. Chinese contributions to literature, in this case to the keywords monopulse/low sidelobes/array, have really picked up in the last couple of years as shown by table 3. Most of these Chinese publications have focused on synthesis rather than actual fabrication due to the inherent difficulties in constructing such designs. Table 3 is a chart of relevant Chinese publication amounts in the array of monopulse. While this table does not capture all the publications, it does show an important trend that reveals the fact that Chinese contributions have skyrocketed in the last 3 years.

Table 3. (U//~~FOUO~~) Chinese Publications in the Area of Monopulse

Year	Relevant Chinese Publications
2009 (Aug.)	4
2008	16
2007	12
2006	1
2005	2
2004	1
2003	2
2002	5
2001	1
2000	6
1999	1
1998	2
1997	1
1996	1
1995	1

(U//~~FOUO~~) Another interesting thing to note is where these Chinese publications originate. The top Chinese institutions for publishing monopulse research are:

1. State Key Lab of Millimeter Waves, Southeast University, Nanjing 210096
2. Beijing Research Institute of Telemetry, Beijing 100076
3. School of Electronic Engineering, Xidian University, Xian, Shaanxi 710071
4. Department of Electronic Engineering, Beijing Institute of Technology, Beijing 100081
5. College of Information Science and Technology, Nanjing 210016

(U//~~FOUO~~) The next topic of interest is electronically steered arrays. The United States and Russia, as well as Europe, have made significant strides on beam steering for decades. The F-22 AN/APG-77 radar is equipped with a relatively wideband active electronically steered array. In recent years the rest of the world has been catching up. Nowhere is this more noticeable than China. Most of the Chinese publications on this topic originate from Chinese journals, so a Mandarin speaker versed in technical translation is needed to verify the works maturity level. Most of the published electronic steering research coming out of China is still in the study or synthesis stages. However, the work being done is fairly sophisticated and rigorous. It appears that much of this research has yet to make the jump to actual hardware, although figure 14 points to the contrary. It should also be noted that much of the work has been published since 2000 showing China's recent commitment to parity in these areas. Some of the pertinent Chinese publications on the subject of electronic steering are:[38,39,40,41]

1. "Measurement phased array beam steering radar control system," Chen Feng, Meng Qingci, and Ding Lijun. *Measurement and Control Technology*, 2009.
2. "Research of radar beam steering system for phased array radar," Gao Yun Zhu andWang Sheng Da. *Microcomputer Information*, 2008.
3. "Multi-beam forming technology in the phased array radar applications," Zhang Guangyi. Four Anti-New Technology and Information Research Symposium, 2006.
4. "Scanning space analysis of ground based phased array radar," Wen-Chen Li, Liu Fu Bing, Yuan Xiangyu, and Chen Jiang Wei. *Radar Science and Technology* 2004.

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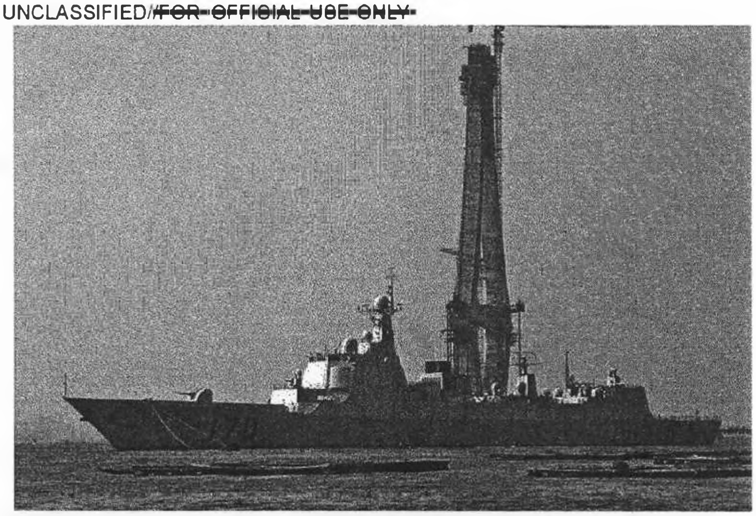

Figure 14. **(U//~~FOUO~~) Luyang II Type 052C Destroyer Equipped with Type 348 Active Phased Array Radar**

(U//~~FOUO~~) The last topic of interest is synthetic aperture radar, or SAR. The United States has contributed greatly to this area. Europe has also been active in SAR in recent years, and Israel, Russia and Japan have also done work. Sandia has been at the forefront of SAR for decades. Figure 15 is a description from Sandia's website visually describing SAR.

