A Reconfigurable Leaky-Wave/Patch Microstrip Aperture for Phased-Array Applications

James Sor, *Student Member, IEEE*, Chin-Chang Chang, *Student Member, IEEE*, Yongxi Qian, *Senior Member, IEEE*, and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*—A novel reconfigurable leaky-wave/patch microstrip aperture is introduced and characterized. The structure consists of a long leaky-wave microstrip antenna that has been segmented into several smaller patch antennas. The multimode structure can be reconfigured into a patch antenna anywhere along the aperture of the leaky-wave antenna with two degrees of freedom. p-i-n-diode switches are utilized to switch between the different aperture configurations. The structure's unique field profile is utilized to minimize insertion loss in the leaky-wave mode and also to maximize isolation between the different aperture ports. Radiation patterns demonstrate excellent radiation characteristics consistent with standard leaky-wave and patch-antenna patterns. The reconfigurable leaky-wave/patch concept is applied to realize some unique multimode array configurations offering wide scan coverage and enhanced flexibility over traditional phased-array systems.**

***Index Terms*—Leaky-wave antenna, patch antenna, phased array, reconfigurable aperture.**

I. Introduction

THE emergence of the wireless communications era has brought about an explosion in the number of antennas both on the ground and in orbital space. The need to reduce both the antenna size and number of antennas has accordingly become more important, particularly in payload situations where space comes at a premium. This is particularly true in the case of radar and defense applications, where multiple frequency bands are common. One alternative to using multiple individual antennas is to use broad-band phased arrays. However, even today's most advanced phased arrays do not exhibit enough bandwidth to completely support a multitude of applications by itself. It is highly desirable, therefore, to develop topologies and techniques where a number of antennas that cover different frequency bands and/or serve different functionalities can share a single physical aperture without sacrificing system performance. One such approach that has garnered increased attention in the literature recently is the reconfigurable aperture approach [1]–[3].

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J. Sor, C.-C. Chang, and T. Itoh are with the Microwave Electronics Laboratory, University of California at Los Angeles, Los Angeles, CA 90095 USA.

Y. Qian was with the Microwave Electronics Laboratory, University of California at Los Angeles, Los Angeles, CA 90095 USA. He is now with the MicroWaveSys Division, Microsemi Corporation, Santa Ana, CA 92704 USA.

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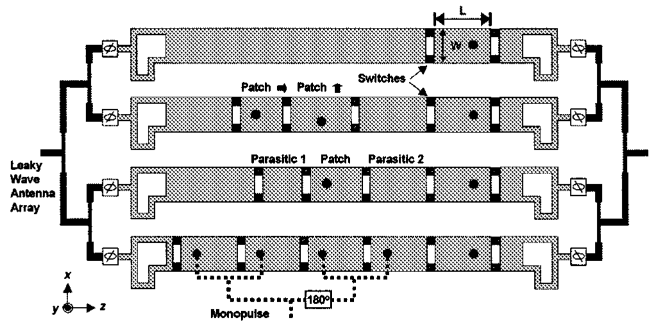

Fig. 1. Schematic of reconfigurable leaky-wave/patch-aperture array.

To this end, we recently proposed in [4] a reconfigurable leaky-mode/multifunction patch-antenna array structure, as shown in Fig. 1. In this scheme, long leaky-wave apertures form a linear array along the x-axis and can be frequency scanned with high gain (∼12 dB). Using conventional or microelectromechanical system (MEMS) switches, each of the leaky-wave apertures can be segmented into several smaller patch-antenna apertures, with the mode of operation controlled by the state of the switches. The switches act simply as short circuits when turned on and as open circuits when turned off. This unconventional, but versatile system presents a number of advantages over traditional phased-array systems. First, the combination of the patch and leaky-wave apertures provides multiband frequency coverage with a wide variety of radiation characteristics. For example, the individual resonant patches can be designed to operate at multiple frequency bands with moderate gain about broadside, while the high-gain leaky-wave apertures provide moderate bandwidth about the elevation angle. Collectively, the radiating apertures provide more flexibility and wider frequency coverage than traditional phased-array systems. Second, the aperture itself is relatively simple to implement and construct, utilizing only a moderate number of switches in contrast to other proposed configurations [5], [6]. Systems that rely on an excessive number of switches will inevitably suffer from poor efficiency and integration issues. Additionally, the uniplanar nature of the reconfigurable aperture enables the aperture to be conformably mounted to any flat surface. Finally, both the leaky-wave and patch-antenna structures to be used in our reconfigurable aperture are unidirectional radiators exhibiting moderate to high gain [7]. This improves the overall efficiency of the system and is particularly attractive for target tracking applications. In [8] and [9], we demonstrated the viability of this unique phased array through several topologies based upon the reconfigurable

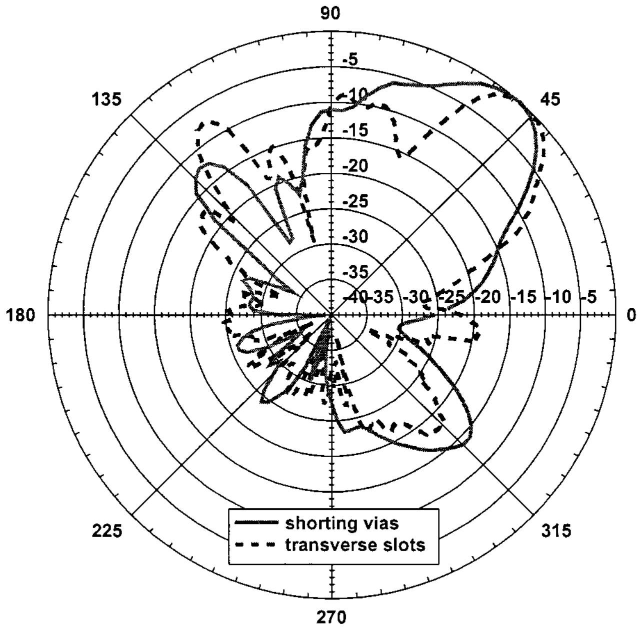

Fig. 2. Comparison of measured leaky-wave radiation patterns using different mode suppressors.

