Active Integrated Antennas

Kai Chang, *Fellow, IEEE*, Robert A. York, *Senior Member, IEEE*, Peter S. Hall, *Fellow, IEEE*, and Tatsuo Itoh, *Fellow, IEEE*

Invited Paper

***Abstract*—This paper provide a review of the active integrated antenna (AIA) technologies. After a brief introduction on the definition and some historical remarks, the paper concentrates on the research effort on the past decades or so. The AIAs are reviewed in its various functions. First, an oscillator-type AIA is presented, followed by very interesting aspects of coupled oscillator arrays for phase control. Use of an AIA concept for efficient RF front end is described with examples on high-power amplifier AIAs. Next, a phase-conjugation-based retrodirective array is reviewed. Finally, AIA systems for receiving, transmitting, and duplexing are reviewed.**

***Index Terms*—Amplifier, antenna, array, oscillator.**

I. Introduction

THE active integrated antenna (AIA) has been a growing area of research in recent years, as the microwave integrated circuit and monolithic microwave integrated circuit technologies became more mature allowing for high-level integration. From a microwave engineer's viewpoint, an AIA can be regarded as an active microwave circuit in which the output or input port is free space instead of a conventional 50-Ω interface. In this case, the antenna can provide certain circuit functions such as resonating, filtering, and duplexing, in addition to its original role as a radiating element. On the other hand, from an antenna designer's point-of-view, the AIA is an antenna that possesses built-in signal- and wave-processing capabilities such as mixing and amplification. A typical AIA consists of active devices such as Gunn diodes or three-terminal devices to form an active circuit, and planar antennas such as dipoles, microstrip patches, bowties, or slot antennas.

Looking back in history, the idea of using active antennas can be traced back to as early as 1928 [1]. At that time, a small antenna with an electron tube was commonly used in radio broadcast receivers around 1 MHz. After the invention of high-frequency transistors, the study of active antennas received much more attention and several pioneering works were reported [2]–[11] in the 1960s and 1970s. Several advantages of implementing the active devices in passive radiating elements were discussed in [12]. For instance, these works include increasing the effective length of short antenna and increasing antenna bandwidth, decreasing the mutual coupling between array elements, and improving the noise factor.

Over the past ten years, the major driving forces for the research on AIAs are the development of novel efficient quasi-optical power combiners [13], [14]. The original purpose for the quasi-optical power combining is to combine the output power from an array of many solid-state devices in free space to overcome combiner loss limitations, which are significant at millimeter-wave frequencies [15], [16]. Since quasi-optical power combing is given elsewhere, this topic will not be discussed here. Rather, this paper reviews more on the functional performance of individual AIA or a small array thereof.

Recently, numerous innovative designs based on the AIA's concept have been proposed and successively demonstrated. AIA technology has evolved to a point where practical implementation for use in the latest microwave and millimeter-wave system is considered feasible. It is currently pursued in a number of related fields such as power combining, beam steering and switching, retrodirective arrays, as well as high-efficiency power-amplifier designs. These AIA-based designs are particularly attractive for millimeter-wave systems because they provide an effective solution to several fundamental problems at these frequencies, including higher transmission-line loss, limited source power, reduced antenna efficiency, and lack of high-performance phase shifters.

This paper reviews the recent research activities related to this emerging technology with emphasis on its applications in integrated antenna oscillators, coupled oscillators and phase control, high-efficiency RF front-ends, and retrodirective arrays. AIA systems are also discussed. For those who have not closely followed the development in this area, [13] and [17] present a more detailed description of the constructing elements of AIAs, as well as some application examples.

II. Integrated Antenna Oscillators

An integrated antenna oscillator is formed by integrating an active solid-state device directly with an antenna. The active solid-state device could be a diode such as Gunn, IMPATT, BARITT, etc., or a transistor such as MESFET, high electron-

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K. Chang is with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, Texas 77843-3128 USA (e-mail: chang@ee.tamu.edu).

R. A. York is with the Department of Electrical and Computer Engineering, University of California at Santa Barbara, Santa Barbara, CA 93106 USA (e-mail: rayork@ece.ucsb.edu).

