Foreword

INTRODUCTION

RF TECHNOLOGY has advanced significantly in the past two decades largely through the investments in microwave integrated circuits (MIC's) by several governments and through the rapid growth of commercial wireless communications. Technological advancements have been particularly strong in the microwave and millimeter frequency bands between approximately 1–100 GHz. Government investment in these frequencies has been dominated by defense, national-security, and scientific-research systems, particularly for radar, communications, electronic warfare, missile seekers, and radiometry. Commercial wireless frequencies are mainly in the 0.8–2.5-GHz range, with current military mobile communications systems being lower in frequency due to the operational requirement for over-the-horizon coverage. New commercial interest is growing for local multipoint distribution service (LMDS) around 30 GHz and for vehicular collision-avoidance radar between 60–77 GHz. Military satellite communications require frequencies between 12–45 GHz and various mobile military-radar and missile-seeker applications run the range from approximately 3–95 GHz. Due to the strong molecular oxygen absorption, frequencies near 60 GHz have potential applications for wireless local area nets (WLAN's), especially nets within buildings, and for other commercial or military applications requiring isolated links or paths of signal propagation. For example, satellite-to-satellite covert communications are possible without interference with, or interception by, terrestrial stations, and highly localized wireless nets are possible with easy reuse of frequencies.

Throughout this period of activity, the government interest has been focused largely on performance requirements specific to military systems, such as power, sensitivity, and instantaneous bandwidth. The commercial activity has focused primarily on affordability, reliability, manufacturability, and other issues germane to commercial products. At present and into the foreseeable future, the focus in both areas is being replaced by broader demands on performance and affordability alike. With reduced or stagnant budgets, high-performance RF systems can no longer reach the stage of defense acquisition unless they are substantially more affordable than in previous times. Conversely, commercial wireless systems and products have already become so affordable that specific performance characteristics such as range and dropout rate in wireless telephones are becoming key issues in their procurement. The situation is similar in some ways to the dilemma facing digital electronics where a concern in the Department of Defense is the availability and affordability of ultra-high-performance digital-signal processors, and a key concern in the commercial arena is the performance of manifestly affordable microprocessors, particularly for the speed of desktop computers and the power consumption of portables.

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In addition to the new demands on performance and affordability, the following improvements in RF systems are needed to better exploit the microwave region and to fully realize the benefits promised by millimeter-wave operation:

1) more available spectrum;
2) higher bandwidth;
3) reduced size and weight for mobile and airborne platforms;
4) propagation control;
5) compromise between propagation and resolution conditions in the frequency range between optical and radar frequencies.

Currently, there are many radar and communications applications in the microwave spectrum, including wireless systems. There are relatively few applications in the millimeter-wave region primarily because of the cost or unsatisfactory performance of RF components, both active and passive. This is particularly true for solid-state millimeter-wave power transmitters where MIC solid-state technology can bring significant advantages of batch fabrication, compactness, light weight, and reliability, but the power-handling capability decreases very rapidly with frequency.

With the broad demands now placed on RF systems, there is a strong incentive to consider technology that can impact performance and affordability at the same time. Our viewpoint, and the theme of this TRANSACTIONS, is that such an impact can be achieved by innovations in RF system architecture. By RF architecture, we mean the physical structure and electromagnetic (EM) relationship between the components and devices that process the RF signals and power, particularly in the system front-end. Traditional RF architecture is based on a "plumbing" approach whereby signals are routed through waveguides or coaxial lines that have excellent RF characteristics and allow for three-dimensional system integration, but necessarily require rather large components in separate packages or modules. Modern hybrid and monolithic integrated circuits (IC's) have fostered a major reduction in the volume and weight of RF components and subsystems, but have often fallen short of the traditional systems in terms of performance or cost because of MIC circuit losses, device shortcomings, expensive semiconductor materials, or other reasons. Innovative architectures should strive to meet or surpass the performance of traditional systems, while achieving comparable or superior levels of integration relative to MIC technology. The important issue of new circuit-integration techniques has been the subject of a number of recent military research and development programs sponsored by various laboratories and research offices of the three services, by the Office of the Secretary of Defense, by DARPA, and by NASA.

