

Metamaterials: The early years in the USA

Richard W. Ziolkowski*

Department of Electrical and Computer Engineering, The University of Arizona, Tucson, AZ, USA

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Abstract – Metamaterials are artificial materials formed by embedding highly subwavelength inclusions in a host medium, which yield homogenized permittivity and permeability values. By design they offer the promise of exotic physics responses not generally available with naturally occurring materials, as well as the ability to tailor their properties to specific applications. The initial years of discovery emphasized confirming many of their exotic properties and exploring their actual potential for science and engineering applications. These seed efforts have born the sweet fruit enjoyed by the current generation of metamaterials scientists and engineers. This review will emphasize the initial investigative forays in the USA that supported and encouraged the development of the metamaterials era and the subsequent recognition that they do have significant advantages for practical applications.

Key words: Artificial dielectrics, Double negative materials, Epsilon negative materials, Metamaterials, Mu negative materials, Plasmonics.

1 Introduction

Artificial materials have had an enormous impact historically. Well-known examples include the beautiful 13th century stained glass windows in Notre-Dame Cathedral and La Sainte-Chapelle in Paris, their colors originating from plasmonic effects arising from various metallic inclusions in the glasses. In the late part of the 19th century, Jagadis Chunder Bose published his work on the rotation of the plane of polarization by man-made twisted structures, which were indeed artificial chiral structures by today's definition [1]. Karl Ferdinand Lindman studied artificial chiral media formed by a collection of randomly-oriented small wire helices in 1914 [2]. In the 1950's and 1960's, the work of Kock [3], for example, explored artificial dielectric light-weight microwave antenna lenses for satellite applications. To understand the Mercury and Gemini spacecraft re-entry communication blackout periods, the "bed of nails" wire grid medium was introduced in the early 1960's to simulate the propagation of waves in plasmas [4]. Artificial electric and magnetic materials were at the heart of the stealth aircraft programs in the 1980's and beyond. Similarly, the resurrected interest in artificial chiral materials in the 1980's and 1990's (see, e.g., [5]) arose from their potential applications as microwave radar absorbers.

Ziolkowski at the University of Arizona (UAz) was contacted in July 1999 by Prof. Rodger M. Walser, University of Texas at Austin (UT Austin), about an invitation-only DARPA

Workshop to be held in November, 1999. These are the kind of events in which the participants have the chance to influence a call-for-proposals (CFP). I quite naturally agreed to participate. I was invited because of our artificial atom/molecule investigations and their applications to radar absorbing materials (RAMs) and smart skins (surfaces that could change their characteristics in response to an interrogating signal) [6–11]. These efforts had already led to our studies on how one might use these artificial material models to realize absorbing boundary conditions (ABCs) in finite difference time domain (FDTD) simulations [12–15]. They were "physical" realizations of the (at the time) revolutionary perfect matched layer (PML) ABCs [16].

Walser released the general invitation in September 1999 stating: "DARPA is interested in gathering information concerning the area of artificially constructed materials, or Metamaterials, which possess qualitatively new responses that do not occur in nature". This was the first time I had seen the phrase "Meta-materials". As he did in a later paper [17], Walser explained at the workshop that the choice of name came from the desire to achieve material performances "beyond" the limitations of conventional composites. The workshop program consisted of an *Applications Section* [18] and a *Materials Modeling and Processing Section* [19]. Drs. Stu Wolf and Bill Coblenz of DARPA/DSO (Defense Sciences Office) and Dr. Valerie Browning, who was at NRL and coming on board at DARPA at the time, ran the workshop. The presentations were an interesting mixture of results on electromagnetic band-gap structures and complex media.

