Abstract—A novel dual-band reconfigurable aperture (RECAP) design is introduced for operation over a two-octave bandwidth. The proposed RECAP consists of interleaved crossed-slot elements for dual-polarized and broad-band array operation without grating lobes. The dimensions of the array elements can be reconfigured by using radio-frequency switches such as micro-electromechanical systems or PIN diodes. The array elements along with the switches are integrated into the top layer of a multilayered composite structure consisting of passive, resistively loaded frequency selective surface (FSS) elements that form a broad-band ground plane system. Excitation is provided through a broad-band balanced/matched feed, and reconfiguration allows for broad-band operation using the same FSS substrate. The FSS substrate, shorting pins, can be employed within the cavity to enhance gain performance. Significant analysis and understanding of the FSS/slot array configuration is presented along with measurements that should serve as a reference in future developments of these layered arrays.

Index Terms—Antenna isolation, broad-band balun, broad-band substrate, frequency selective surface, mode suppression, reconfigurable aperture, slot antenna array.

I. INTRODUCTION

RECONFIGURABLE antennas and arrays have been of interest for a variety of wireless communications applications [1]–[7]. The reconfiguration allows for a single aperture to replace two or more narrower band apertures at a reduction in the size and weight where element size (thus frequency) [8]–[10], polarization [11], [12], and interelement spacing can be configured in real-time. In this paper, we introduce a novel reconfigurable aperture (RECAP) design (Fig. 1) operating over two octaves. The novelty of the proposed RECAP is that it incorporates a new reconfigurable slot aperture with a frequency selective surface (FSS) substrate along with possible vertical pins and a broad-band feed in a manner that provides a practical realization of a reconfigurable slot array which boasts a 0.8–3.2 GHz bandwidth. To our knowledge, this is the first published reconfigurable slot aperture design that integrates all these individual components to achieve broad-band array performance.

The proposed RECAP (see Fig. 1) is comprised of crossed slot elements whose dimensions are altered by using radio-frequency (RF) switches such as MEMS [9], [10], [13], optoelectronic switches [14], or PIN diodes [8], [15]. The interleaved two-band configuration of the array elements is considered in order to reduce the array size significantly [16]–[18]. This configuration choice also provides broad-band array performance without grating lobes by choosing the element spacings sufficiently small [19]–[21]. The array elements along with the switches are integrated into the top layer of a multilayered composite structure consisting of passive, resistively loaded FSS elements that form a broad-band ground plane system [22]. Excitation is provided through a broad-band balanced/matched feed [23], and reconfiguration allows for continuous broad-band operation using the same FSS substrate. That is, the same FSS can be used for the low-band (designated as 0.8–1.6 GHz) as well as the high-band...
Fig. 3. Unit cell geometry of the designed slot/fan-FSS configuration.

Fig. 4. Broadside input impedances (real part) of the designed slot/fan-FSS configuration depicted in Fig. 3.

(Designated as 1.6–3.2 GHz) array operation. Some loss is introduced within the FSS to avoid substrate modes without the need of cavity walls. However, a lower loss substrate can be developed by introducing vertical shorting pins in the substrate between the array elements. This approach is shown to provide gain enhancement at the low-band operation.

The proposed reconfiguration scheme of the paper is an important contribution of this work. Although the FSS backing was used for the dipole array before [22], here we introduce it for slot arrays. In fact, this paper is an application and adaptation of the concepts used for reconfigurable dipole arrays to the present situation of a reconfigurable slot array. In addition, the inclusion of vertical pins is a new modification essential to reducing losses within the FSS. Further, the proposed broad-band feed mechanism is quite critical for the success of the reconfigured array. It is important to note that we are presenting here a system that combines several ideas with appropriate modifications to design a broad-band array. Such designs have their individual uniqueness and challenges as discussed in detail later in the paper.