(U//~~FOUO~~) Sandia has flown the smallest lightweight high-resolution Ku-band SAR to date (MiniSAR), including one attached to the Class-III UAV shown in figure 16. The antenna is also inset in the figure.

(U//~~FOUO~~) Another Sandia contribution is the X-band system used for discerning crevasses in the Antarctic ice sheet. One such image is shown in figure 17, along with the gimbal assembly.

(U//~~FOUO~~) In recent years, the usual players have continued to perform research on SAR. What is surprising is the recent increase in SAR research coming out of China. Again, most of this work is published in Chinese literature. Some of the papers are:[42,43,44,45]

1. "Shipborn phased array radar target detection in visual simulation," Song Yuan, Zhang Xinhua, Zhang Shanbin, and Xu Kin Zhou. *Journal of Data Acquisition and Processing*, 2008.
2. "Use of phased array system, ship-borne radar and electronic warfare systems," Gao Yun Zhu and Wang Sheng Da. *Microcomputer Information*, 2008.
3. "Engineering design of spaceborne SAR antenna," Ji-Xue. *Areospace Shanghai*, 2003.

4. "A procedure for analyzing ground clutter spectrum in sum and difference channels for airborne phased array radars," Song Xudong, Wang Xue-Gang, and Xiang Jincheng. *Signal Processing*, 2002.

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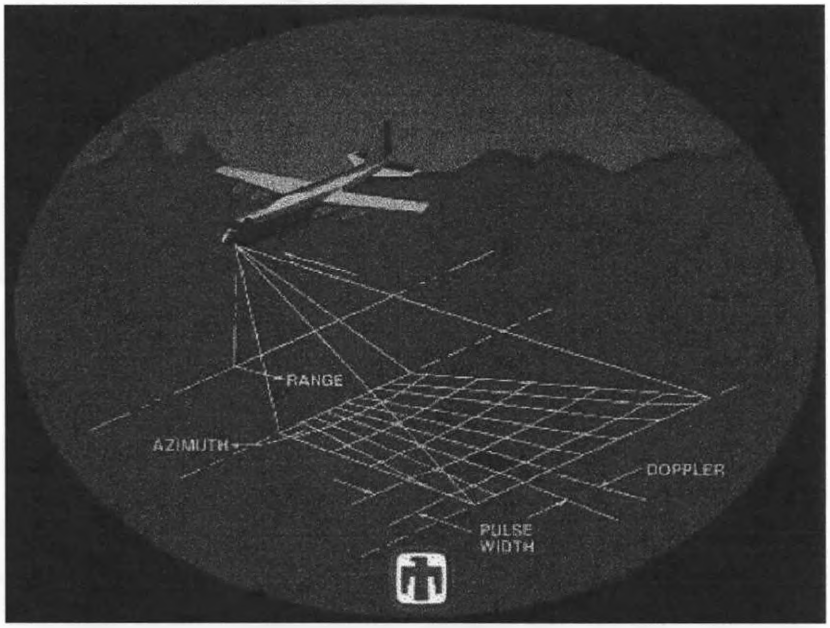