P. S. Hall is with the Department of Electrical and Electronic Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, U.K. (e-mail: p.s.hall@bham.ac.uk).

T. Itoh is with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095-1594 USA (e-mail: itoh@ee.ucla.edu).

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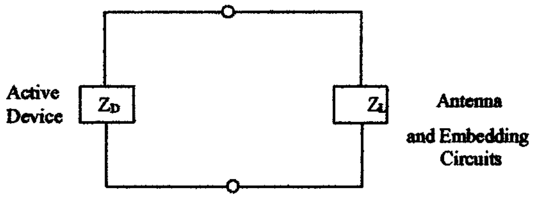

Fig. 1. General integrated antenna oscillator circuit.

mobility transistor (HEMT), heterojunction bipolar transistor (HBT), etc. In the conventional approach, the antenna and oscillator are two separate components interconnected by a transmission line. There is freedom to optimize the performance of the oscillator and antenna independently because there is an obvious distinction between the circuit component and radiating structure. In the integrated antenna oscillator, there is no obvious distinction or boundary between the oscillator and antenna. The active device lies within the volume normally associated with the radiating structure. The antenna serves both as a load and radiator for the active device. The AIA oscillator has the advantages of smaller size, lower cost, and lower loss, as compared to the conventional approach.

The general integrated antenna oscillator circuit is shown in Fig. 1. For a transistor with three terminals, Z_D is the input impedance looking into the transistor with one port terminated. The active device impedance is a function of frequency (f), dc-bias current (I_0), RF current $(I_{\rm RF})$, and temperature (T). Thus,

$$\begin{aligned} Z_D &= Z_D(f, I_0, I_{\rm RF}, T) \\ &= R_D(f, I_0, I_{\rm RF}, T) + jX_D(f, I_0, I_{\rm RF}, T) \end{aligned} \quad (1)$$

where R_D is negative for an oscillation to occur.

The load impedance including the device embedding circuits and the antenna structure can be expressed as

$$Z_L(f) = R_L(f) + jX_L(f). \quad (2)$$

The oscillation occurs when the following two conditions are satisfied [18]:

$$X_L(f_0) + X_D(f_0, I_0, I_{\rm RF}, T) = 0 \quad (3)$$

$$R_L(f_0) \le |R_D(f_0, I_0, I_{\rm RF}, T)| \quad (4)$$

where f_0 is the oscillating frequency. The first condition requires the circuit at resonance and f_0 is determined by the circuit resonant frequency given by (3). The second condition requires the negative device resistance is greater than the load resistance. The location of the active device in an antenna needs to be designed correctly to satisfy the above conditions.

Early integrated active antenna concept surfaced in 1960s. Antennas integrated with a parametric amplifier, tunnel diode, and transistor were reported [19]–[21]. The idea found very little use until the mid-1980s when integrated circuit antennas became popular for compact mobile systems and spatial power combining was sought to solve power deficiencies of solid-state devices.

In 1984 and 1985, Thomas *et al.* [22], [23] reported a Gunn-integrated rectangular microstrip patch antenna operating at X-band frequencies. The active microstrip patch was a compact inexpensive microwave source, which could be used for Doppler-sensing or spatial power-combining applications. The design consists of a Gunn diode and a rectangular microstrip patch antenna. The antenna serves as a resonator and load for the radiating oscillator. Fig. 2 shows the configuration of the active antenna oscillator [22]. The Gunn diode was mounted between the patch and ground-plane offset along the patch to locate it at the 10-Ω feed point. For better phase noise, the integrated Gunn patch-antenna oscillator can be injected locked to a sable source using an external source or mutual coupling [24]–[26]. IMPATT diodes integrated with patch diodes were also demonstrated [27]–[29]. A microstrip patch antenna integrated with an FET transistor was also reported, as shown in Fig. 3 [30]. The patch serves as a feedback element for the FET oscillator circuit and a radiator. Since then, many different active antenna oscillators have been reported. They can be found in several books [14], [31]–[34] and review papers [13], [17].

