INVITED PAPER *Special Section on Metamaterials for Microwave and Millimeter-Wave Applications*

Metamaterial-Based Antennas: Research and Developments

Richard W. ZIOLKOWSKI[†a)], ***Nonmember***

SUMMARY A brief review of metamaterials and their applications to antenna systems is given. Artificial magnetic conductors and electrically small radiating and scattering systems are emphasized. Single negative, double negative, and zero-index metamaterial systems are discussed as a means to manipulate their size, efficiency, bandwidth, and directivity characteristics.

key words: *metamaterials, electrically small antennas, complex media, artificial magnetic conductors*

1. Introduction

Maxwell's equations allow for a wide variety of interesting physical phenomena. Many of these occur because of interesting material properties. For instance, a change in the index of refraction from one region of space to another is responsible for phenomena such as refraction and total internal reflection. Periodic media changes allow or prevent the propagation of certain wave vectors and frequencies. Wave interactions can stimulate energy exchanges with active media. Basic phenomena such as these are responsible for devices such as lenses, dielectric guides, filters, and amplifiers. These devices are used, for example, in electromagnetic wave systems from UHF to microwave to millimeter wave to terahertz wave to optical frequencies.

Unfortunately, the possible variations in the permittivities and permeabilities of materials available in nature, e.g., their magnitudes, losses, frequency dependencies, and signs, are limited. Even traditional composite materials formed from combinations of naturally occurring substances have limited responses. More often than not, one must build a device or system based upon such a restricted set of material choices. If there was a means of designing and building materials with permittivity and permeability values that can be tailored to a specific application, the potential benefit to electromagnetic systems would be enormous.

Metamaterials (MTMs) are artificial media characterized by constitutive parameters generally not found in nature whose values can be engineered to specified values. To date they have been realized mainly as composite artificial media formed by periodic arrays of dielectric or metallic inclusions in a host substrate. The "meta" refers to the resulting effective properties whose electromagnetic responses are "beyond" those of their constituent materials. It has been discussed how metamaterials can have counterintuitive properties in their interactions with electromagnetic waves, e.g., [1]–[3]. They have been considered for use in a wide variety of guiding and radiating structures [1]–[3]. Here a brief review of some of the attractive properties of metamaterials and their potential applications to antenna systems, which have been discussed recently in the technical literature, is given. Particular emphasis will be given to electrically small metamaterial-based resonant radiating systems that arise by designed pairings of conventional materials with metamaterials and that can be used to overcome conventional physical limitations.

Materials may be categorized by their constitutive parameters ε and μ according to the diagram shown in Fig. 1. If both the permittivity and permeability have positive real parts as in the first quadrant of Fig. 1, as most of the materials in nature do, they will be called "double positive (DPS)" media. In contrast, if both of these quantities are negative, as in the third quadrant of Fig. 1, they will be called "double-negative (DNG)." The materials with one negative parameter, quadrants two and four, will be called "single-negative (SNG)." If the permittivity is negative, as in the second quadrant, these SNG materials will be called "epsilon-negative (ENG)." The ionospheric plasma layer exhibits this behavior at AM radio frequencies while natural plasmonic materials (noble metals and some dielectrics) do at optical frequencies. If the permeability is negative, as in the fourth quadrant, they will be called "mu-negative (MNG)." Ferromagnetic materials exhibit this behavior in the VHF and UHF regimes. If both ε and μ are zero or very close to zero,

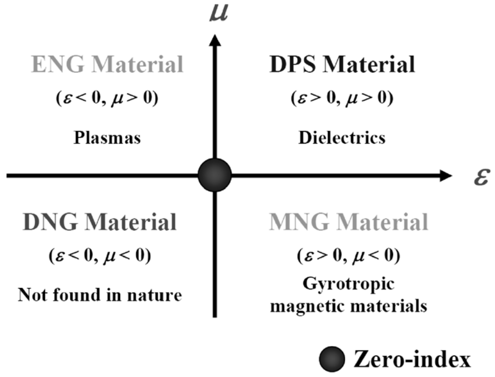


Fig. 1 Classification of metamaterials by the real parts of their constitutive parameters, i.e., their permittivity and permeability.

Manuscript received May 15, 2006.

[†] The author is with University of Arizona, Department of Electrical and Computer Engineering, 1230 E. Speedway Blvd., Tucson, Arizona, 85721-0104 U.S.A.

a) E-mail: ziolkowski@ece.arizona.edu

DOI: 10.1093/ietele/e89–c.9.1267

the materials will be called "zero index." This nomenclature will be used throughout this review. We note that the realization of SNG materials may be relatively easier than that of DNG materials. Therefore, many recent efforts have been aimed at exploring if SNG media can be used to achieve some of the applications originally proposed for DNG media.

To achieve negative values of the constitutive parameters ε and μ, metamaterials must be dispersive, i.e., their permittivity and permeability must be frequency dependent, otherwise they would not be causal [4]. As will be discussed below, this dispersive behavior constrains the performance of metamaterial-based antenna systems. To maintain independently the positive definiteness of the electric and magnetic field energies in a passive medium, this frequency dependent behavior should satisfy [5]

$$\frac{\partial(\omega\epsilon)}{\partial\omega} \geq 0, \frac{\partial(\omega\mu)}{\partial\omega} \geq 0. \tag{1}$$

The two-time derivative Lorentz material (2TDLM) model encompasses the metamaterial models most commonly discussed; it has the frequency domain susceptibility [6]

$$\chi = \frac{\omega_p^2\chi_\alpha + j\omega_p\chi_\beta\omega - \chi_\gamma\omega^2}{\omega_{00}^2 + j\omega\Gamma - \omega^2} \tag{2}$$

There would be independent models for the permittivity and permeability: $\varepsilon(\omega) = \omega_0(1+\chi_e)$ and $\mu(\omega) = \mu_0(1+\chi_m)$. This 2TDLM model produces a resonant response at $\omega = \omega_{00}$ when $\Gamma = 0$. It recovers the Drude model when this resonant frequency goes to zero, ω_{00} , and the constants $\chi_\alpha = 1, \chi_\beta = \chi_\gamma = 0$ so that, for instance, $\varepsilon(\omega) = \varepsilon_0[1 - \omega_p^2/\omega(\omega - j\Gamma)]$. The real part of this permittivity is clearly negative for all $\omega < \sqrt{\omega_p^2 + \Gamma^2}$. The Drude model is obtained with the bed-of-nails medium [7]–[9]. In contrast to any resonant behavior, it produces a broad bandwidth response. The standard Lorentz model is obtained immediately with $\chi_\beta = \chi_\gamma = 0$. The magnetic split ring resonator (SRR) response [10], [11] is recovered with $\chi_{\alpha m} = \chi_{\beta m} = 0$, $\chi_{\gamma m} = -F$. Note that it must be understood that whatever material model is used to describe the electromagnetic response of any inclusion-based metamaterial, the model is in reality localized to a particular set of frequencies, i.e., to obtain an effective material model, the intrinsic length of the inclusions should be on the order of or smaller than $\lambda/10$, a condition which would be violated as the frequency becomes high enough.