Figure 15. **(U//~~FOUO~~) Sandia Visual Description of SAR**

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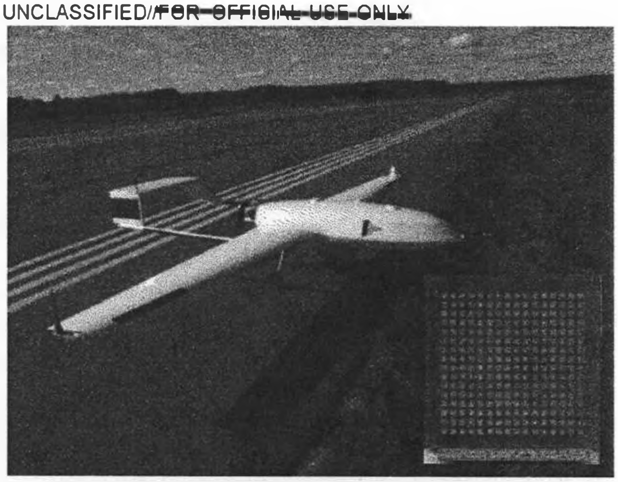

Figure 16. **(U//~~FOUO~~) MiniSAR/Sky Sprit Demo (Antenna Shown in Inset)**

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Figure 17. **(U//~~FOUO~~) Antarctic SAR with Gimbal Assembly**

(U//~~FOUO~~) As was the case before, most of the SAR research coming out of China is still in the preliminary study stages. However, the SAR work being done is, by all appearances from the titles, as sophisticated and rigorous as the work being done in the United States and Europe. Again, it should also be noted that much of the work has been published since 2000, showing China's recent commitment to parity in SAR and associated SAR capabilities such as ground clutter improvements and target detection. If the recent trends continue over the next decade, it is foreseeable that China could become a dominant contributor in this area, especially when one extrapolates out future available funding resources. Thus, researchers in the Western states may be leveraging knowledge from China instead of the other way around.

(U) Advances in Materials Integration

(U//~~FOUO~~) In any communication system, it is the raw materials/components (for example, dielectric substrate, metallic waveguides/radiating elements, active components, and the adhesives/ encapsulants/paints) that define the performance and functionality of the device. Advances in materials science and chemistry coupled with that of advanced fabrication techniques have allowed for the integration of dissimilar components unlike anything we have seen previously. No longer is the system designer limited to the surface mounted components on a traditional planar, two-dimensional printed circuit board (PCB); cost effective, three-dimensional fabrication techniques are readily available. Table 4 illustrates the global efforts with respect to materials science related research to antenna-related technologies.

(U/~~FOUO~~) In recent years, a large effort has been focused on the deposition of metallic systems via advanced printing techniques (for example, direct write, ink-jet and m-contact printing)[46,47,48] Such printing techniques are attractive alternatives to conventional photolithography and electroless routes, which are time-consuming, complicated, and expensive. With the emergence of flexible electronics (for example, liquid crystal substrates), the ability to integrate dissimilar materials—that is, ceramics, metals, semiconductors, and polymers—onto a single, temperature-sensitive substrate enables the fabrication of volumetrically-concise, multi-functional packages. In the past, the technical advances in low temperature co-fired ceramic (LTCC) packages allowed for integration of screenprinted metal traces at temperatures of approximately 800–900° C. Coupling "drop-on-demand" deposition technologies with ink formulations based on nanoparticle, chemical solution precursors, and/or UV-curable chemistries provide lower-temperature, less than 200° C, routes for deposition of highly conductive traces on polymeric commercial substrates. This presents an alternative maskless, cost-effective route to that of electrodeposited cladded substrates.

Table 4. (U//FOUO) Publications in the Area of Materials Science and RF-Related Technologies

Country	Publications	Country	Publications
United States	2,154	Singapore	209
China	1,076	Hong Kong	129
Japan	1,013	Turkey	109
Taiwan	876	Russia	85
South Korea	852	Iran	76
Germany	594	Greece	69
France	558	Malaysia	55
United Kingdom	543	Ukraine	53
Canada	457	Egypt	53
India	357	Israel	45

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(U//FOUO) Researchers at the University of Illinois at Urbana-Champaign have designed metallic-based colloidal chemistry that allows for omnidirectional printing of flexible, stretchable, and spanning silver microelectrodes via a direct-write printing technique.[46] Initial efforts have indicated that the designed chemistry offers the ability to directly fabricate ESAs that approach the Chu-Wheeler-McClean limit, but temperature requirements for metallic densification requires further study. Internationally, most studies on similar topics involve the use of chemistries deposited by ink-jet technologies.