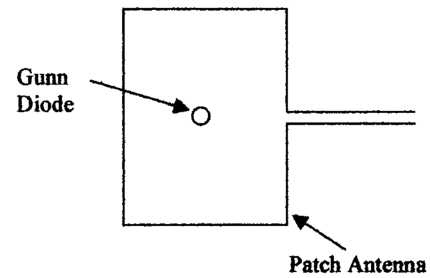

Fig. 2. Integrated Gunn patch-antenna oscillator.

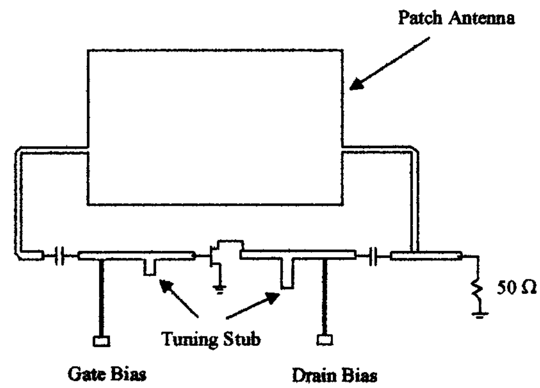

Fig. 3. Integrated FET patch-antenna oscillator.

III. Coupled Oscillators and Phase Control

Injection-locking and phase-locked-loop techniques have been used to achieve synchronous operation of a number of integrated antenna oscillator elements. In addition to achieving phase coherence for power-combining purposes, it has been found that such techniques also allow for the manipulation of the phase distribution without additional phase-shifting circuitry, suggesting a potential for low-cost beam-scanning systems.

Fig. 4 shows three possibilities for synchronization of integrated antennas by injection locking. Each array element is a self-contained voltage-controlled oscillator that includes an an-

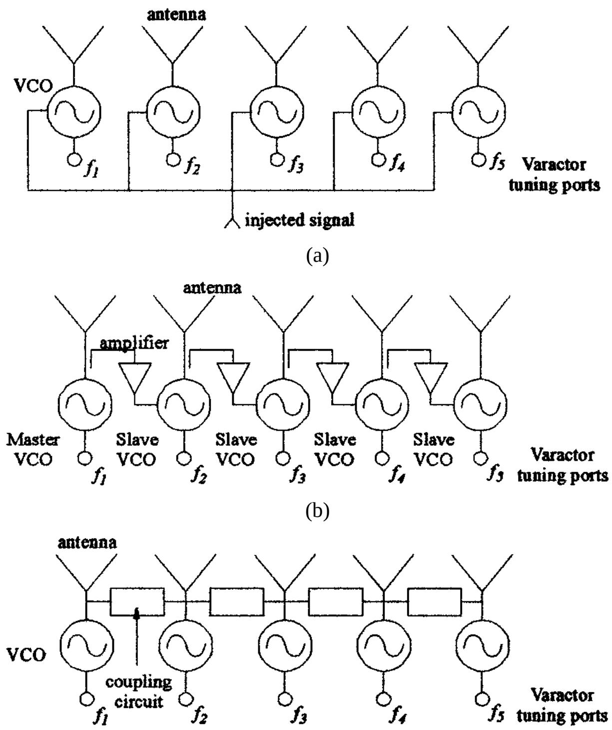

Fig. 4. Three different topologies for synchronization of active antenna oscillators by injection locking. (a) External locking to a common source. (b) Unilateral locking in a chain. (c) Mutual (bilateral) locking.

tenna as the resonator and load. In Fig. 4(a), the oscillators are all slaved to a common signal (the desired output signal) that is distributed using a corporate feed network. According to the basic laws of injection locking [35], the phase of each oscillator can be changed relative to the reference signal (and, hence, the other oscillators) by adjusting the oscillator tuning voltage (the free-running frequency). A 4 $\times$ 4 array using this topology was reported in [36] for power combining. A 2 $\times$ 2 “monopulse” beam-switching array, capable of generating sum and difference patterns for angle-tracking, was also developed using injection-locked active antennas [37].