2. Surface and Volumetric AMCs

One significant area of metamaterials research has been the development of artificial magnetic conductors (AMCs) for wireless applications. These AMCs have been realized mainly as high impedance surfaces that produce an in-phase reflection coefficient. One of the best known is the Sievenpiper mushroom or thumbtack high-impedance surface [12], which consists of an array of metal patches on a flat dielectric slab, the patches being arranged in a two-dimensional lattice with each being connected to a ground plane by metal-plated vias to form a continuous conductive metal texture. With the period being much smaller than a wavelength, this surface can be analyzed as an effective medium with its impedance represented by effective lumped-element circuit parameters [13]. An incident electric field across the gaps of the patches produces a capacitance C; the currents that flow between neighboring patches through the vias and the ground plane produce an inductance L. The effective L and C form a parallel resonant circuit that dictates the electromagnetic behavior of the material. In particular, its surface impedance is given by the expression $Z_s = j\omega L/(1 - \omega^2 LC)$. The high impedance properties are thus obtained in a certain band of frequencies in the neighborhood of the resonant frequency $\omega_0 = 1/\sqrt{LC}$.

By combining multiple elements, this resonant frequency can be lowered significantly [14]. These mushroom surfaces have been considered for a number of antenna systems. Combining active elements, for instance, with the patches, one can obtain a tunable impedance surface for beam steering [15]. By placing a horizontal dipole antenna above an AMC, it will have an image current with the same phase as the current on the dipole, resulting in enhanced radiation performance from a very low profile configuration [16]. Moreover, the vias produce a structure that prevents the propagation of surface waves along the ground plane, a useful property for arrays of antennas [17], [18].

These in-phase reflection and surface wave suppression properties can be obtained with other types of engineered electromagnetic surface textures, e.g., as with frequency selective surfaces (FSSs), the AMC properties can be achieved with designed resonant inclusions on a nonconducting host substrate layer in parallel with a conducting ground plane [19], [20]. These textured surfaces also provide a way to design new boundary conditions for building electromagnetic structures, such as for varying the radiation patterns of small antennas [21]. Moreover, the texturing can be made extreme, for example with space filling curves, to achieve electrically small antenna systems at the cost of some bandwidth [22]–[24]. Bandwidth properties can be enhanced with fractal designs [25].

All of these surface-based AMCs include a PEC ground plane and thus guarantee, at least, high reflectivity. In contrast, in [26] a volumetric AMC was realized with only the capacitivelyloaded loop (CLL) based MNG material shown in Fig. 2(a), i.e., there was no ground plane and the CLL element is a simplified form of the SRR. This aspect demonstrates that the response of the MNG material can be made large enough by itself to realize the requisite in-phase reflectivity. Moreover, the associated surface modes are dramatically different from those associated with the ground plane-based AMCs. The predicted radiation patterns for a dipole antenna near the CLL-based AMC block are compared to those of a dipole radiating in free space in Figs. 2(b) and 2(c). Current investigations into this volumetric AMC include the integration of a printed dipole into the block structure, achieving high directivity, and optimizing

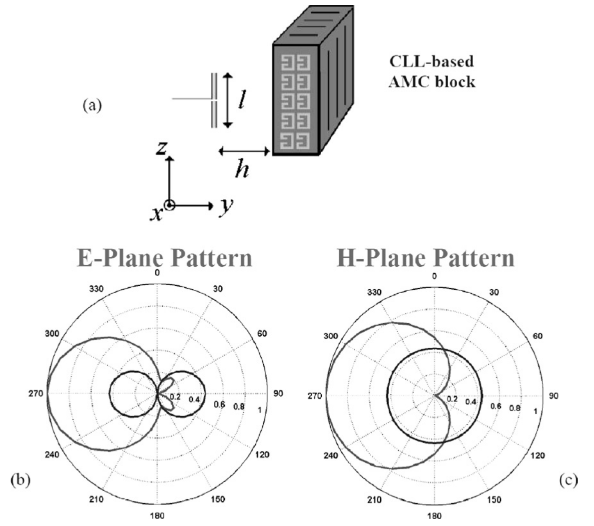


Fig. 2 A CLL-based AMC block will act as an in-phase reflector for a low-profile dipole antenna near it: (a) geometry, (b) E-plane and (c) H-plane patterns compared to the dipole radiating in free space.

the front-to-back ratios.

3. MTM-Based Electrically Small Antennas

The use of metamaterial coatings to enhance the radiation and matching properties of electrically small electric and magnetic dipole antennas has been championed in [27]–[31]. The unconventional properties exhibited by metamateials, such as the resonances in electrically-small cavities, scatterers, and radiators, occur when they are paired with materials having at least one oppositely-signed constitutive parameter. In such electrically small electromagnetic systems, these "complementary" interfaces allow a squeezing of the resonant dimensions, the effect being dependent on specific filling ratios between the SNG and DNG metamaterials and the DPS materials rather than on the total electrical size of the system.

An electrically small dipole antenna is known to be a very inefficient radiator, i.e., because it has a very small radiation resistance while simultaneously having a very large capacitance reactance, a large impedance mismatch to any realistic power source exists. Dedicated matching networks must be designed and added to such electrically small antennas to make them efficient radiators. The matching network (a large inductor and a quarter-wave transformer) is thus an actual part of the antenna system; its size significantly reduces the effective miniaturization of the overall antenna system. It has been demonstrated recently [27]–[31] that enclosing an electrically small dipole antenna in an electrically small epsilon-negative (ENG) shell leads to an efficient radiator. The inductive nature of the ENG shell compensates for the capacitive nature of the electrically small electric dipole antenna and functions as a distributed matching element. When the geometrical parameters are correctly selected, an *LC* resonance occurs. The dipole and the entire matching network are contained within the outer radius