(U//FOUO) Integration of antenna design with soft materials has potential for unique and enabling applications. Research at the University of Alabama at Huntsville demonstrated a skin structure exhibiting flexibility, self-healing properties, and damage-sensing capabilities.[49] The skin was fabricated on a substrate of copper-clad polyimide sheets in a layer-by-layer technique using polyimide sheets and an ultraviolet (UV)-curable epoxy. The UV-curable epoxy is used as both a structural adhesive and as the self-healing fill material. The skin structure is integrated with an array of LC circuits, where each circuit is characterized by a unique resonant frequency. If the skin is damaged, the UV-curable epoxy is released and is cured by ambient sunlight. Further, damage affects one or more of the LC circuits, altering its resonant frequency. An integrated antenna coil detects and locates the damaged portion of the skin.

(U//FOUO) By employing soft lithographic and rapid prototyping methods, injection of a room temperature liquid metal alloy into microfluidic channels within a silicone elastomer, researchers have demonstrated reconfigurable, reversibly deformable, and mechanically tunable dipole antennas.[50,51] Owing to high conductivity of the liquid metal alloy, and large cross dimensions of the microstructured channels, low conductive loss and high radiation efficiencies of the antenna are expected. J.-H. So and co-workers have demonstrated a fluidic dipole that radiates with 90 percent efficiency over a broad frequency range (1,910–1,990 megahertz), which is equivalent to the expected efficiency for a similar dipole with solid metallic elements such as copper. For example, eutectic gallium indium (EGaIn), is a low-viscosity liquid at room temperature and possesses a thin oxide skin that provides mechanical stability to the fluid within the elastomeric channels. Because the conductive element of the antenna is a fluid, the mechanical properties and shape of the antenna are defined by the elastomeric channels, which are composed of polydimethylsiloxane (PDMS). The antennas can withstand mechanical deformation (stretching, bending, rolling, and twisting) and return to their original state after removal of an applied stress. The ability of the fluid metal to flow during deformation of the PDMS ensures electrical continuity. The shape, and thus the function, of the antenna, is reconfigurable. The resonant frequency can be tuned mechanically by elongating the antenna via stretching without any hysteresis during strain relaxation. Figure 18 illustrates the ability to stretch the antenna allowing for mechanical tuning of the resonant frequency.

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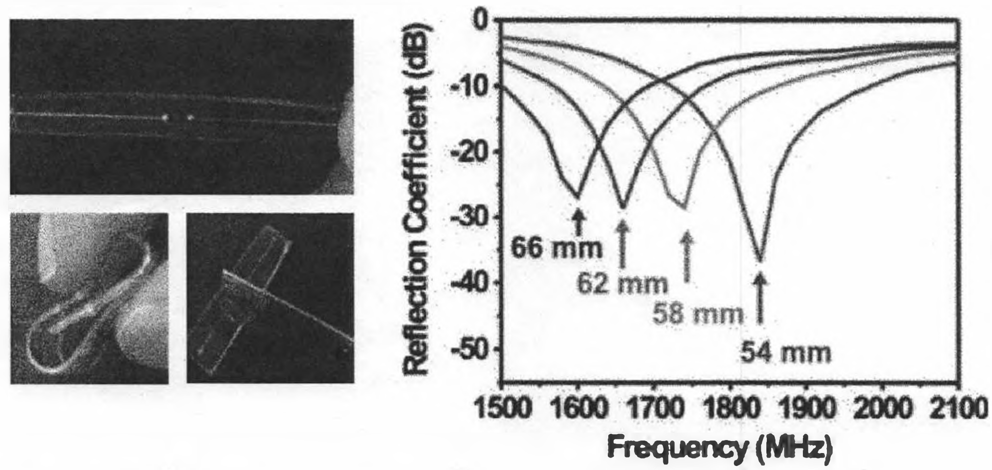