*e-mail: ziolkowski@ece.arizona.edu;
ziolkows@email.arizona.edu

The workshop led to an eventual DARPA MURI (Multi-University Research Initiative) CFP (MURI Call for Proposals: Topic 33, Electromagnetic Metamaterials) in 2001 whose stated objective was: “To model, synthesize, characterize, and develop new synthetic metamaterials which exhibit properties that can be used in a wide range of applications spanning the electromagnetic spectrum”. The winning proposal was entitled “Scalable and Reconfigurable Electromagnetic Metamaterials and Devices”; the team consisted of several well-known talents [20]. Dr. Browning later described her new program on Metamaterials at the DARPA Tech 2002 meeting by saying that [21]: “A metamaterial is an engineered composite that exhibits superior properties not observed in nature or in the constituent materials”. I believe that it is an interesting historical observation that the term “metamaterials” was truly introduced into the community because of a DARPA funding opportunity.

2 Initial physics and engineering proof-of-concept efforts

Much of the effort in the early metamaterials period in the USA, like elsewhere in the world, emphasized investigating and proving the exotic physics properties of metamaterials. The first negative index and then negative refraction investigations and experiments were performed at UC San Diego (UCSD) [22–25]. At the same time, the seminal applications paper on the “perfect lens” concept appeared [26]. Full-wave vector simulations and a detailed analysis of double negative (DNG) metamaterials confirmed their negative index properties [27]. One very important precursor to these experiments was the IEEE MTT special issue on electromagnetic periodic structures [28]. Several notable papers were included that emphasized artificial magnetism. The split ring resonator (SRR) was introduced by an Imperial College-GEC-Marconi team [29]. Structured surfaces that act as artificial magnetic conductors (AMCs) were introduced by UCLA teams: the mushroom surface type [30] and the frequency selective surface (FSS) type [31, 32]. Given the timing on all of these papers in relation to the DARPA workshop, they clearly had a significant impact on the outcome of the above mentioned DARPA MURI CFP.

3 Optics contributions

The excitement about metamaterials at the time became contagious. Since the original artificial magnetic experiments were in the microwave regime and given the potential of a perfect lens, the physics/optics community quickly tried to push the concepts up to optical frequencies. A special issue of *Optics Express* with Pendry as its Guest Editor summarizes some of the thrusts at that time [33]. These included advances in simulating the propagation in and scattering from DNG media at UCSD, ISU, and UAz [34–36]; advances in superlens technologies at UCLA [37]; refinements of the negative refraction experiments at Boeing [38]; reports of yet more exotic phenomena by Penn State University [39], MIT [40], and Purdue University (Purdue) [41]; and illustrating DNG phenomena can be

obtained from electromagnetic band-gap (EBG) structures by a MIT-Imperial College team [42].

A metasurface at telecom frequencies based on SRRs was reported by the collaborative team from Iowa State University, Karlsruhe Institute of Technology, and FORTH in Crete [43]. This Soukoulis-Wegener-led collaboration has led to numerous contributions to the successful development of optical metamaterials [44, 45]. However, this team pointed out earlier that because of kinetic inductance effects, SRR-based unit cells would not reach visible frequencies [46] and suggested an alternative approach [47]. A University of New Mexico and Columbia University team proposed yet a different architecture [48]. The first demonstration of metamaterials in the visible, which employed a fishnet structure, was reported in [49] by the ISU-Karlsruhe team. Shalaev reviewed the state-of-the-art in [50] and his Purdue team officially reached visible frequencies with their fishnet structure in [51]. The Nanophotonics Group at Purdue with their outstanding fabrication capabilities in the Birck Nanotechnology Center has continued to push DNG effects further into the visible regime. Shalaev and Boardman organized another OSA focus issue on metamaterials published in 2006 [52].

On the West coast, Zhang moved from UCLA to UC Berkeley in 2004 and established the NSF Nano-Scale Science and Engineering Center (NSEC). They have demonstrated and verified many of the hyperlens and superlens concepts [53–55]. They made one of the first examples of a superlattice optical metamaterial [56]. They have demonstrated plasmon lasers at visible frequencies [57]. In the South, Scalora at the Redstone Arsenal in Alabama and his collaborators have considered numerous aspects of DNG media and subwavelength focusing [58].