An example of superior architecture addressed in this TRANSACTIONS is three-dimensional integration using conventional semiconductor devices with unconventional RF coupling technology. Two examples of unconventional RF coupling are bulk-micromachined circuits and quasi-optical structures, both of which are discussed in several of this TRANSACTIONS papers. In a sense, these architectures are the best of both worlds, having the three-dimensional benefit of the traditional RF circuit approach, and the integration benefits of the MIC approach. Both techniques are highly compatible with planar solid-state fabrication technology. Other novel architectures addressed in this TRANSACTIONS are active integrated antennas and frequency-control structures. In some cases, papers are presented which include a good overview of the subject. In other cases, the state-of-the-art is well documented elsewhere, and this TRANSACTIONS focuses on recent progress. In this case, we have tried here to provide key references to the state-of-the-art. All of the authors in this TRANSACTIONS were encouraged to include intelligent speculation of potential future advances of their techniques.

The first three papers discuss an exciting new approach to circuit integration using micromachined silicon substrates, which has the potential for high-performance circuits in a broad frequency range from 1 to over 100 GHz with much lower cost, lighter weight, and smaller size than traditional circuits. This technique provides a natural way to integrate very high functionality circuits by using flip-chip techniques to incorporate chips on other material substrates for optoelectronic or high-frequency microwave functionality into the silicon-based circuit. Silicon CMOS and SiGe microwave components can be naturally fabricated in the silicon micromachined substrates. Channels are etched in the substrate and coplanar transmission line fabricated in the channels. A matching channelized substrate can be used to cap the lower substrate enclosing the transmission lines. The channels can be metalized, effectively isolating the enclosed lines and eliminating radiation loss. Active elements can be integrated in enclosed chambers connected by the transmission-line channels. The channels can be sized to insure cutoff of critical frequencies, thus isolating circuit elements within a channel. As a result of this increased isolation, circuit densities can be significantly increased for microwave and millimeter wave IC's. The coplanar lines are fabricated in such a way that dielectric material is eliminated from key portions of the substrate, resulting in an elimination of dielectric loss and substrate modes. High Q inductors and low dielectric-loss capacitive elements can be integrated into planar IC's. Discrete inductors can have Q's between 50–100, with cutoff frequencies well above 40 GHz. At higher frequencies, very high Q distributed filters are possible. High Q filters can also be constructed from coupled resonant cavities in the silicon substrate and the filters can be tuned using microelectromechanical system (MEMS) structures. Performance of these circuits is limited only by ohmic losses. The performance of micromachined circuits can approach the performance of waveguide circuits for many applications, but with less than one-twentieth of the size and weight. The final capping layer of silicon substrate provides an effective hermetic seal and self-packaging for the circuit, with very controllable EM coupling effects. As a result, the cost of packaging for millimeter-wave IC's can be reduced by as much as two orders of magnitude over the cost of traditional packaging techniques. Two good reviews of this circuit integration technique are contained in [1] and [2].

The paper by Lubecke *et al.* is an overview of micromachined circuit techniques for very high-frequency applications. It also discusses a combination of MEMS techniques with the micromachined circuits. The integration of MEMS and micromachined circuit techniques is a natural extension. The paper by Herrick *et al.* discusses the extension of the micromachining technique to three-dimensional layered circuit integration for very high-density microwave and millimeter-wave solid-state components. The paper by Robertson *et al.* describes a compact lightweight 20-dB directional coupler with 0.5-dB insertion loss, as an example of a high-performance microchined circuit component. An alternative new integration technique involves air-gap transmission lines fabricated on glass substrates, which are glass microbump bonded to silicon substrates. This technique is discussed in the paper by Chuang and El-Ghazaly. It is intriguing to ask if this technique could be usefully combined with silicon micromachined circuit techniques.

The paper by ul Haq *et al.* describes a new approach to mode control structures. Traditionally, these components have been fabricated from periodic structures. With the advent of readily available high computational power, it is possible to remove the restriction for periodicity in designing these structures and to achieve the same performance in smaller structures. The results reported in the paper are for waveguide and optical circuits, but the extension to planar IC's, particularly in micromachined channels, may be very interesting. The optical circuits described in this paper have natural microwave and millimeter-wave analogs in possible quasi-optical circuit architectures.

MEMS techniques have been very successful in addressing RF applications, particularly for switching components. RF MEMS switches can provide high performance with very low power dissipation and in circuits compatible with very large-scale integration (VLSI). The paper by Brown is an overview of RF-MEMS switch technology and its applicability to reconfigurable RF circuits, including antennas. The paper by Barker and Rebeiz discusses a new switch architecture, which provides true time-delay phase shifters and high isolation wide-band switches with relatively low pull-down voltages.