Figure 18. **(U//~~FOUO~~) Photographs of a Prototype Antenna Being Stretched and Rolled (Left); Reflection Coefficient Measurements of the Liquid Dipole Antenna as a Function of Mechanical Elongation (Right)**

(U//~~FOUO~~) As indicated in the section detailing the structure of this report, all information compiled in this document is collected and analyzed from public domain sources. During the analytical sessions focused on materials integration and development, it was evident of the Chinese recent interest in technology related to radio-frequency (RF) stealth and radar absorbing materials (RAM). As highlighted in table 5, publication amounts have increased in the last five years. While RF stealth technologies are not new, current research interest and efforts are often highly shrouded in secrecy.

(U//~~FOUO~~) However, the Chinese publications have provided topics of interest and detailed information on the funding sources throughout several branches of the military. Several papers which caught the attention of the author include:[52,53,54,55,56,57]

1. "Study on the modification of epoxy adhesive for anti-radar coatings," Gao, H.-F., Quan,X.-J., Xie, Z.-M., Zheng, G.-Y., Luo, T.-Y. Binggong Xuebao/*Acta Armamentarii*, 2007.
2. "Analysis of influence of rivets' space to stealth property of 2-D SRAM skin," Li, J.-H.,Sun, Q., Ma Y.-E. Yuhang Xuebao/*Journal of Astronautics*, 2005.
3. "Analysis of launching safety for stealth projectiles fired by artillery," Zhang, P.-Z.,Wang,H., Mi, Z.-H. Dandao Xuebao/*Journal of Ballistics*, 2006.
4. "Analysis of stealthy effect for the stealth aircraft under ns pulse irradiation," Li, Y.,Zhang, W.-J., Zhang, W., and Yuan, N.-C. Yuhang Xuebao/*Journal of Astronautics*, 2007.
5. "Acoustic stealth design of underwatersa ndwich composite added structure under obliqueincidence," Lou, Z., Zhu, X., Jian, L.-A., Li, Y.-Q., and Li, H.-D. Zhendong yu Chongji/*Journal of Vibration and Shock*, 2009

6. "Electromagnetic scattering characteristics of serpentine inlet," Shi, L. and Guo, R. Hangkong *Xuebao/Acta Aeronautica et Astronautica Sinica*, 2007.

Table 5. (U//FOUO) Chinese Publications in the Area of RF Stealth and RAM Technologies

Year	Relevant Publications
2009 (Aug.)	9
2008	21
2007	11
2006	9
2005	7
2004	6
2003	1
2002	2
2001	2
2000	1
1999	0
1998	1

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(U//FOUO) Even a joint US-Chinese collaboration between the University of Toledo and the Chinese Academy of Sciences, was identified, where numerical predictions were studied for new radar absorbing silicon carbide foams.[58]

(U//FOUO) Again, an interesting piece of information to note is the affiliation of the publication. Chinese institutions publishing on the topic of RF stealth and RAM technologies include:

1. Natural Environmental Test and Research Center of Commission of Science, Technology and Industry for National Defense, Chongqing 400039.
2. Baicheng Ordnance Test Center, Baicheng 137001.
3. Research Institute of Power Electronic Technique, Navy University of Engineering, Wuhan 430033.
4. Microwave Center, National University of Defense Technology, Changsha 410073.
5. Staff Room of Armed Services, Nanchang Army College, Nanchang 330103.
6. College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016.

(U) Enabling Technologies

(U) Metamaterial Antennas

(U) Challenges

(U//FOUO) Broadband, low-loss antennas based on metamaterial design and fundamentals are difficult to design and synthesize. Specifically, the ability to design a highly sensitive element in a confined location, such as a cell phone, entitles many intricate details with respect to near-field and far-field characteristics.