On the East coast, Engheta at the University of Pennsylvania (UPenn) had been involved with complex media for many years. He developed a variety of RAMs based on bi-anisotropic materials [59]. It has been demonstrated by many groups now that the Ω -medium he introduced [60] can be designed to exhibit DNG properties [61]. He also has introduced and developed the paradigm of Metatronics [62–64] and with Alù, whose is now at UT Austin, considered how basic antenna concepts can be used successfully to design and analyze nano-antennas and their properties [65, 66].

An important aspect to note about the first wave of discoveries in the early days was the controversy surrounding negative refraction and perfect lensing [67–73]. While such discussions can be healthy, they tend to be distracting, impacting both progress and effort levels. Nevertheless, Dr. Browning recognized the importance of the debate. Because one of the issues was the impact the size of the negative index wedge may have had on the original experiments, she asked the Boeing Phantom Works (now Boeing Research and Development) team [74] to construct a larger version which was tested successfully by several independent laboratories and was highlighted in [75]. She also held a workshop at DARPA in 2003 [76] to which both critics and proponents alike were invited to discuss metamaterial issues such as negative refraction. A second DARPA MURI CFP on metamaterials later occurred in 2004.

4 Electromagnetics contributions

While the concept of artificial magnetism at optical frequencies captured the attention of the optics community, it was, as noted above, not new to the engineering electromagnetics community. Other aspects of metamaterials, however, were of immediate interest to the microwave community. The original negative index experiments exhibited performance characteristics that were not acceptable for practical microwave applications. However, Ziolkowski demonstrated in [77] that low-loss DNG bulk metamaterials could be designed to be matched to free-space. Engheta ascertained how (extremely) electrically small resonant cavities could be realized with matching DNG metamaterials with double positive (DPS) materials [78]. Ziolkowski employed this concept, for instance, to achieve highly subwavelength, ultra-thin laser designs [79]. It was also recognized that planar metamaterials were possible by employing transmission line concepts. In particular, two-dimensional transmission line metamaterials were realized simultaneously at the University of Toronto [80] and at UCLA [81]. Both groups also recognized that the metamaterial approach provided the first means for scanning a leaky wave antenna (an array formed by a periodic arrangement of DNG unit elements) from the backfire, through the broadside, and to the endfire directions [82, 83]. Furthermore, it was reported by different UCLA groups [31, 84] and by a team from the European Space Agency and the University of Navarra [85], that electromagnetic band-gap structures could impact the performance of antennas and arrays of them.

To get the word out about these exciting developments, Engheta and Ziolkowski organized special sessions associated with metamaterials at the 2002 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, San Antonio, Texas, June, 2002. They solicited contributors there and issued a call for papers as the guest editors for the first IEEE special issue on metamaterials. This issue, which was sponsored by the IEEE Antennas and Propagation (AP) Society, was published in October 2003 [86]. A second special issue was published in April 2005 with Itoh and Oliner as the Guest Editors [87] and was sponsored by the IEEE Microwave Theory and Techniques (MTT) society.

The AP-S issue included several topics reported by USA groups who continued to contribute into the second half of the first decade of metamaterials. The first paper by the UAz group on metamaterial-based electrically small antennas appeared in it [88]. Several years of their metamaterial-inspired antenna efforts were summarized in [89]. They also developed a bulk metamaterial AMC (with no ground plane) to realize a low-profile antenna system [90]. The first paper by the UPenn group on cloaking (transparency or scattering cancellation) and tunneling also appeared in it [91]. They have continued their contributions to the development of cloaking approaches [92–94]. An HRL team introduced a tunable version of the Sievenpiper mushroom surface to achieve beam steering [95]. Other antenna contributions included the UCLA realization of low profile antennas using EBG ground planes [96] and the investigations of lowering the mutual coupling between antenna elements in arrays [97]. Their continued efforts have been compiled in the book [98]. Another low profile antenna system

introduced by an Arizona State University-Etenna Corp. team took advantage of the high impedance mushroom surface as an AMC [99]. A University of Michigan team led by Volakis used topological optimization to design a metamaterial to improve the bandwidth of a patch antenna [100]. After his move to Ohio State University, Volakis has used a variety of metamaterial constructs to enhance various antenna performance characteristics [101–103]. Another University of Michigan team led by Sarabandi also has investigated a variety of metamaterials and their antenna applications [104–107]. A NIST-Boulder and UC Boulder team reported the proper characterization of meta-surfaces [108, 109]. They have worked with several collaborators to continue to refine their approach for a variety of meta-film constructs [110–112].