A variation of the injection-locking concept that eliminates the corporate feed structure is to cascade the oscillators, as in Fig. 4(b), where each array element is injection-locked unilaterally to the preceding element in the array. This has been demonstrated for beam-scanning applications [37], [38]. Amplifiers are used to couple the injection-signals to neighboring oscillators to insure unilaterial locking, and also enhance the locking bandwidth.

A third extension of the injection-locking concept is an array of mutually synchronized oscillators, shown in Fig. 4(c). Each oscillator is bilaterally coupled to neighboring array elements. This system was first proposed by Stephan [39] who described the system as “inter-injection-locked” oscillators. In this case, the steady-state phase relationships are more difficult to calculate. A theory for computing these relationships is described in detail in [40] and [41], and leads to a set of coupled differential equations describing the phase dynamics. Attempts to solve these equations have led to interesting approaches to beam scanning. Stephan and Morgan [42] describe one technique whereby two coherent injected signals with a fixed phase offset are injected at opposite ends of the array. Stephan and Morgan found that, under certain conditions, the phase difference between the two injected signals is divided uniformly along the array to produce a constant phase progression.

Another method, developed by Liao and York [43], exploits the dependence of the steady-state phase distribution on the distribution of free-running frequencies or oscillator “tunings.” It was found that a constant phase progression could be realized by adjusting the free-running frequencies of only the end elements in the array. Several demonstrations are described in [40] and [41].

One feature of all injection-locked arrays is that the near-carrier noise properties are governed primarily by the master oscillator or reference signal, even if the oscillators themselves are quite noisy. The coupling network will have some influence, however, on the specific noise reduction. Analysis of phase noise in free-running and injection-locked arrays is described in [41]. The phase noise of free-running arrays is shown to decrease as $1/N$, where N is the number of oscillators in the system.

An apparent limitation of the injection-locked or coupled-oscillator topologies (for some applications) is the limited range of phase shifts that can be synthesized, in the range -90° to $+90^\circ$. This could be improved by introducing a frequency-doubler circuit after each oscillator. Subharmonic injection locking is an alternative method, which has been shown to allow up to 360° phase shifts [44]. It may also be possible to use self-oscillating mixers as the array elements in order to combine transmit and receive functions or phase-locked loops (PLLs) [45] as the array element for increased bandwidth. These and other variations are described in more detail in [37] and the references therein.

IV. Amplifying AIA

The most power-hungry component in transmitter designs are power amplifiers; therefore, high-efficiency power amplifiers are the essential key components for highly compact and lightweight transmitters in wireless communication systems. Even a few percent of improvement in power-added efficiency (PAE) can be significant if it can be designed without the major degradation in linearity. Reference [46] has shown that improving the PAE of an onboard 2-kW solid-state power amplifier (SSPA) in a communication satellite from 25% to 30% will reduce the waste heats substantially from 6 to 4.7 kW.

Several new design architectures for high-efficiency and good linearity power amplifiers have been investigated. Another promising technique for achieving high efficiency and minimum circuit size is using the AIA concept. In this scheme, an antenna is used as a harmonic tuning load of a power amplifier, in addition to its original role as a radiating element. As mentioned in [47], an antenna used in the AIA approach must radiate efficiently with acceptable patterns. In addition, in a high efficient power-amplifier design, the load impedance should provide a reactive termination at the higher harmonics.

The first demonstration of power-amplifier design using the AIA concept was a class-B GaAs FET power amplifier integrated with a patch antenna, which is shorted in the middle so

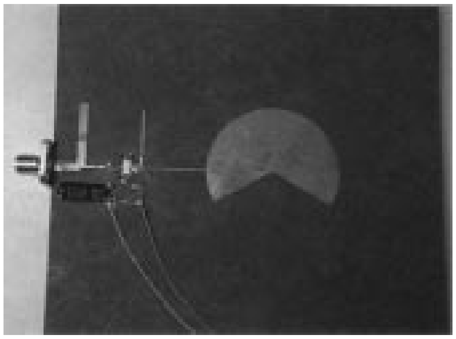

Fig. 5. Prototype class-F PA with a circular segment microstrip antenna.