Initially we considered a planar cavity-backed slot (CBS) element for the array due to its manufacturability (i.e., low-profile and flush-mounting features) as well as its ability to be fed by a printed corporate network. Earlier work on CBS antennas was reported by Long in the late 1970s [24], [25]. Also, [26]–[30] discuss array versions of such elements. Nevertheless, the bandwidth of CBS antennas has been limited to an octave at best. In this context, we remark that Newman and Thiele [31] extended the bandwidth of the CBS to an octave by using a T-bar. However, this design relies on individually separated slots (each slot must have its own cavity) and a rather complex manufacturing process to implement the T-bar and assure that the ends of the T-bar are short-circuited to the cavity walls. Consequently, it is less attractive for conformal larger array applications. Traveling-wave slot elements [32], [33] configured as spiral slot radiators have also been demonstrated over multioctave bandwidths, but these elements cannot be arrayed closed enough together to provide grating-lobe free array operation. In this paper we demonstrate bandwidth enhancement for the planar slot arrays by introducing a broad-band substrate/feed design.

When slots are arrayed over a planar or curved substrate, their impedance bandwidth and radiation characteristics are altered due to coupling of the slot to the resonant parallel plate modes or surface wave modes within the substrate. Previously these modes were suppressed by placing cavity walls in between the elements within the substrate. This approach restricts broad-band operation of the slot elements especially when they strongly couple to the resonant cavity modes. Hence, it is essential to suppress the resonant modes by introducing a frequency-dependent substrate that loads the cavity while providing better matched substrate impedance to the radiator element. A broad-band solution can be achieved by using a multilayer FSS [34], [35] or frequency selective volume configuration [36]–[39] as an artificial substrate with a tailored frequency response.

Previously, we employed the FSS substrate consisting of fan-like elements to enhance the performance of reconfigurable dipole arrays [22]. In this paper use of an FSS substrate is extended to reconfigurable slot arrays. In [22] it was demonstrated that coherence between the direct antenna radiation and that caused by reflections from the substrate leads to broad-band operation. This is achieved when the phase of the FSS reflection coefficient at the aperture is maintained nearly constant and
around 0° (−/+/50°). Such FSSs behave as high impedance magnetic ground planes [40] and can substantially enhance the radiation properties of printed antennas. The smooth phase response is attained by using resistive loading at the expense of some gain [22].

In this paper, we employ a similar FSS substrate for planar slot arrays [23] as depicted in Fig. 2. The FSS substrate still provides for nearly constant phase response but with a level well above 0°. In this case, the coupling mechanisms between the slot and FSS cause some loss in efficiency. The effect of FSS parameters (resistive loading and element orientation) on array performance is also examined in this paper. We note that a fast infinite array simulator was used for the design of the array/FSS configurations considered throughout the paper. This well-validated analysis tool employs the hybrid finite element-boundary integral (FE-BI) method [41] in conjunction with the fast spectral domain algorithm (FSDA) [42].

In our simulations, we used current probe-feeds [41] for the excitation of slots (see Fig. 3). These ideal broad-band feeds are placed at the center of the slot elements and across their width. However, broad-band excitations are not readily realized in the case of slot radiators. A balanced and matched feed structure compatible with the slot/FSS configuration is key to achieving broad-band operation. To this end, we introduce a broad-band balun/feed design consisting of a Y microstrip-to-slotline transition with a tapered slot-line providing for a 6:1 bandwidth with a voltage standing-wave ratio (VSWR) < 3:1 when terminated with 100-200 Ω loads (representing slot impedances) [23]. The designed slot/FSS/balun configuration is displayed in Fig. 2 and is a key part of the developed slot array. The slot elements are excited by the balun/feed structure placed vertically within the substrate whereas the FSS layer combines with the substrate material to act as an artificial substrate. This structure was fabricated and measured to validate our simulations. We will demonstrate that the proposed configuration provides for nearly 2:1 impedance bandwidth matched to a 50 Ω system. However, the balun can be used without any modification for other slot configurations that can afford additional bandwidth.