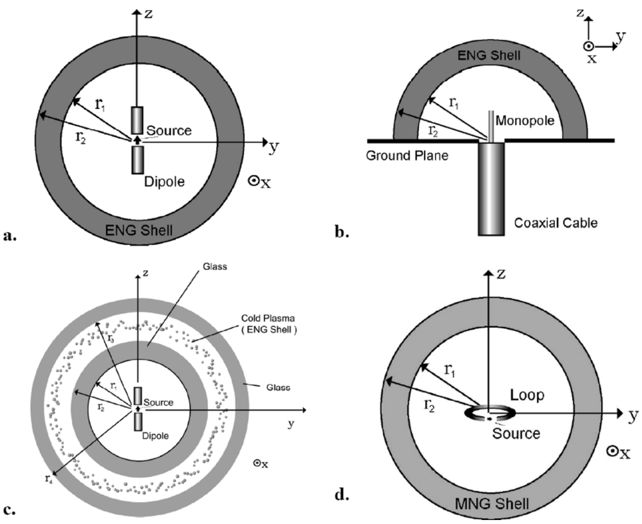
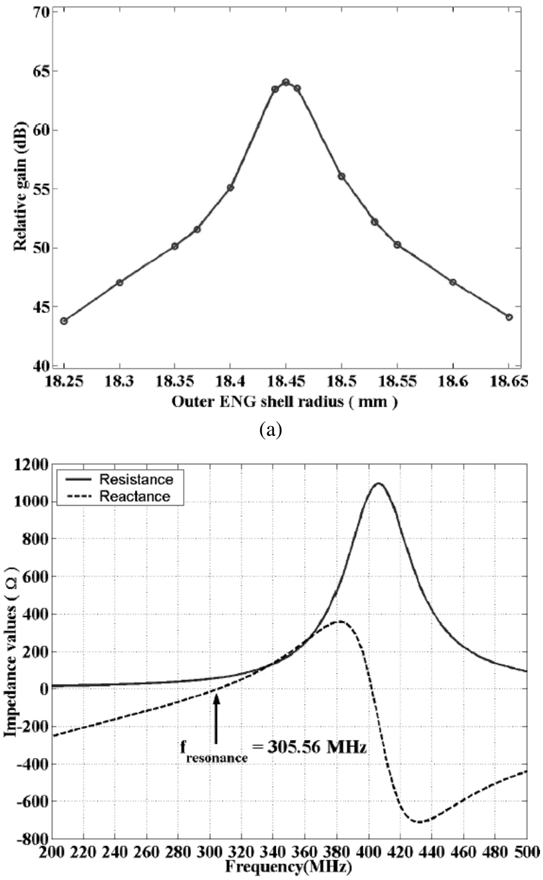


Fig. 3 Electrically-small metamaterial-based antenna systems that have been modeled numerically with HFSS. (a) Electric dipole-ENG shell, (b) Coax-fed monopole-ENG shell, (c) Dipole-(DPS-ENG-DPS) shell, and (d) Loop antenna-MNG shell.

of the ENG shell. It was shown in [28] that this naturally resonant radiating system is reciprocal to the resonant scattering of a plane wave from the corresponding ENG-coated DPS sphere. Additionally, by duality, the capacitive nature of an MNG shell can be designed to compensate for the inductive nature of an electrically small magnetic loop antenna to achieve such a resonant system. Several variations on these metamaterial-based shell systems have been considered [29]–[31]. These include analytical models of an electrically small (constant current) electric dipole antenna in multilayered ENG-based spherical shell systems and ANSOFT High Frequency Structure Simulator (HFSS) numerical models of an electrically small center-fed electrical dipole in the same multilayered shell system and a coaxially-fed monopole in the corresponding hemispherical shell system, as well as an electrically small loop antenna in the corresponding MNG-based shell systems. Illustrations of these numerical models are given in Figs. 3(a)–3(d).

The analytical models are numerically efficient, allowing many variations of the properties of the systems they describe in order to explore their resonant properties. Moreover, they allow a straightforward means to introduce dispersion into the metamaterial regions. Unfortunately, while the total radiated power can be calculated easily with these analytical models, they do not provide the corresponding input impedance of the system. On the other hand, the HFSS models do provide both the total radiated power and the input impedance. Thus, the HFSS models provide a complete prediction of the overall efficiency of the system. Nonetheless, the introduction of dispersion into the HFSS models is very problematic because of the required number of simulations as well as the requisite fineness of the frequency steps. A combination of the two approaches allows a reasonable prediction of the performance of these systems. In particular, when an analytical configuration exhibits a natural resonance, the corresponding numerical model also will and then the antenna and shell parameters of that numerical model can be further optimized to achieve a matched antenna resonance (zero total input reactance and input resistance matched to the feedline). For example, a constant current infinitesimal electric dipole antenna driven at $f_0 = 300\,\mathrm{MHz}$ at the center of an inner radius, $r_{\mathrm{inner}} = 10.0\,\mathrm{mm}$, frequency independent ENG shell with $\varepsilon_r = -3.0$, $\mu_r = +1.0$, produces a 63.22 dB resonant peak in the radiated power ratio (RPR), i.e., the ratio of the total radiated power in the presence of the shell to its value in free space for the same 1A driving current, when the outer radius $r_{\mathrm{outer,max}} = 18.79\,\mathrm{mm}$. As shown in Fig. 4(a), the corresponding HFSS model: a 10 mm long, 0.1 mm radius center-fed electric dipole, predicts a resonant behavior of the relative gain (ratio of the total radiated power when 1 W is delivered to the dipole in the presence of the ENG shell to when the same antenna is radiating in free space) whose peak value is 64.05 dB when the outer radius $r_{\mathrm{outer,max}} = 18.45\,\mathrm{mm}$. The decrease in the shell thickness occurs because the shell must now also match an additional capacitance value, which is introduced by the feed gap. This resonance is a dipolar mode and, thus, the radiation pattern is that of a dipole. With further modifications of the antenna and shell dimensions (i.e., increasing the radius of the wire to 2.5 mm and the outer radius of the ENG shell to 19.51 mm), a resonant center-fed electric dipole-ENG shell system was achieved. As shown in Fig. 4(b), the (resonance) zero crossing of the input reactance occurred at 305.56 MHz with a resistance value of 58.44 Ω. The input impedance at 300 MHz was $Z_{\mathrm{input}} = 52.54 - j17.00\ \Omega$. Thus, the overall efficiency of this system for a 50 Ω source at 300 MHz was found to be 97.18%. The electrical size of this resonant antenna system at 300 MHz was $ka = 0.123$.



(a)

(b)

Fig. 4 The HFSS model of a center-fed electric dipole-ENG shell system predicts a natural resonance when the system is electrically small. The system can then be adjusted to produce a matched resonance to a 50 Ω feedline, thus realizing a high overall efficiency. (a) Relative gain and (b) Input impedance.