(U) Current status

(U//FOUO) As advertised and marketed, Rayspan Corporation (US) is the world's leading innovator of revolutionary metamaterial air interface solutions for high performance wireless communication networks. They have licensed and patented a suite of antenna technologies that are metamaterial-derived, including the Rayspan MTM-E solution offering integration of LTE, 3G, Bluetooth, and GPS operation bands all from a single-feed antenna solution. While the advertised feat is remarkable, whether the design routes are truly metamaterial-based are subject to continued conversations.

(U) Non-Foster Network Matching

(U) Challenges

(U//FOUO) Through simulation and initial experimental demonstrations, it has been realized that a wide assortment of active devices (for example, op-amp, current-fed amplifiers, and floating negative resistors) can potentially provide larger bandwidth while maintaining modest efficiencies. The two major problems associated with the technique, currently, include (1) development of a stable network over the frequency range of interest, and (2) the development of higher quality active components.

(U) Current status

(U//FOUO) Electrically small antennas, regardless of their shape and type, have high Q, and are inherently narrowband and difficult to match. Currently, the non-Foster topic is purely academic, but if the development of non-Foster matching techniques advances from an academic topic to a realizable technology, the increased capabilities and capacities would be beneficial to many parties, including industry and military.

(U) True Time Delay-Enabled Via Dispersion Engineering

(U) Challenges

(U//FOUO) Over the last half century, material scientists have developed sophisticated techniques and principles to understand how to tailor dielectric and magnetic properties, but few have attempted to engineer the dispersion (for example, optical fibers and photonic crystals). As a result of the advances in metamaterial design, the engineer is now no longer restricted by the materials electromagnetic constitutive parameters that are readily available in nature, allowing for the potential control over dispersive properties.

(U) Current status

(U//FOUO) Again, this topic is purely academic, but there is a growing interest in several communities. While metamaterials is one route for dispersion engineering, several alternative methodologies have been proposed. If a robust, flexible route was identified, the result would be transformational with respect to waveguide/transmission line technologies.

(U) Key Efforts

(U//FOUO) Texas A&M University has active electromagnetic and microwave research areas that focus on the theoretical and experimental aspects of antennas, electromagnetic theory, electromagnetic wave scattering, active and passive microwave and millimeter wave circuits, linear and non-linear optical or microwave guiding systems, and microstrip antennas. Sponsors include NSF, NASA, General Dynamics, Raytheon, Siemens, and more. Select research projects include:

- Biologically inspired concepts for reconfigurable antennas and multifunctional smart skins
- Multifunctional antenna systems and smart structures that support critical components of emerging DoD platforms
- Compact UWB microwave and millimeter-wave systems

(U//~~FOUO~~) The University of Illinois at Urbana-Champaign is one of the largest research institutions in the world, and its Department of Electrical and Computer Engineering is the main contributor to antenna research that takes place on campus. ECE researchers collaborate with industry, government, peer institutions, and each other in their research endeavors—including ONR, NASA, AFOSR, DARPA, AT&T, Motorola, Samsung, and Sony Corporation. Projects include:

- Adaptive Space-Time Codes for General MIMO Channels
- Antennas for Wireless Sensors
- Intelligent Portable Antenna Systems for High-Speed Wireless Communication
- Low-Profile Radiators in Aperiodic Wideband Arrays
- Reconfigurable Antennas for High Data Rate Multibeam Communication Systems
- Mechanically Conformal and Electronically Reconfigurable Aperture for Space-Based Radar Applications
- Antenna Tunability and Compatibility

(U//~~FOUO~~) The University of Texas at Austin's Electrical and Computer Engineering Department has been one of the top in the country for over a decade. Within the electromagnetics research thrust is an antenna design area, focusing on unique designs include electrically very small high frequency antennas (approaching 0.01 λ) and very wide band antennas for ultra-wideband (UWB) usage. Sponsors and industrial affiliates include National Instruments, Nortel, Yokogawa, Panasonic, the Department of Defense, Qualcomm, Dell, AT&T, Texas, BAE Systems, Boeing, Cisco, DTRA, Intel, MIT, NSF, the US Army, and more.