Like Eleftheriades' U Toronto group, the Itoh-Caloz UCLA team used transmission line metamaterials to achieve numerous microwave engineering devices and antenna systems since their inception. For instance, the U Toronto group reported a compact phase shifter in [113]. In the MTT special issue, the UCLA team, which became the UCLA-Montreal University team in 2004, reported a compact diplexer [114]. A summary of several of their antennas was given in [115]. A summary of various metamaterial-based antennas was given by UCLA in [116].

Yet another IEEE special issue, highlighting both the microwave and optical regimes, was guest edited recently by Eleftheriades and Engheta [117]. Several more summary papers of the metamaterial efforts reported by many USA and international groups can be found in it.

The second DARPA MURI on Metamaterials started in 2005 [118] and was led by the Boeing Phantom Works team. While several of its outcomes were mentioned topically above, it also led to some of the electrically smallest single negative (SNG) and DNG unit cells produced to date. The experiments confirmed the designs; a low loss DNG bulk metamaterial was realized at UHF frequencies [119, 120].

5 Active and extreme contributions

Important classes of metamaterials that I would like to highlight in closing are those involving active elements and those which exhibit extreme properties. Several have garnered enormous attention both technically and generally in recent years.

Active molecules were reported in [9–11], for instance, for smart skins; but the idea of using active inclusions to develop broad bandwidth metamaterials was emphasized by Tretyakov at Aalto University in [121]. Active metamaterials (i.e., metamaterials formed by introducing gain devices such as transistors or operational amplifiers into their inclusions and, hence, unit cells) for RF frequencies have been designed by a team at Duke [122]. These principles have been used by them to realize lossless magnetic [123] and non-reciprocal [124] microwave metamaterials. Non-Foster elements to achieve dispersionless, wide bandwidth and superluminal effects in metamaterials have been studied by Hrabar's team at the University of Zagreb [125–127]. Superluminal waveguides based on non-Foster circuits have been reported by Sievenpiper's UCSD group [128]. Nonlinear metamaterials, emphasizing the SRR type of elements, have been investigated extensively by Kivshar's

University of Canberra team [129–131]. The SRR-type unit cells augmented with non-Foster elements also have been reported for other metamaterial-inspired structures by teams at Northeastern University [132] and Rome Tré [133]. By introducing non-Foster circuit elements into their metamaterial-inspired antenna designs, the UAz team has overcome several basic physics bounds on small radiators to realize electrically small, efficient, broad impedance bandwidth and high directivity systems [134–138]. The U Toronto group has also reported non-Foster augmentations of antennas [139] and has considered alternative designs for non-Foster circuit implementations [140]. Because of the presence of active elements in all these metamaterial-inspired structures, there is a need to understand their stability in practice. While the various individual groups have provided stability analyses of their components, more general considerations have been reported by a team from the University of Carlos III de Madrid and the University of Zagreb [141] and a Queen Mary University of London team [142]. Several successful uses for active metamaterials in the THz regime have been reported by the Boston College (BC)-Boston University (BU) team [143].