We recall that the fundamental limits on the radiation quality factor, Q, associated with electrically small antennas have been explored by many authors, e.g., [32]–[38]. The minimum of the Q, i.e., the Chu limit, has been shown to be:

$$Q_{\mathrm{Chu}} = \frac{1 + 2(ka)^2}{(ka)^3[1 + (ka)^2]} \approx \frac{1}{(ka)^3} \quad \text{for } ka \ll 1 \tag{3}$$

where a is the radius of the radiansphere (minimum radius sphere) surrounding the antenna system. The corresponding fractional bandwidth is

$$FBW_{\mathrm{Chu}} = \frac{\Delta f_{3\,\mathrm{dB}}}{f_{0\,\mathrm{dB}}} = \frac{1}{Q_{\mathrm{Chu}}} \approx (ka)^3 \tag{4}$$

where $f_{+,3\,\mathrm{dB}}$ and $f_{-,3\,\mathrm{dB}}$ represent the frequencies above and below the resonance frequency $f_{0\,\mathrm{dB}}$ where the radiated power falls to half its peak value and $\Delta f_{3\,\mathrm{dB}} = f_{+,3\,\mathrm{dB}} - f_{-,3\,\mathrm{dB}}$. This result shows that if the electrical size ka decreases by a factor of 10, the fractional bandwidth decreases by a factor of 1000. The quality factor and the fractional bandwidth of an antenna approach their Chu limits only if it efficiently utilizes the available volume within the radiansphere.

For the analytical non-dispersive ENG shell case discussed above, one finds for $f_0 = 300\,\mathrm{MHz}$ and $r_{\mathrm{outer,max}} = 18.79\,\mathrm{mm}$ that $ka = 0.118$ and that the fractional bandwidth from the 3 dB points of the RPR values to be $FBW_{3\,\mathrm{dB}} = 10.46\%$ so that $Q_{3\,\mathrm{dB}} = 9.56$. Similarly, from the HFSS model the VSWR bandwidth $FBW_{\mathrm{VSWR}} = 23.65\%$, which according to [36] yields the quality factor $Q_{\mathrm{VSWR}}(f_0) = 2/FBW_{\mathrm{VSWR}}(f_0) = 8.46$. Alternatively, the input impedance according to [36] yields the quality factor

$$Q_{\mathrm{YB}} \approx f_0 |\partial_f Z_{\mathrm{input}}(f_0)| / 2R(f_0) = 8.78 \tag{5}$$

The corresponding fractional conductance bandwidth is thus $FBW_{\mathrm{CD}} = 1/Q_{\mathrm{YB}} = 11.38\%$. All of these quality factors are consistent and are substantially smaller than the Chu limit value $Q_{\mathrm{Chu}} = 617$.

Unfortunately, when dispersion, which is always present in any realistic metamaterial, is taken into account, this behavior changes dramatically. The RPR values for the infinitesimal dipole-ENG shell case when the ENG medium is frequency independent, is described by the lossless Drude model, and is described by the lossless dispersion model

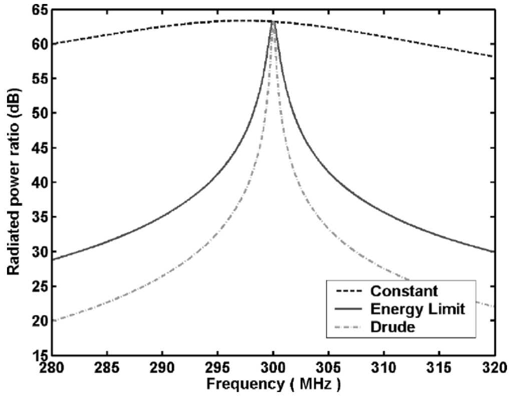


Fig. 5 Radiated power ratio (RPR) for the infinitesimal electric dipole-ENG shell system when the ENG shell is described by various lossless dispersion models.

corresponding to the energy-based constraint (1) are compared in Fig. 5. In all three cases $\varepsilon_r(f_0) = -3.0$; the lossless models are emphasized because any losses would increase the bandwidth and the quality factor would have to be adjusted for the corresponding decrease in efficiency. While all of the RPR values at the resonance frequency f_0 are the same; the narrowing of the bandwidth of the resonance is apparent immediately. The FBW and Q for the Drude case are $FBW_{\text{Drude}} = 0.103\% = 0.636 FBW_{\text{Chu}}$ and $Q_{\text{Drude}} = 971 = 1.57 Q_{\text{Chu}}$; and for the energy limit case they are $FBW_{\text{Limit}} = 0.269\% = 1.66 FBW_{\text{Chu}}$ and $Q_{\text{Limit}} = 372 = 0.60 Q_{\text{Chu}}$. Thus with a proper design of the dispersion properties of the passive ENG metamaterial, the quality factor (bandwidth) associated with the resulting electrically small antenna system can be smaller (larger) than the Chu limit value. Nonetheless, for practical applications, one would ideally wish to achieve the bandwidths associated with the non-dispersive case. It has been demonstrated that with an active ENG metamaterial shell, described by a Lorentz-Lorentz gain doublet permittivity model created with two Lorentz resonances: one active (frequency above the operating frequency) and one passive (frequency below the operating frequency), the bandwidth can approach the frequency independent value [30]. Thus, in principle, there may be a means of achieving not only an efficient electrically small antenna, but one with interesting bandwidth characteristics. The introduction of dispersion-engineered gain media into the electrically small resonant dipole-multilayer ENG spherical shell systems is currently under active investigation.

Realizing an ENG medium with a metamaterial based on *finite-sized* inclusions at UHF frequencies had turned out to be very challenging. Note that the low frequency properties of the bed-of-nails ENG medium occur because the wires are infinite. Cut wires have significantly higher resonant frequencies. On the other hand, as noted above, ENG media occur naturally at very high frequencies. In contrast, an MNG medium is readily obtained at low frequencies while it is difficult to obtain at high frequencies. Consequently, a resonant loop antenna-MNG shell system may be easier to realize at UHF frequencies than the electric dipole antenna-ENG shell system. It is also noted that an ENG medium is straightforwardly obtained with a plasma medium at UHF frequencies. The relative permittivity of a lossy cold plasma is described by the Drude model. A plasma density corresponding to that in a fluorescent light bulb would produce the values considered in the above example [30]. Both of these SNG configurations, as well as lumped element-based ENG inclusions, are currently being investigated in order to achieve a UHF proof-of-concept experiment. It must be emphasized that the coax-fed electric monopole-ENG hemispherical shell antenna systems are the most likely candidates for initial testing since they provide a means to drive the antenna without disrupting the shell properties. It has been demonstrated, as expected, that these metamaterial-based coax-fed monopole antenna cases recover the performance characteristics of the corresponding dipole cases [29]–[31].