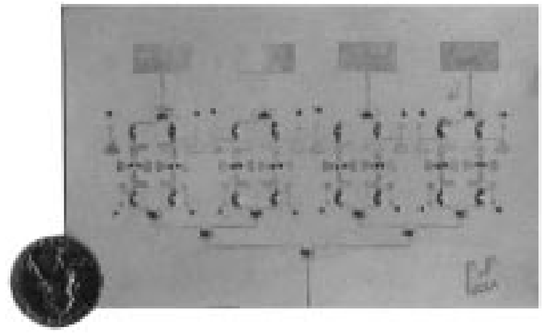

Fig. 6. Prototype four-element retrodirective array.

that the input impedance at the second harmonic becomes zero by eliminating the TM_{20} mode. A 7% improvement in PAE and 0.5 dB in output power have been demonstrated when compared to a reference amplifier using a standard patch antenna without shorting pins [48].

The second single-ended AIA amplifier design employed a modified circular segment microstrip antenna, which is capable of reactively terminating both the second and third harmonics [49]. Fig. 5 presents the photograph of this class-F PA. A relatively high PAE of 63% was achieved at 2.55 GHz with the output power of 24.4 dBm. In addition, there is no major degradation in the antenna radiation patterns with the cross-polarization level below -16 dB at all directions in both the E- and H-planes.

More recently, the AIA concept has been extended into the push–pull power-amplifier designs, where the power of two antiphase-driven class-B power amplifiers are directly combined through a dual-feed planar antenna [50]–[52]. In the traditional microwave-frequency push–pull power amplifier, the two FET devices are combined through a broad-band 180° hybrid or a balun. However, the loss associated with the output hybrid limit the practical efficiency of this type of power amplifier at microwave and millimeter-wave frequencies. In the AIA approach, active devices are directly integrated with the antenna, allowing the antenna to serve as a power combiner and a harmonically tuned load, in addition to its original role as a radiating element, thus minimizing circuit size and insertion loss. In the most recent push–pull PA design [52], the amplifier is integrated with a modified quasi-Yagi antenna, which is capable of reactively terminating the second harmonic. A peak PAE of 60.9% at the output power of 28.2 dBm has been achieved at 4.15 GHz. Additionally, the second harmonic radiation was found to be 30 dB below the fundamental in both E- and H-planes.

V. Signal-Processing Array (Phase Conjugation)

Retrodirective arrays represent a type of special antenna arrays, which reflect any incident signal back toward the source without prior knowledge of the source's location. They do not rely on the sophisticated digital signal-processing algorithms as utilized by so-called "smart antennas." A retrodirective array can provide an omnidirectional coverage, while simultaneously maintaining a high level of antenna gain. This unique property makes retrodirective arrays important in wide range of applications, such as self-steering antennas, radar transponders, search and rescue, and in mobile communication systems [53]–[55].

Retrodirectivity can be realized when each element in the array radiates an outgoing wave whose phase is conjugate to that of the incoming signal relative to a common reference [56]. The classical example of retrodirective array is the Van Atta array, where the conjugated elements of a symmetric array are connected by transmission lines of equal length [57]. However, this classical example has its limitations on symmetry of the array and uniformity of the phase front. To overcome these limitations, a more general approach of phase conjugation based on heterodyne mixing was proposed [58], [59]. The phase conjugation with heterodyne mixing is a simple and effective technique to achieve retrodirectivity using a local oscillator (LO) that has twice the RF frequency. In this scheme, the lower sideband product has the same frequency as the RF, but the phase is conjugated. When combined with an antenna and placed in an array, the phase-conjugated signal from each antenna element will be radiated toward the source direction. However, since the RF and IF share the same frequency in this scheme, good RF/IF isolation cannot be achieved using a filter. Alternative approaches must be used [59], [60]. More recently, an active retrodirective array circuit topology was demonstrated. The use of MESFETs in phase-conjugated circuitry is attractive since these active devices can provide conversion gain in addition to the mixing operation. This allows an array to send amplified signals toward the source location without amplifiers, resulting in compact circuit size and lower cost [61]. Fig. 6 presents a photograph of the prototype four-element retrodirective antenna array using the circuit topology proposed in [62]. The experimental results have shown excellent retrodirective performance. Such type of self-tracking system can be used in advanced wireless applications such as RF ID tags and remote information retrieval.