This paper is subdivided into three parts. We first examine the overall performance of the slot array in the presence of the designed FSS substrate. The slot/FSS/balun design is subsequently presented along with measured data for validation purposes. Third, we introduce the reconfigurable slot aperture designs (RESADs) incorporating FSS substrates and/or shorting pins along with an approximate balun modeling for practical implementations.

II. FSS SUBSTRATE DESIGN

To achieve broad-band operation for an antenna system over a ground plane, the emphasis must be on phase control of the substrate reflection coefficient. As reported in [22], a single layer, resistively loaded fan-shaped FSS element can deliver a fairly flat phase response over a 2:1 impedance bandwidth for printed dipole arrays. The fan FSS element (see Fig. 2) proposed in [22] has been found quite attractive in terms of magnitude bandwidth and phase response. This fan element can be thought of as a loaded loop. By tuning the lengths of the loads and the inner radius of the loop, the resonance behavior of the FSS can be controlled. We also remark that the presence of the FSS element
loop would provide for a stronger magnetic current excitation if it were oriented vertically in the substrate directly below the slot. The magnetic current of the slot and of the loop would be aligned. This configuration, however, is much more difficult and expensive to implement.

In addition, resistive loading can be introduced to generate a smooth phase response. For a broad-band FSS substrate, sharp variations or high oscillations in the phase must be eliminated so that the reflected field from the FSS would have a nearly constant phase response. This can be achieved using resistive cards within the same FSS layer or resistively loaded FSS elements [22]. The latter is applied here and the effect of FSS parameters (resistivity, slot-to-FSS separation, element orientation) on the slot bandwidth is examined.

**A. Bandwidth Performance**

In light of the above observations, we designed a single layer, resistive fan element FSS to enhance the bandwidth performance of the planar slot array [23]. The unit cell geometry of this slot/FSS configuration is shown in Fig. 3. We manually optimized the parameters of the fan FSS as well as the cavity depth and separation between the FSS and the slot. Both the slot array and the FSS are supported by a thin layer of FR4 material for practical purposes. From the simulation results in Fig. 4, the slot array with the resistive fan-FSS configuration provides for a remarkable 2:1 slot bandwidth (a constant impedance bandwidth) as compared to the highly resonant impedance characteristics of the isolated slot (<5% bandwidth) in the absence of the loaded FSS substrate. As seen, the resistive loading smooths out these highly mismatched impedances, resulting in almost constant impedance characteristics with a real part of \(\sim 115\Omega\) over the frequency band of 0.9–1.8 GHz (the imaginary part varies between 0–100 \(\Omega\) [23]).

Here, it is also important to point out the effect of resistive loading on the impedance bandwidth. To demonstrate this effect, we carried out a parametric study of bandwidth versus resistivity per square \(R_c\) [43]. As reported in [43], there is a compromise between loading and bandwidth, with the optimum constant impedance profile over a 2:1 bandwidth achieved with \(R_c = 33\Omega/\text{cm}^2\) (see Fig. 4). For resistivity values less or larger than this, the response deviates from the optimum profile. As the resistivity is increased, the impedance profile approaches that of the slot array with no FSS. On the other hand, as the resistivity is lowered, the response moves toward that of a metallic FSS (no loading) and this is to be expected.

**B. Gain Performance**

To assess the gain performance of the proposed slot array/FSS configuration, we computed the overall gain per unit cell. The overall gain-measure considered here includes relative gain, directivity, and mismatch efficiency [44], where radiated power per unit cell is obtained by integrating the aperture currents over
III. BROAD-BAND BALUN/FEED DESIGN

As mentioned above, a 2:1 slot bandwidth was achieved by means of the FSS substrate (see Fig. 4). In practice, a broad-band balanced/matched feed is required to preserve this bandwidth enhancement. The common approach of feeding a slot radiator using a stripline/microstripline feed is limited in bandwidth. It is also difficult in the case of thick, multilaminate structures to route stripline feeds from the rear of a slot panel to the slots on the front side of the panel. Since coaxial cables are usually employed with practical antenna systems, and these are inherently unbalanced feed components, a viable approach is to incorporate a balun structure to create a balanced feed. Here we employed a YY microstrip-to-slotline balun configuration (see Fig. 6) to achieve a balanced excitation for a slot radiator. We selected this type of balun structure mainly due to its short length, low loss, tight coupling to the slot, and broad-band performance. Also, its compact planar structure allows for ease of integration with the slot configuration of interest (see Fig. 2).