4. Zero-Index MTM Applications

It has been demonstrated that zero-index metamaterials can be used to achieve high directivity antennas. Because a signal propagating in a zero-index metamaterial will stimulate a spatially static field structure that varies in time, the phase at any point in a zero-index metamaterial will have the same constant value once steady state is reached [39]. This coherent response causes the phase across the output face of a slab of zero-index metamaterial to be uniform. Moreover, from Snell's Law, all of the outgoing wave vectors will be normal to the interface. Consequently, this effective aperture will produce the highest-directivity beam. These behaviors have been confirmed with analysis and supporting FDTD simulations [39], [40]. Such highly directive sources have been achieved with electromagnetic band-gap (EBG) structures [41]–[45].

Zero-index metamaterials have also been used to achieve a zeroth-order resonance (ZOR) antenna [46], [47]. Because the index is zero or near zero, the wavelength in the medium is effectively infinite and the resonance is independent of the physical dimensions. The physical size of the antenna can thus be made smaller than a half-wavelength. The perfectly uniform current distribution associated with the zero-order mode may also decrease the overall loss resistance of the system and, hence, provide a higher overall efficiency. Experimental verification of these properties has been accomplished [46], [47].

Another interesting use of near-zero-index metamaterials has been uncovered with optimization studies of multilayered metamaterial-coated sphere systems [31]. It has been found that in the same manner in which there are resonant radiating states for the dipole-ENG shell system, there are also resonant non-radiating (NR) modes. It is believed that these NR modes of the source problem are reciprocal to the transparency scattering states reported in [48]. These NR modes occur when the ENG shell has an effective permittivity approximately equal to zero. Both resonant radiating and non-radiating modes occur for the same configuration

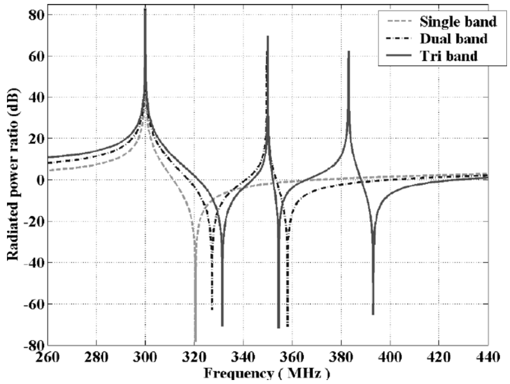


Fig. 6 Optimized RPR values for an infinitesimal electric dipole in a nested dispersive ENG spherical shell system that has one, two, and three metamaterial layers and that produces, respectively, single, dual, and tri band operation.

when the shell is described with a dispersion model, i.e., if a dipole-ENG shell configuration is designed to have a resonant radiating state and the dispersion of the ENG shell is described by the Drude model, then at a higher frequency the real part of the permittivity of the ENG shell will pass through zero and the non-radiating mode will express itself. While the exterior field is large for the resonant radiated mode; the field becomes resonantly trapped in the ENG shell for the NR mode.

With an N-layered nested metamaterial shell system, there can be N different pairs of these radiating and non-radiating states. Consequently, the same electrically small system can be made to be multi-frequency. This is illustrated in Fig. 6. The RPR values are plotted as a function of the frequency for the infinitesimal electric dipole-ENG shell system which has one, two, and three nested spherical dispersive metamaterial layers, each of which is described by a lossless Drude model. One observes that there are one, two, and three resonant radiating (and non-radiating) states, respectively, for the one, two, and three MTM layer systems. By properly dispersion engineering the permittivities in each ENG shell, the frequencies of the resonant radiating and non-radiating states can be designed to specification. The single, dual, and tri band systems in Fig. 6 were optimized so that their first resonant radiating peak occurred at $f_0 = 300\,\text{MHz}$. The second resonant peak was designed to be at 350 MHz for the dual and tri band cases; the third resonant peak occurred at 383 MHz for the tri band case. The relative permittivities in the interior and exterior spherical regions for all cases were set equal to one, the free space value, while the relative permeabilities in each region were set equal to one. The one layer configuration (3 regions) had $r_1 = 8\,\text{mm}$, $r_2 = 10\,\text{mm}$, and $\varepsilon_{2r}(f_0) = -0.1415$; the two-layer configuration (4 regions) had $r_1 = 8\,\text{mm}$, $r_2 = 10\,\text{mm}$, $r_3 = 12\,\text{mm}$, and $\varepsilon_{2r}(f_0) = -0.1897$, $\varepsilon_{3r}(f_0) = -0.4254$; and the three-layer configuration (5 regions) had $r_1 = 8\,\text{mm}$, $r_2 = 10\,\text{mm}$, $r_3 = 12\,\text{mm}$, $r_4 = 14\,\text{mm}$ and $\varepsilon_{2r}(f_0) = -0.2212$, $\varepsilon_{3r}(f_0) = -0.7175$, $\varepsilon_{4r}(f_0) = -0.3967$. Again, it is possible to obtain as many radiating bands in an electrically small geometry as one wishes if one can obtain a corresponding number of nested metamaterial shell layers with the requisite permittivities.

5. Additional MTM Avenues to Sub-Wavelength and Directive Antennas

Patch antennas have become a favorite choice for many applications, including wireless communications and radars. In particular, their low profile characteristics are highly desirable. Moreover, they are generally low weight, cost effective, and can be shaped to fit a particular space requirement. It would be desirable to miniaturize these antennas while enhancing their directivities and bandwidths. Unfortunately, these goals are conflicting. Nonetheless, metamaterial-inspired approaches have led to improved aspects of all of these characteristics.

Since the volume under the patch of a standard patch antenna acts as a cavity resonator with at least one dimension being a half-wavelength, a possible solution to shrink its dimensions would be to fill its volume with a high-permittivity dielectric. This effectively reduces the wavelength inside the cavity and, hence, the physical dimensions required for a resonance. However, grounded substrates with high dielectric constants support surface-wave propagation. Moreover, these high-permittivity dielectrics are quite lossy. The gain, radiation efficiency, and bandwidth are noticeably reduced when the excitation of these modes is increased.