VI. AIA Systems (Receiving, Transmitting, Diplexing)

Sections I–V have described a number of AIA configurations and have suggested appropriate application areas. In seeking to understand whether such technology is applicable to communications and sensors in a wider sense, several system requirements can be cited. For transmitting elements, these include stability and purity, and capability to be frequency tuned and modulated. Sensitivity and selectivity are important for receive elements. Finally, the ability to duplex both transmit and receive functions is necessary for many systems.

A. Transmitting Elements

Standalone antenna oscillators have inherently low stability. The combination of a single active device oscillator with an antenna that generally has a bandwidth of a few percent results in external quality factor less than a few 10 s. While this may be acceptable in short-range sensor systems, such as intruder alarms, it is too low for most multichannel communications applications. In addition, long-term stability must be improved and tuning made more accurate. Patch oscillator control using a PLL [63] has been shown to reduce phase noise to levels acceptable in, for example, the Digital Enhanced Cordless Telephone (DECT) standard. A phase noise of −70 dBc/Hz at 10 kHz has been achieved at an operating frequency around 1.8 GHz. It is estimated that, using chip-based PLLs, a compact single-substrate transmitter could be made with overall size 1.5× the patch-antenna size.

PLL techniques become difficult at very high frequencies and an alternative technique using a coupled cavity beneath the antenna oscillator has been demonstrated [64]. Using scale models at 4 GHz of millimeter-wave oscillators, a phase noise of −78 dBc/Hz at 10-kHz offset was obtained for both a patch and a slot oscillator. Q measurements of copper-plated cavities micromachined in silicon at 34 GHz suggested that better phase noise than the above could be obtained at millimetric wavelengths. Simulations, using the van der Pol method, showed that the use of a coupled cavity increases the oscillator startup time by about a factor of three. The use of a single long cavity beneath two oscillators improved mutual locking so that if the two had slightly different free-running frequencies, due to manufacturing differences, there was an increased chance of the two locking together.

Out-of-band radiation must be suppressed in most practical systems and careful oscillator design is needed. Circular sector patches [65] and shorted quarter-wavelength patches [49] have been shown to give a reduction of over 10 dB in radiation at harmonic frequencies. Analysis is also available [66] to guide design methods.

When locked oscillators are used to provide either frequency or phase modulation, then the finite locking time places a limit on the capacity of the communications link. This effect is increased when locked oscillator arrays are, for simplicity, modulated through the locking signal applied to a single element only. Van der Pol analysis [67] has shown that the data rate is inversely proportional to the array length and for a seven-element linear array is of the order of 10 Mb/s.

B. Receiving Elements

Direct down-conversion receive elements have been widely reported [68]. If increased sensitivity and selectivity is required, then superheterodyne techniques must be used. However, if a single-substrate configuration is used, then considerable radiation from the LO will result. For a 0-dBm LO power, an effective isotropic radiated power of −25 dBm has been measured, with results confirmed by theory [69]. To meet the requirement for unwanted radiation from equipment for the DECT, shielding can be used, but this reduces the degree of integration and will result in increased cost and size.

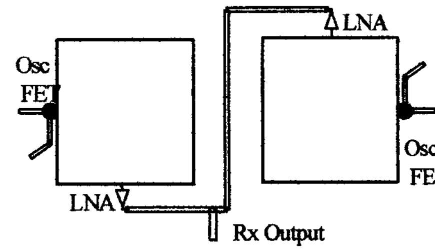

Fig. 7. Simultaneous transmit–receive active antenna.