Even though the double-Y baluns are (in principle) all-pass networks, in practice they do not demonstrate these perfect characteristics. This is because the slotline open circuit is usually realized as a circular slotline which can only provide for a two to three octave frequency range. Therefore, one of the design goals is to optimize the shape as well as the size of the slotline open circuit to achieve a 6:1 bandwidth performance.

It is expected that the balun feed will also have a loading effect on the FSS ground plane, and thus a system analysis is appropriate for the overall balun/cavity/slot configuration. A goal is to also achieve an impedance transformation between the unbalanced input (50 Ω system) and balanced output port, where the slot aperture is located. The corresponding slot impedances at the aperture level were predicted to be on the order of 100-200 Ω. Therefore, the microstripline and slotline parameters of the balun need to be optimized accordingly. That is, the slot impedance at the input port of the balun/feed should be close to the matched value (50 Ω) as much as possible.
shape was chosen for a better incorporation of the balun within the slot/FSS configuration (see Fig. 2). The balun size, especially the height of the open circuit, was minimized to reduce interaction with the FSS layer (which must be perforated for balun installation). The design optimization was then carried out by terminating the slotline with various loads representing equivalent slot impedances.

The designed balun/feed structure was also fabricated and VSWR measurements were carried out accordingly. Fig. 7 displays the simulated and measured data and the agreement is reasonably good. As seen, the designed balun/feed delivers more than a 6:1 bandwidth for VSWR < 3 when terminated with a 150 Ω load. Similar agreement was also observed for the other terminations considered.

Next we incorporate the aforementioned optimized balun design into the slot/FSS configuration of Fig. 3. Measurements for the final configuration (see Fig. 2) were also carried out for validation purposes. We remark that this particular feed configuration is independent of the FSS and can be used for other antenna configurations as well.

B. Slot/FSS/Balun Configuration

To model the combined slot/FSS/balun configuration displayed in Fig. 2, we considered a two-stage modeling of the whole structure due to its computational complexity [23]. This complexity is caused by the much finer features of the balun/feed structure as compared to the slot/FSS configuration. At the first stage, we computed the input impedances \( Z_{in}^{slot} \) for the slot/FSS configuration using the array simulator in the same way as done previously. In the second stage, we considered the balun structure alone with its slotline terminated at the balun installation. The design optimization was then carried out by terminating the slotline with various loads representing equivalent slot impedances.

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Next we incorporate the aforementioned optimized balun design into the slot/FSS configuration of Fig. 3. Measurements for the final configuration (see Fig. 2) were also carried out for validation purposes. We remark that this particular feed configuration is independent of the FSS and can be used for other antenna configurations as well.

A. Balun/Feed Design

Considering the above balun/feed issues, we designed the balun/feed structure depicted in Fig. 6 by means of the array simulator. For the design, we optimized the parameters of microstripline and slotline (no tapering) parameters as well as the shape and size of the virtual open circuit [48] to achieve the aforementioned design criteria. We remark that the rectangular
and slightly reduced impedance levels are observed in the simulated response as compared to the measured data. Nevertheless, the comparison between measurements and calculations is quite good. The differences are likely due to the adaptive modeling approach considered in the simulations. Also, in the measurement setup, the configuration was placed in a cavity to simulate the array environment (waveguide simulator), and this can be another reason for the differences. Of importance is that the slot/FSS/balun configuration provides for an almost constant impedance profile matched to a 50 Ω system over at least a 2:1 bandwidth (from 1 up to 2.25 GHz).