The paper by Qian and Itoh is an overview of recent progress in active integrated antennas. Active antennas are the integration of active devices directly in an antenna circuit. In general, the antenna circuit and active device are integrated so closely that the performance cannot be easily segregated into two separate elements. The antenna circuit and the active device must then be analyzed as a single component. Advantages of this integration include inherently lower losses, the removal of the restriction to impedance match to 50-Ω interconnects, compactness, and the reduction in signal delay so that a nonlinear response can occur directly at the antenna. Optical techniques can also be used to control the active devices in the active antenna. The paper by Radisic *et al.* presents some novel approaches to the harmonic tuning of high-efficiency amplifiers using the EM characteristics of the antenna itself in an active antenna arrangement and/or using frequency-control techniques based on periodic EM structures (the same principles used for photonic bandgap structures).

Several papers in this TRANSACTIONS deal with innovative circuit and architecture solutions for beam-control functions. A novel technique is discussed in the paper by Chang and Fetterman to achieve microwave phase conjugation using nonlinear devices coupled to an array of antenna elements. Here, the pump signal can be fed electrically or for very large arrays optically. Another innovative technique for the control of beam directivity from antenna arrays uses injection-locking and phase-locking techniques for oscillators in active antenna arrays. This potentially low-cost approach to beam scanning is discussed in the paper by York and Itoh. The paper by Li and Chang describes novel techniques for beam steering using dielectric image lines. The paper by Contopanagos *et al.* describes innovative analyses and applications of artificial lattices based on photonic bandgap concepts.

Four papers deal with various issues in quasi-optical architectures or spatial power-combining circuits. These architectures combine power or perform functions on signal as a distributed EM field in free space. This approach has the potential for efficient power combining. By combining the power output from a large number of devices in free space, the losses in interconnects can be eliminated while maintaining high bandwidth performance. It can provide a natural compact technique for higher order functionality, such as beam control and frequency conversions, for architectures that will ultimately radiate from a large aperture, such as an antenna array. The terminology for quasi-optical and spatial combining have become somewhat blurred in the literature, and there is a tendency to use them almost interchangeably. The term "quasi-optical" originally referred to architectures which relied on optics-like elements, such as lenses and reflectors, to control the spatial EM field. Spatial-combining architectures can be divided into space-fed and circuit-fed arrays. Both types combine the output signal or power in the free-space EM field, while the space-fed architecture also derives its input signal from a free-space field. Two types of space-fed architectures are the grid and active antenna arrays. The active devices in a grid array are spaced much closer than a half-wavelength. The entire grid, consisting of the interconnects between active devices, acts as a single-input and single-output antenna. On the contrary, the active antenna array consists of an array of active devices, each with its own antenna element, and with some degree of isolation between each antenna "cell." Two outstanding recent references on this broad topic are [3] and [4], and [5] contains a recent further overview with particular concern for combining efficiency issues.

The papers by De Lisio *et al.* and Moussessian *et al.* describe analyses of efficiency, noise, and complementary symmetry in grid amplifier structures. Taken together with a previous issue's paper in this TRANSACTIONS on stability in grid amplifiers [6], they represent the first comprehensive analyses of grid amplifiers and are important contributions to the fundamental understanding of these architectures. The paper by Popović and Mortazawi discusses the critical issue of bidirectional quasi-optical arrays. For compactness, many communications and radar applications will require bidirectional arrays for transmit and receive. This is especially true for missile-seeker front ends, which must use a single aperture due to space limitations. Here, the circuits in the amplifier array must be able to separate the outgoing power-amplifier function from the incoming low-noise amplifier function with the potential for phase control for beam forming. The examples considered in this paper are all active antenna-array architectures. The paper by Moussessian *et al.* describes a grid frequency doubler for terahertz applications as an example of a quasi-optical architecture for higher order functionality.

LIST OF REVIEWERS AND ACKNOWLEDGMENT

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A. S. Mortazawi
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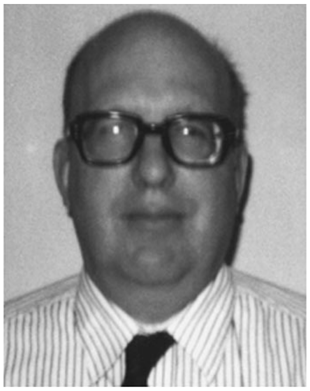
[6] C.-M. Liu, M. P. De Lisio, A. Moussessian, and D. B. Rutledge, "Stability of grid amplifiers," *IEEE Trans. Microwave Theory Tech.,* vol. 46, pp. 769–774, June 1998.