The possibility of using the phase compensation properties of matched DPS-DNG or ENG-MNG bilayers to achieve thin, sub-wavelength cavity resonators, i.e., the ability of oppositely-signed index of refraction layers to attain a zero phase change across the bilayer and, hence, a resonance condition based on a ratio of the dimensions rather than a sum, was suggested in [49]. This subwavelength resonator concept has been used to advance the concept of an ultra-thin laser cavity [50]. It has also been proposed recently as an idea for squeezing the resonant dimensions of a circular ring patch antenna by loading it with a concentric pair of DPS and DNG finite cylinders [51]. Since this configuration is analogous to an infinite line source driving an infinite MTMcoated cylinder [52]–[55], again the frequency of the natural resonance of this structure depends primarily on the ratio of the radii of the DPS and DNG annular cylinders and, thus, the overall dimensions of the cavity can be reduced significantly.

The uses of properly designed slow-wave artificial reactive surfaces and magneto-dielectric layers have also been proposed in [56] and [57] to achieve antenna miniaturization. This slow wave surface approach can reduce the transverse dimensions of a microstrip antenna, but its total thickness is increased and the wideband behavior is related to the overall resonance of the reactive surface and the patch itself. In related work [58] improved bandwidth and impedance matching with smaller thicknesses have been proposed through the use of polygonal patch shapes and proximity coupling feeding techniques. Magnetic metamaterials have been considered for the miniaturization and increase in bandwidth of patch and PIFA antennas in [59], [60]. High-directivity printed dipole and patch antennas have been obtained with combinations of metamaterial-based cavity-size reductions and AMC concepts as well as MNG and DNG substrates and superstrates in [61]–[63].

6. Conclusions

The metamaterials research area has evolved into prominence only very recently. Nonetheless, it is already having a large impact on the international electromagnetics community. Metamaterials have revitalized our interests in complex media; their exotic properties; their analysis and numerical modeling; and their potential applications. There have been large strides in our understanding of their anomalous behaviors and of their possible utilization in many electromagnetic applications from the microwave to the optical regime.

This review has only briefly touched upon some selective research efforts associated with metamaterials and their antenna applications. Metamaterials, because of their promise to provide engineerable permittivities and permeabilities, possess interesting properties for the design of next-generation structures for radiating and scattering applications. Artificial magnetic conductors have been attained with high impedance and frequency selective surface constructs as well as with volumetric inclusion-based media. Resonances arising in electrically small regions of space where single and double negative materials are paired with common double positive materials were shown to have a great potential for overcoming the limits generally associated with several electromagnetic problems by providing a means to engineer the overall responses of the systems. Zero-index metamaterials, media with permittivities and permeabilities with zero or near zero values, may have strong impact in some applications despite their non-resonant character, since they combine anomalous wave interactions with relatively larger bandwidth and lower losses.

Metamaterials have been considered as a means to manipulate the size, efficiency, bandwidth, and directivity of several basic radiating and scattering systems. There are many researchers whose works were not mentioned, and I apologize to all of them. Metamaterials and their antenna applications is a very fertile research area in which there is much interest. The initial seed physics efforts are only now beginning to bear some engineering applications fruit. There remain many challenging and potentially rewarding problems left to solve; we all look forward to sharing these solutions in the near future.

Acknowledgments

This work was supported in part by DARPA Contract number HR0011-05-C-0068.

References

[1] N. Engheta and R.W. Ziolkowski (guest editors), IEEE Trans. Antennas Propag., Special Issue on Metamaterials, vol.51, pp.2546–2750, Oct. 2003.

[2] N. Engheta and R.W. Ziolkowski, "A positive future for double-negative metamaterials," IEEE Trans. Microw. Theory Tech., vol.53, no.4, pp.1535–1556, April 2005.

[3] N. Engheta and R.W. Ziolkowski, eds., Metamaterials: Physics and Engineering Explorations, Wiley-IEEE Press, Piscataway, NJ, 2006.

[4] R.W. Ziolkowski and A. Kipple, "Causality and double-negative metamaterials," Phys. Rev. E, vol.68, 026615, Aug. 2003.

[5] P.W. Milonni, Fast Light, Slow Light and Left-Handed Light, pp.184–185, Institute of Physics Publishing, Philadelphia, PA, 2005.

[6] R.W. Ziolkowski and F. Auzanneau, "Passive artificial molecule realizations of dielectric materials," J. Appl. Phys., vol.82, pp.3195–3198, Oct. 1997.

[7] W. Rotman, "Plasma simulation by artificial dielectrics and parallel plate media," IRE Trans. Antennas Propag., vol.10, no.1, pp.82–95, Jan. 1962.

[8] J.B. Pendry, A.J. Holden, W.J. Stewart, and I. Youngs, "Extremely low frequency plasmons in metallic meso structures," Phys. Rev. Lett., vol.76, pp.4773–4776, June 1996.

[9] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, "Low frequency plasmons in thin-wire structures," J. Phys. Condens. Matter, vol.10, pp.4785–4809, 1998.

[10] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microw. Theory Tech., vol.47, no.11, pp.2075–2081, Nov. 1999.

[11] D.R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," Phys. Rev. Lett., vol.84, pp.4184–4187, May 2000.

[12] D. Sievenpiper, L. Zhang, R.F. Jimenez Broas, N.G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," IEEE Trans. Microw. Theory Tech., vol.47, no.11, pp.2059–2074, Nov. 1999.

[13] S. Clavijo, R.E. Diaz, and W.E. McKinzie III, "Design methodology for Sievenpiper high-impedance surfaces: An artificial magnetic conductor for positive gain electrically small antennas," IEEE Trans. Antennas Propag., vol.51, no.10, pp.2678–2690, Oct. 2003.

[14] A.S. Barlevy and Y. Rahmat-Samii, "Characterization of electromagnetic band-gaps composed of multiple periodic tripods with interconnecting vias: Concept, analysis, and design," IEEE Trans. Antennas Propag., vol.49, no.3, pp.343–353, March 2001.

[15] D. Sievenpiper, J. Schaffner, R. Loo, G. Tangonan, S. Ontiveros, and R. Harold, "A tunable impedance surface performing as a reconfigurable beam steering reflector," IEEE Trans. Antennas Propag., vol.50, no.3, pp.384–390, March 2003.

[16] F. Yang and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," IEEE Trans. Antennas Propag., vol.51, no.10, pp.2691–2703, Oct. 2003.

[17] R. Gonzalo, P. de Maagt, and M. Sorolla, "Enhanced patch antenna performance by suppressing surface waves using photonic-bandgap substrates," IEEE Trans. Microw. Theory Tech., vol.47, no.11, pp.2131–2138, Nov. 1999.

[18] F. Yang and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: A low mutual coupling design for array applications," IEEE Trans. Antennas Propag., vol.51, no.10, pp.2936–2946, Oct. 2003.