Also displayed in Fig. 9 are the slot impedances for the slot/FSS configuration (computed at the first stage). As expected, the slot/FSS configuration has very different impedance characteristics as compared to the case with the balun feed. In particular, the resonance peak observed in the response is quite characteristic. Also, note that in the simulations, we used a loaded fan element with the resistivity of 50 Ω/cm², the resistive card value available to us for measurements. The interactions among the slot/balun/FSS fan element are very complex indeed. With the balun located at the center of the fan element and attached to the radiating slot, a new slot is created utilizing the slotline of the balun and half the length of the radiating slot. This slot also strongly couples to the antisymmetric loop mode (common mode) of the FSS fan element thereby reactively loading it. As a result, it resonates at a lower frequency. The shape of the real and imaginary parts of the impedance is typical of a resonant slot or dipole. At the lower frequency where the balun slotline is resonant, it radiates within the substrate whereby these excited modes are then suppressed by the loss in the fan element.

IV. RECONFIGURABLE SLOT APERTURE DESIGN

Now we consider the performance of a reconfigurable slot aperture in the presence of a similar FSS substrate. This dual-polarized array of closely packed crossed slots is shown in Fig. 10. Element spacing is selected to prevent array grating lobes at the highest operating frequency. At the lower frequencies, the active elements are chosen farther apart leaving inactive elements in between. This gives the array the appearance of an interleaved two-band configuration of the elements and provides for at least 36% reduction in array real estate as compared to an arrangement of two separate arrays. In fact, this percentage even increases as the number of array elements increases.

Neglecting polarization selectability, array reconfiguration is achieved in two ways: 1) by means of switches (see Fig. 10) and 2) by means of switching pertinent feed nodes to the appropriate ports of the beamformer. The latter involves standard RF network switching and hence will not be discussed here. The devices that reconfigure the slots, however, are modeled as on/off switches by means of a metallic pad across the width of each slot element. When the switches are open (off-state), they behave

1For example, consider two separate arrays of interleaved crossed-slot elements. One of them is an array of $2 \times 2$ Band-1 slots placed within an area of $16 \ U^2$ (unit cell size: $2 \ U \times 2 \ U$). The other one is an array of $3 \times 3$ Band-2 slots and occupies an area of $9 \ U^2$. The total area of two arrays is then $25 \ U^2$. However, one can place these two arrays together in a configuration similar to the one in Fig. 10, resulting in an array real estate of $16 \ U^2$. This means a reduction of 36% in the total array size.
like capacitors (~4 fF) and yield high isolation at lower frequencies. In our case, a slight frequency shift in the impedance curve was observed with the inclusion of the switch [43]. As can be seen from Fig. 10, two types of switches (referred to as #1 and #2) are utilized for reconfiguration. With switches #2 opened (off-state), the length of the slot dipoles is increased providing for the low-band operation (0.8–1.6 GHz). In this case, switches #1 are also closed (on-state) to provide isolation between the low-band slots. On the other hand, when switches #1 are opened (off-state) and switches #2 are closed (on-state), the slot lengths are shortened providing for the high-band operation (1.6–3.2 GHz).

The above reconfiguration allows for broad-band operation without a need to change the FSS design, which serves as an artificial substrate. Here, we present various RESADs operating over those designated bands. In these designs, the entire band coverage is achieved by a single layer FSS substrate at the expense of some efficiency losses. To improve the gain performance, shorting pins within the structure have been found useful, particularly for the low-band operation. This is considered next.

A. RESAD With an FSS Substrate and/or Shorting Pins

The unit cell geometry for the optimized RESAD is shown in Fig. 11. As seen in Fig. 12, the pins play a crucial role during Band-1 operation where a strong coupling between the active Band-1 slots and inactive (parasitic) Band-2 slots is expected. In fact, the pins improve the gain by up to 6 dB in the Band-1 region. On the other hand, the FSS played a rather important role during Band-2 operation where it greatly enhanced the return loss characteristics [43] at the expense of some efficiency losses (up to 2 dB) as shown in Fig. 12. Also, the FSS inclusion removes the gain dip occurring around 3.8 GHz. We further considered a design with both pins and FSS present. As seen, optimum gain characteristics are obtained over the whole band in this case. However, the inclusion of pins adds much complexity in the manufacture of an array panel. Hard rigid contact between the top and bottom skins of a conformal panel is not desirable especially in structures where there is significant movement between these layers. Therefore, the pins considered in the assembly are held rigidly on one face but contact the other face via a spring-loaded contact. This approach also permits easy access to the core of the structure for repairs if necessary.