While many of these lower frequency applications have added performance enhancements, the concept of introducing gain into metamaterial structures to overcome the losses associated with their constituents has become critical in the optical domain. Whether it is optical metamaterials, core-shell nanoparticles or plasmonic-based devices, the losses associated with their metal constituents is unforgiving. Gain is a possible enabling technology to significantly improve the possible applications of metamaterial structures in the visible. For example, the Purdue team originally recognized gain was a path to a high figure of merit in [144]; they demonstrated a lossless visible metamaterial in this manner in [145]. The UAz team has considered overcoming losses in the visible with gain in metallic-dielectric core-shell nanoparticles. While they demonstrated the possibility of core-shell nano-lasers [146] and active epsilon-near-zero (ENZ) meta-surfaces [147], collaborations between the UAz, Technical University of Denmark (DTU) and Shanghai Jiao Tong University (SJTU) have extended these designs to demonstrate super-resonant scattering [146, 148], gain-enhanced metamaterial-inspired nano-antennas [149], and active quantum jammers [150]. It should be added that loss compensation with gain is also intimately connected to the coupling between metamaterial and the gain medium. Without sufficient coupling, no loss compensation can happen, nor can the transmitted signal be amplified. Therefore, it is of vital importance to understand the mechanism of the coupling between the metamaterial and the gain medium. The issue was tackled in the papers from the ISU-Karlsruhe [151, 152] and Imperial College London [153] teams.

One metamaterial topic that has garnered enormous attention since 2006 is cloaking. The Duke-Imperial College team first reported their cloaking success in [154], based on their transformation optics (TO) approach [155]. Whether you are of the Klingon-Star Trek or Harry Potter ages, this work was exciting and has greatly stimulated efforts in the electromagnetics, acoustics and elastic communities worldwide. Another related concept at the other extreme is the perfect absorber reported by a BC-Duke collaboration [156], which has initiated

a flurry of papers considering numerous designs and potential applications.

One aspect of the TO or the UPenn scattering cancellation/transparency approaches to cloaking is the need to have metamaterials whose material properties are extreme, i.e., either close to zero or close to infinity. The high impedance surfaces realizing AMCs (i.e., they act as ENZ or permittivity-to-infinity metamaterials) or their duals are further examples. The UPenn team has employed the ENZ concepts effectively to achieve a variety of super-coupling effects [157, 158].

An interesting related issue with the transmission line metamaterials is the fact that in their balanced condition, the propagation constant $\beta = 0$, which means the index of refraction is zero. Consequently, the wavelength and phase speed are infinite at the point between which the transmission line is left-handed or right-handed [159]. This behavior led to the concept of infinite wavelength resonances and devices [160]. On the other hand, the UAz team recognized that since one can tune the permittivity or permeability to any value one would like and since matching is important for any source or scattering problem, one could consider making a metamaterial with both its permittivity and permeability being zero, i.e., a matched zero index metamaterial [161]. It was recognized that with a zero-index medium, one could achieve high directivity sources or could tailor phase fronts to any desired shape. The UPenn team illustrated how one could perform similar operations with ENZ metamaterials [162].

Indeed, exploiting extreme properties to control wave-matter interactions continues to be an active area of investigation. A number of very interesting linear and nonlinear properties are being discovered and reported. Fascinating applications has been uncovered and a variety of them are being pursued currently.

6 Summary

The early years of metamaterials took the science and engineering communities by storm. I have tried in this paper to provide some additional perspectives and details about the work done in the USA during this time period. Many more of the early technical accomplishments were captured in the first three metamaterial reference books [163–165]. While the early years emphasized understanding the basics, the following years began a transition into potential and actual applications.

The interest and level of activity of the first decade of metamaterials has been sustained and has even increased going into the second one. However, the metamaterials community is now faced with the need to demonstrate the usefulness of its work to society by succeeding in the development of useful current and future applications. Maybe we should call them meta-applications – those beyond what we could have only done with the old ideas and materials of the previous century. It will be a great pleasure to watch more of the discoveries and developments in metamaterials and meta-applications unfold in the pages of this new journal, EPJ AM.

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- Speakers included: Ken Suslick (U Illinois), Bruce Dunn (Penn State U), Ray Baughman (Allied Signals), Chris Murray (IBM), Mike Cima (MIT), Steve Chou (Princeton), and John Halloran (U Michigan).
- Team Members included: Xiang Zhang (PI, UC Berkeley), Eli Yablonovitch and Tasuo Itoh (UCLA), Sheldon Schultz and David R. Smith (UCSD), Gang Chen and John Joannopoulos (MIT) and John Pendry (Imperial College); <http://xlab.me.berkeley.edu/MURI/muri.html>
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