James F. Harvey (M'91) received the B.S. degree in engineering from the U.S. Military Academy, West Point, NY, in 1964, the M.A. degree in physics from Dartmouth College, Hanover, NH, in 1972, and the Ph.D. degree in applied science from the University of California at Davis, in 1990, with research performed at Lawrence Livermore National Laboratory.

He is currently a Research Program Manager at the U.S. Army Research Office, with primary responsibility in the fields of electromagnetics, antennas and antenna structures, millimeter-wave circuit integration, low-power/minimum-power system design, and land-mine detection. His programs include a focus on small multifrequency multifunctional antennas for Army vehicles, radio propagation over complex terrain affecting data communications, and new millimeter-wave circuit integration techniques such as spatial power combining and micromachining. His personal research interests are in the fields of quasi-optics and multiresolution analysis of EM structures.

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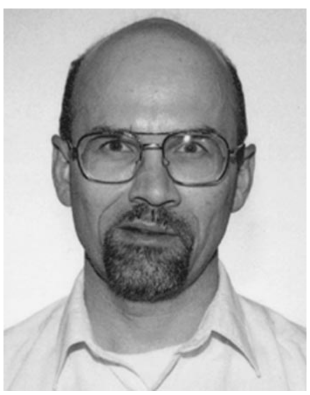

Elliott R. Brown (M'92–SM'97) received the B.S. degree in physics from the University of California at Los Angeles (UCLA), in 1979, and the Ph.D. and master's degrees in applied physics from the California Institute of Technology, Pasadena, in 1985 and 1981, respectively, where he conducted research on millimeter-wave and terahertz mixers made from semiconductor hot-electron bolometers and magnetically quantized photoconductors.

He is currently a Professor of electrical engineering at UCLA, and is a part-time Technical Staff Member at the Jet Propulsion Laboratory, Pasadena, CA. He is currently developing research projects in power electromagnetics, ultrafast electronics and optoelectronics, advanced RF sensor technology, and biomedical engineering. Prior to joining UCLA, he was a Program Manager at the Defense Advanced Research Projects Agency (DARPA Electronics Technology Office), Arlington, VA where he helped create and manage programs in advanced RF technology (MAFET Thrust 3), high-power solid-state electronics (Megawatt), highly controlled infrared dielectric emissivity (HIDE), and advanced acoustics technology (Sonoelectronics). Each of these programs was aimed at revolutionary breakthroughs in device and component technology, and was tailored for system integration and transition of the successful technologies. For example, the MAFET Thrust-3 Program introduced several new device and circuit technologies, such as RF MEMS switches and three-dimensional bulk-micromachined IC's, which are already being transitioned to system programs. Prior to DARPA, he was an Assistant Group Leader and Staff Researcher at the MIT Lincoln Laboratory, Lexington, MA, where he conducted original research and development in advanced electromagnetics, ultrafast electronics and optoelectronics, solid-state device physics, and high-frequency receiver technology. Among his key inventions and discoveries were the photonic-crystal planar antenna, the low-temperature-grown-GaAs terahertz photomixer, the resonant-tunneling-diode relaxation oscillator, normal-incidence absorption in semiconductor quantum wells, and shot-noise suppression and quantum-transport inductance in resonant-tunneling devices. Each of these has been unique in terms of device performance or scientific contribution. For example, the photonic-crystal planar antenna was the first RF application that utilized the three-dimensional nature of the photonic stopbands, and has helped point towards a new direction in monolithic IC's, whereby the semiconductor substrate can be fabricated to improve rather than degrade the performance of passive RF components. From 1977 to 1981, he received fellowships at the Hughes Aircraft Company, where he worked on key components in millimeter-wave radiometers and high-speed (>1 Gbit/s) laser communications systems for the Space and Communications Group, El Segundo, CA.

Dr. Brown is a member of Phi Beta Kappa, the American Physical Society, and the Materials Research Society. He was the recipient of a 1998 Achievement Award presented by the Office of Secretary of Defense.