In the simulations discussed above, we considered only one diagonal center-feed (probe-feed) component for each crossed slot element instead of two off-center feed components per one crossed slot element. This choice was to avoid possible crosstalk problems (observed in practice) due to close proximity of the feed components. The diagonal feeding, however, was found to lead to some bandwidth degradation. Also, the feed elements considered above were modeled as probe-feeds and the simulations did not, therefore, indicate the true effect of a practical feed. Next a practical balun/feed component is considered in the modeling and a validation with measurements is given.

B. RESAD With a Balun Model

To examine/validate the loading effect of a practical balun/feed, we considered an approximate balun model in our simulations as depicted in Fig. 13. We still used a probe-feed as a slot excitation at the aperture, but we included an approximate balun model which consisted of a thin substrate and shorting pins along the cavity length coupled with butterfly bow-ties just underneath the slots as shown in Fig. 13. Note that the bow-tie pads are practical in the mechanical assembly of the array panel and quite forgiving with respect to balun/slot alignment when coupling from the balun/slotline to the slot aperture (see Fig. 2). In addition, the noncontact feed assembly relaxes the stiffness requirements of the array panel skin covers. Fig. 14 displays the bore-sight gain for the diagonally fed Band-2 slots in presence of shorting pins and the balun. As seen, the simulations with the approximate balun model agree reasonably well with the measurements of the actual balun/feed over the Band-2 region (1.6–3.2 GHz). We also display the simulated data without the balun model included and we observe a 1–6 dB gain reduction beyond 2.5 GHz due to the balun inclusion. This result clearly shows the expected loading effect of the balun at higher frequencies.

Fig. 15. Reconfigurable slot aperture testbed configuration in presence of shorting pins and approximate balun model: top views for the slot aperture and the surface underneath it (see Figs. 11 and 13 for slot, cavity, pin, and balun parameters).
C. Gain/Pattern Performance for a Testbed Configuration

Finally, we consider a finite array testbed configuration to examine the effect of balun and pins on gain as well as patterns. The testbed array is depicted in Fig. 15 along with corresponding bow-tie/balun/pin configuration. As shown, only the center slot element is fed in the array and all others are parasitics. Note also that we used our finite array simulator [49] for modeling this configuration. Corresponding gain results are shown in Fig. 16. As noted earlier, the inclusion of pins improves the gain profile over the whole band. Similarly, we observe the loading effect of the balun on gain performance. Inclusion of both the pins and the balun results in 0–5 dB gain over the 1–3.5 GHz band (see Fig. 16).

We also computed the patterns for the testbed array with and without the presence of the pins and/or balun. We observed that inclusion of the balun model and (primarily) the pins greatly improved the pattern deterioration over the whole band, mostly observed in E-plane. H-plane patterns did not show much deterioration in all cases considered.

V. CONCLUSION AND DISCUSSION

The key aspect of this paper was the integration of a new reconfigurable slot aperture, an FSS substrate with possible vertical pins, and a new broad-band feed in a manner that yielded a practical realization of a reconfigurable slot array which boasts a 0.8–3.2 GHz bandwidth. We demonstrated that a reconfigurable slot element along with the FSS substrate provided for an array with multi-octave frequency bandwidth at the expense of some gain reduction. However, as demonstrated in this paper, a substrate with less loss could be developed via a more complex pin insertion between the array elements, providing gain enhancement in the low-band operation.