C. Duplex Elements

Various forms of duplex elements have been demonstrated. If the oscillator active device is also used as a self-oscillating mixer, then simple Doppler radar elements can be made. A time-division communications function can be performed by switching the oscillator between transmit and LO frequency. Polarization duplexing, with an oscillating active device connected to one side of a square patch and a low-noise amplifier attached to an orthogonal side, as shown in Fig. 7, allows simultaneous transmit and receive operation [70]. Rotation by 180° of one of a pair of elements is used to increase the isolation in a two-element array, which was measured at 45 dB. This isolation would allow a pair of 8 × 8 element arrays to form a duplex link with a range of approximately 100 m. Simultaneous transmit–receive operation on the same frequency and polarization has been demonstrated by the integration of an active circulator in the form of a ring with three embedded amplifiers surrounding a quarter-wavelength patch [71]. Isolation of 25 dB was achieved over a relatively narrow bandwidth.

VII. Concluding Remarks

As presented above, the AIA is an interesting subject of study with many examples presented above. The topic is rather interdisciplinary in nature and, hence, is challenging, but provides many opportunities. However, this technology is still in its infancy. As such, it is important to identify its attractive features and limitations, particularly in terms of system applications. Some of them have been identified in this paper. For instance, an AIA's structural simplicity may be advantageous where system requirements such as those for phase noise are not severe. It is hoped that this technology with possible modifications and supplements find its usage in many engineering applications.

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Kai Chang (S’75–M’76–SM’85–F’91) received the B.S.E.E. degree from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1970, the M.S. degree from the State University of New York at Stony Brook, in 1972, and Ph.D. degree from The University of Michigan at Ann Arbor, in 1976.

From 1972 to 1976, he was with the Microwave Solid-State Circuits Group, Cooley Electronics Laboratory, The University of Michigan at Ann Arbor, where he was a Research Assistant. From 1976 to 1978, he was with Shared Applications Inc., Ann Arbor, MI, where he was involved with computer simulation of microwave circuits and microwave tubes. From 1978 to 1981, he was with the Electron Dynamics Division, Hughes Aircraft Company, Torrance, CA, where he was involved in the research and development of millimeter-wave solid-state devices and circuits, power combiners, oscillators, and transmitters. From 1981 to 1985, he was with TRW Electronics and Defense, Redondo Beach, CA, where he was a Section Head involved with the development of state-of-the-art millimeter-wave integrated circuits and subsystems, including mixers, voltage-controlled oscillators (VCOs), transmitters, amplifiers, modulators, upconverters, switches, multipliers, receivers, and transceivers. In August 1985, he joined the Electrical Engineering Department, Texas A&M University, College Station, as an Associate Professor, and became a Professor in 1988. In January 1990, he became an E-Systems Endowed Professor of Electrical Engineering. He has authored and co-authored several books, including *Microwave Solid-State Circuits and Applications* (New York: Wiley, 1994), *Microwave Ring Circuits and Antennas* (New York: Wiley, 1996), *Integrated Active Antennas and Spatial Power Combining* (New York: Wiley, 1996), and *RF and Microwave Wireless Systems* (New York: Wiley, 2000). He has served as the Editor of the four-volume *Handbook of Microwave and Optical Components* (New York: Wiley, 1989 and 1990). He is the Editor of *Microwave and Optical Technology Letters* and the Wiley Book Series on “Microwave and Optical Engineering.” He has also authored or co-authored over 350 technical papers and several book chapters in the areas of microwave and millimeter-wave devices, circuits, and antennas. His current interests are in microwave and millimeter-wave devices and circuits, microwave integrated circuits, integrated antennas, wide-band and active antennas, phased arrays, microwave power transmission, and microwave optical interactions.

Dr. Chang was the recipient of the 1984 Special Achievement Award presented by TRW, the 1988 Halliburton Professor Award, the 1989 Distinguished Teaching Award, the 1992 Distinguished Research Award, and the 1996 Texas Engineering Experiment Station (TEES) Fellow Award presented by Texas A&M University.

Robert A. York (S’85–M’89–SM’99) received the B.S. degree in electrical engineering from the University of New Hampshire, Durham, in 1987, and the M.S. and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, NY, in 1989 and 1991, respectively.