(U//~~FOUO~~) Rayspan Corporation (US) is the world's leading innovator of revolutionary metamaterial air interface solutions for high performance wireless communication networks. Maha Achour is Rayspans co-founder and Chief Technology Officer. As advertised, Rayspan's proprietary metamaterial solutions will displace conventional antennas and RF components and enable a true nextgeneration of extremely high performance mobile terminals. Recent announcements from the company website (www.rayspan.com) include the Rayspan MTM-E solution as the only antenna technology that offers integrated LTE, 3G, Bluetooth and GPS all from a single-feed antenna solution. MTM-E is the only antenna solution that can support six or more bands operating from 698 MHz to 960 MHz in the low band and 1,710–2,170 MHz as well as 2.6 GHz in the high band without requiring any switching elements or matching circuits. Rayspan's MTM-B has been designed to meet the requirements for single band 2.4 or 5.0 GHz designs as well as dual band 2.4/5.0 GHz devices, in a small form factor of 15 mm × 14 mm, which is 80 percent smaller than typical dipole solutions offered today.

(U//~~FOUO~~) The University of Arizona has an active research area in the study of how metamaterial-inspired electrically small resonators may be used as near-field parasitics to achieve efficient, electrically small, broad bandwidth antennas. Recent publications detail the design and fabrication for efficient, low profile, electrically small, VHF 3-D magnetic EZ antennas and multiband extensions of the electrically small metamaterial-engineered Z antenna.[59,60]

(U//~~FOUO~~) The University of California–Los Angeles has an active research area in Active Integrated Antennas, which provides a new opportunity by combining active microwave circuits and devices with integrated antennas. Professor T. Itoh the leader of this effort and a proponent for TL-MM design. The research activities listed above have been strongly supported by governmental and industrial organizations. They include the Army Research Office, Office of Naval Research, Air Force Office of Scientific Research (JSEP), DARPA, Matsushita, Hughes, TRW, Rockwell, and the ThermoTrex Corporation.

(U//~~FOUO~~) University of Zagreb (Croatia) has an active area in the integration of metamaterial components for the development of sub-wavelength resonators, waveguides, and antennas for the manufacturing of miniaturized microwave packages.[61]

(U//~~FOUO~~) Helsinki University of Technology and Aalto University (Finland), lead by Sergii Tretyakov, have developed in-depth programs relating electromagnetic theory to multiple metamaterial related topics: near-field effects, antennas, and cloaking.

(U//~~FOUO~~) Researchers at the Saint Petersburg State Electrotechnical University (Russia) are developing alternative approaches for microwave metamaterials based on low loss dielectrics, for example, Mie scattering. Successful development would result in the first demonstration of three dimensional, isotropic metamaterials, allowing for unique radomes, substrates, and potential antenna designs.[62]

(U//~~FOUO~~) Researchers at the National University of Singapore have studied the role of metamaterials in microstrip antennas and arrays since early 2002. Professor Joshua Le-Wei Li, with the support from A-STAR, has focused on the efficient and fast design of radio frequency metamaterials. Supported by the US Air Force AFOSR and AOARD since 2006, research efforts have focused on fast solvers for the RF metamaterials characterizations and designs. He was one of nine individual principal investigators in the AFOSR NIM Program, and the only non-US citizen who was awarded research grant in 2006. After several years, recent success was achieved with respect to broad bandwidth and high gain metamaterial microstrip or patch antennas and arrays using the metamaterial concepts. This success serves as an important progress of metamaterials in RF applications, because the narrow bandwidth and high loss are two key issues in the metamaterial research and development and they prevent the further progress in the RF metamaterials development.[63]

(U//~~FOUO~~) Loss and bandwidth have been a major problem that has limited the potential metamaterial applications for a long time. Research at the State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, China, is currently looking to identify broadband, low-loss, non-resonant routes to RF metamaterials.[63]

(U) Capability Forecast

(U) Short-Term Capabilities (Less than Five Years)

(U//~~FOUO~~) The biggest near-term opportunities for antenna technologies will probably be a result of the marketing schemes for metamaterial based antennas. The RF infrastructure opportunity alone is highlighted by a United Kingdom Office of Science and Technology report as being well over $150 billion, and the same report positions metamaterials as capable of significantly advancing the capabilities of integrated RF circuitry. Rayspan has obtained large-scale production contracts for its prototypes, which include Netgear wireless routers and LG cell phones. It has been reported that more than 20 million antennas were shipped in 2009.