[19] F.-R. Yang, K.-P. Ma, Y. Qian, and T. Itoh, "A uniplanar compact photonic-bandgap (UC-PBG) structures and its applications for microwave circuit," IEEE Trans. Microw. Theory Tech., vol.47, no.8, pp.1509–1514, Aug. 1999.

[20] R. Cocciolo, F.R. Yang, K.P. Ma, and T. Itoh, "Aperture coupled patch antenna on UCPBG substrate," IEEE Trans. Microw. Theory Tech., vol.47, no.11, pp.2123–2130, Nov. 1999.

[21] Y. Zhang, J. von Hagen, and W. Wiesbeck, "Patch array as artificial magnetic conductors for antenna gain improvement," Microw. Opt. Technol. Lett., vol.35, no.3, pp.172–175, Nov. 2002.

[22] J. Zhu, A. Hoorfar, and N. Engheta, "Bandwidth, cross polarization, and feed-point characteristics of matched Hilbert antennas," IEEE Antennas Wireless Propag. Lett., vol.2, pp.2–5, 2003.

[23] J. McVay, N. Engheta, and A. Hoorfar, "High impedance metamaterial surfaces using Hilbert-curve inclusions," IEEE Microwave Wireless Components Lett., vol.14, no.3, pp.130–132, March 2004.

[24] J. Zhu, A. Hoorfar, and N. Engheta, "Peano antennas," IEEE Antennas Wireless Propag. Lett., vol.3, pp.71–74, 2004.

[25] D.H. Werner and S. Ganguly, "An overview of fractal antenna engineering research," IEEE Antennas Propag. Mag., vol.45, no.1, pp.38–56, Feb. 2003.

[26] A. Erentok, P. Luljak, and R.W. Ziolkowski, "Antenna performance near a volumetric metamaterial realization of an artificial magnetic conductor," IEEE Trans. Antennas Propag., vol.53, no.1, pp.160–172, Jan. 2005.

[27] R.W. Ziolkowski and A. Kipple, "Application of double negative metamaterials to increase the power radiated by electrically small antennas," IEEE Trans. Antennas Propag., vol.51, pp.2626–2640, Oct. 2003.

[28] R.W. Ziolkowski and A.D. Kipple, "Reciprocity between the effects of resonant scattering and enhanced radiated power by electrically small antennas in the presence of nested metamaterial shells," Phys. Rev. E., vol.72, 036602, Sept. 2005.

[29] R.W. Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas," IEEE Trans. Antennas Propag., vol.54, no.7, pp.2113–2130, July 2006.

[30] R.W. Ziolkowski and A. Erentok, "At and beyond the Chu limit: Passive and active broad bandwidth metamaterial-based efficient electrically small antennas," submitted to IEE Proceeding, Dec. 2005.

[31] A. Erentok and R.W. Ziolkowski, "A hybrid optimization method to analyze metamaterial-based electrically small antennas," submitted to the IEEE Trans. Antennas Propag., March 2006.

[32] L.J. Chu, "Physical limitations of omnidirectional antennas," J. Appl. Phys., vol.19, pp.1163–1175, Dec. 1948.

[33] H.A. Wheeler, "Fundamental limitations of small antennas," IRE Proc., vol.35, pp.1479–1484, Dec. 1947.

[34] R.P. Harrington, Time Harmonic Electromagnetic Fields, pp.414–420, McGraw-Hill, New York, 1961.

[35] R.E. Collin and S. Rothschild, "Evaluation of antenna Q," IEEE Trans. Antennas Propag., vol.AP-12, no.1, pp.23–27, Jan. 1964.

[36] R.C. Hansen, "Fundamental limitations in antennas," Proc. IEEE, vol.69, pp.170–181, Feb. 1981.

[37] J.S. McLean, "A re-examination of the fundamental limits on the radiation Q of electrically small antennas," IEEE Trans. Antennas Propag., vol.AP-44, no.5, pp.672–676, May 1996.

[38] A.D. Yaghjian and S.R. Best, "Impedance, bandwidth, and Q of antennas," IEEE Trans. Antennas Propag., vol.53, no.4, pp.1298–1324, April 2005.

[39] R.W. Ziolkowski, "Propagation in and scattering from a matched metamaterial having a zero index of refraction," Phys. Rev. E, vol.70, 046608, Oct. 2004.

[40] R.W. Ziolkowski, "Antennas and propagation in the presence of metamaterials and other complex media: Computational electromagnetic advances and challenges," IEICE Trans. Electron., vol.E88-B, no.6, pp.2230–2238, June 2005.

[41] M. Thevenot, C. Cheype, A. Reineix, and B. Jecko, "Directive photonic-bandgap antennas," IEEE Trans. Microw. Theory Tech., vol.47, no.11, pp.2115–2122, Nov. 1999.

[42] R. Biswas, E. Ozbay, B. Temelkuran, M. Bayindir, M.M. Sigalas, and K.M. Ho, "Exceptionally directional sources with photonic-bandgap crystals," J. Opt. Soc. Am. B, vol.18, no.11, pp.1684–1689, Nov. 2001.

[43] B. Gralak, S. Enoch, and G. Tayeb, "Anomalous refractive properties of photonic crystals," J. Opt. Soc. Am. A, vol.17, no.6, pp.1012–1020, June 2000.

[44] S. Enoch, B. Gralak, and G. Tayeb, "Enhanced emission with angular confinement from photonic crystals," Appl. Phys. Lett., vol.81, no.9, pp.1588–1590, Aug. 2002.

[45] S. Enoch, G. Tayeb, P. Sabouroux, N. Gu'Lerin, and P. Vincent, "A metamaterial for directive emission," Phys. Rev. Lett., vol.89, 213902, 2002.

[46] A. Lai, T. Itoh, and C. Caloz, "Composite right/left-handed transmission line metamaterials," IEEE Microw. Magazine, vol.5, no.9, pp.34–50, Sept. 2004.

[47] C. Caloz and T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications, IEEE Press and Wiley, New York, 2005.

[48] A. Alu and N. Engheta, "Achieving transparency with plasmonic and metamaterial coatings," Phys. Rev. E, vol.72, 016623, July 2005.

[49] N. Engheta, "An idea for thin, subwavelength cavity resonators using metamaterials with negative permittivity and permeability," IEEE Antennas Wireless Propag. Lett., vol.1, pp.10–13, 2002.

[50] R.W. Ziolkowski, "Ultra-thin metamaterial-based laser cavities," J. Opt. Soc. Am. B, vol.23, no.3, pp.451–460, March 2006.