He is currently a Professor of electrical and computer engineering at the University of California at Santa Barbara (UCSB), where his group is currently involved with the design and fabrication of novel microwave and millimeter-wave circuits, high-power microwave and millimeter-wave amplifiers using spatial combining and wide-bandgap semiconductor devices, and application of ferroelectric materials to microwave and millimeter-wave circuits and systems.

Dr. York was the recipient of the 1993 Army Research Office Young Investigator Award and the 1996 Office of Naval Research Young Investigator Award.

Peter S. Hall (M’88–SM’93–F’01) received the Ph.D. degree in antenna measurements from Sheffield University, Sheffield, U.K., in 1973.

He then spent three years with Marconi Space and Defence Systems, Stanmore, U.K., where he was largely involved with a European Communications satellite project. He then joined The Royal Military College of Science as a Senior Research Scientist and progressed to Reader in electromagnetics. In 1994, he joined the University of Birmingham, Edgbaston, Birmingham, U.K., where he is currently a Professor of communications engineering and Head of the School and Head of the Communications Engineering Group, School of Electronic and Electrical Engineering. He has extensively performed research in the areas of microwave antennas and associated components and antenna measurements. He has authored or co–authored four books, over 130 learned papers, and holds various patents. From 1991 to 1995, he was an Honorary Editor of the *Proceedings of the Institution of Electrical Engineering, Part H*, and is currently an Editorial Board member of the *International Journal of RF and Microwave Computer Aided Engineering* and *Microwave and Optical Technology Letters*.

Dr. Hall Professor Hall is a Fellow of the Institution of Electrical Engineers (IEE), U.K. He is a past chairman of the IEE Antennas and Propagation Professional Group and of the organizing committee of the 1997 IEE International Conference on Antennas and Propagation. He has been associated with the organization of many international conferences and was a member of the Technical Committee of AP2000 in Switzerland and was an overseas corresponding member of ISAP2000 in Japan. He was the recipient of six IEE Premium Awards, including the 1990 IEE Rayleigh Book Award for the *Handbook of Microstrip Antennas*.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois at Urbana-Champaign. From April 1976 to August 1977, he was a Senior Research Engineer in the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor at the University of Kentucky, Lexington. In July 1978, he joined the faculty at The University of Texas at Austin, where he became a Professor of electrical engineering in 1981 and Director of the Electrical Engineering Research Laboratory in 1984. During the summer of 1979, he was a Guest Researcher at AEG-Telefunken, Ulm, Germany. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at The University of Texas at Austin. In September 1984, he was appointed Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department, The University of Texas at Austin. In January 1991, he joined the University of California at Los Angeles (UCLA), as Professor of electrical engineering and Holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He was an Honorary Visiting Professor at the Nanjing Institute of Technology, Nanjing, China, and at the Japan Defense Academy. In April 1994, he became an Adjunct Research Officer for the Communications Research Laboratory, Ministry of Post and Telecommunication, Japan. He currently holds a Visiting Professorship at The University of Leeds, Leeds, U.K., and is an External Examiner of the Graduate Program of the City University of Hong Kong. He has authored or co–authored 274 journal publications, 540 refereed conference presentations, and 30 books/book chapters in the area of microwaves, millimeter-waves, antennas and numerical electromagnetics. He has generated 49 Ph.D. students.

Dr. Itoh is a member of the Institute of Electronics and Communication Engineers of Japan and Commissions B and D of USNC/URSI. He became an Honorary Life Member of the IEEE MTT-S in 1994. He was the editor-in-chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1983–1985) and the IEEE MICROWAVE AND GUIDED WAVE LETTERS (1991–1994). He serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He was vice president of the IEEE MTT-S in 1989 and president in 1990. He was the chairman of USNC/URSI Commission D (1988–1990), and Chairman of Commission D of the International URSI (1993–1996). He is the chair of the Long Range Planning Committee of URSI. He serves on advisory boards and committees of a number of organizations. He has been the recipient of a number of awards, including the 1998 Shida Award presented by the Japanese Ministry of Post and Telecommunications, the 1998 Japan Microwave Prize, the 2000 IEEE Third Millennium Medal, and the 2000 IEEE MTT-S Distinguished Educator Award.