(U) Medium-Term Capabilities (Five to 10 Years)

(U//~~FOUO~~) With respect to military focused advanced antenna array architectures, more complex architecture will be realized as simulation capacity increases. Most arrays of reasonable size (that is, 16 × 16 elements) require significant computational resources for accuracy. Certainly within the medium term, both electromagnetic software and computers will be greatly enhanced, allowing for more complex radiators and arrays to be studied in much shorter time intervals, especially when many layers are used as in the case for some of the more complex planar arrays. Significant moves towards lightweight, low-profile, and increased bandwidth arrays will probably be realized. Volumetric arrays that are waveguide- or coaxially-based will most likely see performance enhancements as well as be combined with active devices. These active devices include phase shifters, amplifiers, and so forth.

(U) Long-Term Capabilities (More Than 10 Years)

(U//~~FOUO~~) Over the long term, two research topics are highlighted for the potential to enable gamechanging technologies: non-Fostering network matching and dispersion engineering. However, being labeled as an academic topic presently, the ability to increase bandwidth of inherently, high-Q electrically small antennas serves as an important research topic for next generation applications. Additionally, with the ability to control dispersion, a key science and technology obstacle could be overcome with respect to broadband true time delay devices, for example, in electronically scanning, phased array antennas. The topics are limited to a select group of academic researchers, but the topics are gaining interest in the global scientific community.

(U) Concluding Remarks

(U//~~FOUO~~) As data rates and the complexity of wireless devices increase at an enormous pace, so do the constraints on antenna designers. However, no wireless device is possible without the ability to transduce from on-board signal to that of free space. Electrically small antenna investigations will continue worldwide (specific to the end-user application—indust rial and military); however, it will often be a sub-component of the total research investigation. The use of non-Foster idealizations does offer the potential for increased bandwidth capabilities at the expense of higher power consumption—albeit at an academic setting presently. Metamaterial-based technologies are best summarized by a recent statement by a DoD representative: "It is quarter to midnight in the eyes of the DoD. If there is no discernible advantage for the utilization of metamaterial based technologies, research efforts and funding will be re-focused." However, another academic topic—dispersion engineering—does offer real potential for game-changing technologies. Advanced antenna array architectures will continue to receive a high level of interest as a new generation of cellular infrastructure is erected that expects to bear an enormous, service-driven user population. Specifically with respect to military application, mono-pulse radar techniques with low-side lobe characteristics will be a key research topic globally as more sophisticated platforms are transitioned from simulation-capable to hardware-producible. Coupling the theoretical and simulation headway in antenna design with that of advanced materials development and integration will truly enable game changing technologies in the near future.

(U) Acronyms and Abbreviations

AMC	artificial magnetic conductor
EBG	electromagnetic bandgap
dB	decibel
DNG	double negative metamaterials
EGaIn	eutectic gallium indium
ESA	electrically small antenna
HIS	high impedance surface
LHM	left-handed media
LTCC	low-temperature co-fired ceramic
NIM	negative index metamaterial
MM	metamaterial
MOST	Ministry of Science and Technology
NIC	negative impedance converter
NSFC	National Natural Science Foundation of China
PCB	printed circuit board
PDMS	polydimethylsiloxane
PAA	phased-array antennas
RAM	radar absorbing materials
RF	radio frequency
RFID	radio frequency identification
RHM	right handed media
SAR	synthetic aperture radar
SLL	sidelobe level
SME	subject matter expert
TRL	technology readiness level
UV	Ultraviolet
UWB	ultra-wideband
VSWR	voltage standing wave ratio

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