This paper focused on a single-layer FSS substrate within a layered composite structure to achieve a dual-band array performance over two octaves. Nevertheless, the concept can be expanded to using a multilayer FSS substrate to enhance the bandwidth coverage even more. In [50], the authors demonstrated that a double-layer FSS substrate could provide for an operation over 0.8–6.4 GHz band with reconfiguration. Some gain gaps were however present when switching from one band to another. To close those gaps, the radiating slot design was altered by introducing reactive loading along the length of the slot [43]. As a result, the high-band response was shifted downwards, and the impedance response was more uniform across the entire band. Such a loading technique provided for an almost 10:1 impedance bandwidth (0.7–7 GHz) coverage with reconfiguration [43].

REFERENCES

Yunus E. Erdemli

Yunus E. Erdemli (‘96–M’02) was born on March 12, 1970, in Tatvan, Turkey. He received the B.S. degree from Middle East Technical University, Ankara, Turkey, in 1992 and the M.S. and Ph.D. degrees from the University of Michigan, Ann Arbor, in 1996 and 2002, respectively, all in electrical engineering.

In 1992, he joined Turkish Military Electronics, Inc., Ankara, as an RF Design Engineer. During 1994–2002, he was a Graduate Research Assistant at the University of Michigan Radiation Laboratory, where he also served as a Postdoctoral Research Associate afterwards. Since October 2002, he has been an Assistant Professor in the Department of Electronics and Computer Education, Kocaeli University, Kocaeli, Turkey. His research interests include numerical analysis and design of conformal/reconfigurable slot arrays, frequency selective surfaces, and metamaterials.

Dr. Erdemli received an Abroad Ph.D. Fellowship from The Higher Educational Council in Turkey in 1993.
John L. Volakis (S’77–M’82–SM’89–F’96) was born on May 13, 1956, in Chios, Greece. He received the B.E. degree (summa cum laude) from Youngstown State University, Youngstown, OH, in 1978 and the M.Sc. and Ph.D. degrees from The Ohio State University, Columbus, in 1979 and 1982, respectively.

From 1982 to 1984, he was with Rockwell International, Aircraft Division, Lakewood, CA, and during 1978 to 1982, he was a Graduate Research Associate at the ElectroScience Laboratory, The Ohio State University. Since 1984, he has been a Professor in the Electrical Engineering and Computer Science Department, University of Michigan, Ann Arbor, where from 1998 to 2000, he also served as the Director of the Radiation Laboratory. Since January 2003, he has been the Roy and Lois Chope Chair Professor of Engineering at The Ohio State University, Columbus, and also serves as the Director of the ElectroScience Laboratory. He has published over 200 articles in major refereed journal articles (nine of these have appeared in reprint volumes), more than 240 conference papers and nine book chapters.

In addition, he coauthored two books *Approximate Boundary Conditions in Electromagnetics* (London, U.K.: IEE, 1995) and *Finite Element Method for Electromagnetics* (New York: IEEE Press, 1998). From 1994 to 1997, he was an Associate Editor of *Radio Science* and is currently an Associate Editor for the *Journal of Electromagnetic Waves and Applications*. His primary research deals with computational methods, electromagnetic compatibility and interference, design of new RF materials, multiphysics engineering and bioelectromagnetics.

Dr. Volakis is a Member of Sigma Xi, Tau Beta Pi, Phi Kappa Phi, and Commission B of the International Scientific Radio Union (URSI). In 1998, he received the University of Michigan College of Engineering Research Excellence award and in 2001 he received the Department of Electrical Engineering and Computer Science Service Excellence Award. He served as an Associate Editor of the *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION* from 1988 to 1992, and is currently an Associate Editor for the *IEEE ANTENNAS AND PROPAGATION SOCIETY MAGAZINE* and the *URSI Bulletin*. He chaired the 1993 IEEE Antennas and Propagation Society Symposium and Radio Science Meeting, and was a Member of the AdCom for the IEEE Antennas and Propagation Society from 1995 to 1998. He currently serves as the President of the IEEE Antennas and Propagation Society. He is listed in several *Who's Who* directories, including *Who’s Who in America*. 