[51] S.F. Mahmoud, "A new miniaturized annular ring patch resonator partially loaded by a metamaterial ring with negative permeability and permittivity," IEEE Antennas Wireless Propagat. Lett., vol.3, pp.19–22, 2004.

[52] S.A. Tretyakov, S.I. Maslovski, A.A. Sochava, and C.R. Simovski, "The influence of complex material coverings on the quality factor of simple radiating systems," IEEE Trans. Antennas Propag., vol.53, no.3, pp.965–970, March 2005.

[53] J. Sun, W. Sun, T. Jiang, and Y. Feng, "Directive electromagnetic radiation of a line source scattered by a conducting cylinder coated with left-handed material," Microw. Opt. Technol. Lett., vol.47, pp.274–279, Nov. 2005.

[54] S.R. Nelatury, "Comparing double-negative and double-positive covers around a radiating line current," Microwave Opt. Technol. Lett., vol.48, pp.250–252, Feb. 2006.

[55] S. Arslanagic, R.W. Ziolkowski, and O. Breinbjerg, "Excitation of an electrically small metamaterial-coated cylinder by an arbitrarily located line source," Microw. Opt. Technol. Lett., submitted March 2006.

[56] H. Mosallaei and K. Sarabandi, "Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate," IEEE Trans. Antennas Propag., vol.AP-52, no.9, pp.2403–2414, Sept. 2004.

[57] H. Mosallaei and K. Sarabandi, "Magneto-dielectrics in electromagnetics: Concept and applications," IEEE Trans. Antennas Propag., vol.AP-52, no.6, pp.1558–1567, June 2004.

[58] F. Bilotti, M. Manzini, A. Alu, and L. Vegni, "Polygonal patch antennas with reactive impedance surfaces," J. Electromagn. Waves Appl., vol.20, no.2, pp.169–182, 2006.

[59] P. Ikonen, S. Maslovski, and S. Tretyakov, "PIFA loaded with artificial magnetic material: Practical example for two utilization strategies," Microw. Opt. Technol. Lett., vol.46, no.3, pp.205–210, 2005.

[60] M. Karkkainen and P. Ikonen, "Patch antenna with stacked split-ring resonators as artificial magneto-dielectric substrate," Microw. Opt. Technol. Lett., vol.46, no.6, pp.554–556, 2005.

[61] S.N. Burokur, M. Latrach, and S. Toutain, "Theoretical investigation of a circular patch antenna in the presence of a left-handed medium," IEEE Antennas Wireless Propagat. Lett., vol.4, pp.183–186, 2005.

[62] J. Hu, C.-S. Yan, and Q.-C. Lin, "A new patch antenna with metamaterial cover," J. Zhejiang University SCIENCE A, vol.7, pp.89–94, Jan. 2006.

[63] A. Ourir, A. de Lustrac, and J.-M. Lourtioz, "All-metamaterial-based subwavelength cavities ($\lambda/60$) for ultrathin directive antennas," Appl. Phys. Lett., vol.88, 084103, Feb. 2006.

Richard W. Ziolkowski received the Sc.B. degree in physics magna cum laude with honors from Brown University in 1974, the M.S. and Ph.D. degrees in physics from the University of Illinois at Urbana-Champaign in 1975 and 1980, respectively. He was a member of the Engineering Research Division at the Lawrence Livermore National Laboratory from 1981 to 1990 and served as the leader of the Computational Electronics and Electromagnetics Thrust Area for the Engineering Directorate from 1984 to 1990. Prof. Ziolkowski joined the Department of Electrical and Computer Engineering at the University of Arizona as an Associate Professor in 1990, and was promoted to Full Professor in 1996. He was selected by the Faculty to serve as the Kenneth Von Behren Chaired Professor for 2003–2005. He holds a joint appointment with the College of Optical Sciences at the University of Arizona. His research interests include the application of new mathematical and numerical methods to linear and nonlinear problems dealing with the interaction of acoustic and electromagnetic waves with complex media, metamaterials, and realistic structures. Prof. Ziolkowski is a member of Tau Beta Pi, Sigma Xi, Phi Kappa Phi, the Institute of Electrical and Electronics Engineers (IEEE), the American Physical Society, the Optical Society of America, the Acoustical Society of America, and Commissions B (Fields and Waves) and D (Electronics and Photonics) of URSI (International Union of Radio Science). He is an IEEE Fellow. He served as the Vice Chairman of the 1989 IEEE/AP-S and URSI Symposium in San Jose, and as the Technical Program Chairperson for the 1998 IEEE Conference on Electromagnetic Field Computation. He was an Associate Editor for the IEEE Transactions on Antennas and Propagation from 1993–1998. He served as a member of the IEEE Antennas and Propagation Society (AP-S) Administrative Committee (ADCOM) from 2000–2002. He served as the IEEE AP-S Vice President in 2004 and President in 2005. He is currently serving as a Past-President member of the AP-S ADCOM. He was a Steering Committee Member for the 2004 ESA Antenna Technology Workshop on Innovative Periodic Antennas. He served as a co-Chair of the International Advisory Committee for the inaugural IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, IWAT2005, and as a member of the International Advisory Committee for IWAT2006. He was member of the International Advisory Committee for the IEEE 2005 International Symposium on Microwave, Antenna, Propagation and EMC Technologies, MAPE2005. He was a Co-Guest Editor (with Prof. Nader Engheta) for the October 2003 IEEE Transactions on Antennas and Propagation Special Issue on Metamaterials. For the US URSI Society he served as Secretary for Commission B (Fields and Waves) from 1993–1996 and as Chairperson of the Technical Activities Committee from 1997–1999, and as Secretary for Commission D (Electronics and Photonics) from 2001–2002. He served as a Member-at-Large of the U.S. National Committee (USNC) of URSI from 2000–2002 and is now serving as a member of the International Commission B Technical Activities Board. He is a Fellow of the Optical Society of America. He was a Co-Guest Editor (with Prof. Kurt Oughstun) of the 1998 special issue of J. Opt. Soc. Am. A featuring Mathematics and Modeling in Modern Optics. He was a Co-Organizer (with Dr. Brent Little) of the Photonics Nanostructures Special Symposia at the 1998, 1999, 2000 OSA Integrated Photonics Research (IPR) Topical Meetings. He served as the Chair of the IPR sub-committee IV, Nanostructure Photonics, in 2001. Prof. Ziolkowski was awarded the Tau Beta Pi Professor of the Year Award in 1993 and the IEEE and Eta Kappa Nu Outstanding Teaching Award in 1993 and 1998. He also holds the title of Sensei with a Nidan rank in Matsunoryu Goshin Jujitsu and a Shodan rank in Kajukenbo.