leaky-wave/patch concept. In this paper, we aim to illuminate and explore the inherent design issues associated with our proposed reconfigurable leaky-wave/patch aperture.

II. Aperture Design Issues

Before we examine the reconfigurability of the shared aperture, we must first ensure that each of the respective antennas operates correctly in its isolated state. For the leaky-wave antenna, this first means proper excitation of the desired first higher order leaky mode. A slotline-fed structure should ideally excite a pure odd leaky mode, but the radiation efficiency was found to be inferior to a coplanar stripline (CPS)-fed approach [10]. CPS feeding, however, requires either a microstrip- or coplanar waveguide (CPW)-based transition to realize the required 180° phase shift. The frequency dependence of these baluns causes a substantial portion of the even mode to be excited, especially when a broad-band design is required. This issue can be addressed by utilizing a broad-band microstrip-to-CPS balun, which we previously reported in [11] to demonstrate nearly 70% bandwidth in a back-to-back configuration. To ensure suppression of the undesired fundamental even mode, two mode suppressors, as originally proposed by Menzel in [12], in the form of transverse slots and shorting vias are investigated. Finite-difference time-domain (FDTD) optimizations are employed to determine optimal size and spacing of each of these mode suppressors placed along the center of the leaky microstrip line [13]. The use of either mode suppressor results in broad-band leaky-mode excitation (~15%). However, the use of shorting vias less perturbs the current flow of the first higher order leaky mode while providing better suppression of the fundamental microstrip mode than transverse slots. The advantage of using shorting vias is clearly seen in Fig. 2, where we compare the measured radiation patterns of a leaky-wave antenna utilizing transverse slots to one utilizing shorting vias

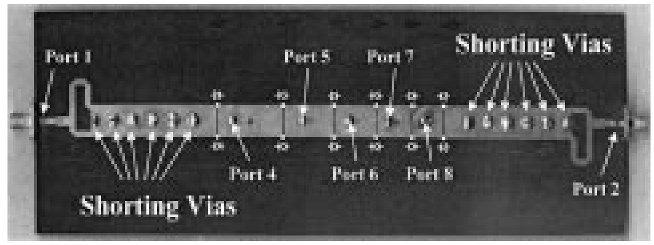

Fig. 3. Single reconfigurable leaky-wave/patch aperture. Diode positions are indicated by the white dots and their orientation by the diode symbols. The patch-antenna ports have been assigned out of order to correspond with intended design frequencies.

at 8.75 GHz. The use of shorting vias as the mode suppressor results in the characteristic leaky-wave pattern, with the backfire beam better than 12 dB down from the main beam. In contrast, the leaky-wave antenna utilizing transverse slots exhibits undesirable traits, showing a reflected backfire beam that is 8 dB down from the main beam. This degradation results from the reflection of the leaky-mode wave as it encounters the open circuit at the end of the microstrip line. Although this reflection is evident in both leaky-wave patterns, the effect is much more pronounced and acute when transverse slots are used as the mode suppressor.

To explore the issues associated with the patch-antenna aperture, a single reconfigurable leaky-wave/patch aperture is built, as shown in Fig. 3, and all p-i-n-diode switches (Agilent Technologies HPND-4005) are turned off. The structure is built on a 31-mil (0.7874-mm) substrate with a dielectric constant of 2.33. Ports 1 and 2 correspond to the leaky-wave antenna ports designed to operate between 8–10 GHz. The leaky microstrip line is segmented into patch antennas that are probe fed to operate at 4–8 GHz. For simplicity, these ports are denoted as ports 4–8, respectively. This first prototype should be distinguished from the one presented in [8], where the patch apertures were placed at the end of the leaky-wave antenna; in the old structure, most of the leaky-wave field has vanished due to radiation by the time the wave arrives at the patch ports.

In order to properly excite the patch antenna to resonate along its length L rather than the width W, the probe location must be carefully chosen to give a 50-Ω impedance match. For an isolated patch antenna, this value can be determined through various well-known techniques [14], [15]. Based on the symmetry of the patch antenna, four possible probe-feed locations exist for a 50-Ω impedance match. By noting that a null exists in the center of the leaky-wave field profile, we can ensure maximum isolation between the patch-antenna ports and the leaky-wave port by placing the feed to the patch-antenna port in the null of the leaky mode. Another consideration to account for is that the patches see an effective length $L_{\rm eff}$ that is longer than the physically etched patch length L. The added length arises predominantly from the loading effects due to adjacent patch antennas, and is significant enough to shift the operational frequency of the patch antenna by up to 10%. Therefore, the positioning of the probe feed must be made with respect to $L_{\rm eff}$ and not simply L. The shift in operating frequencies can be seen in Fig. 4. In this return-loss plot, the measured operating frequencies of the patch antennas have shifted down from the design frequencies

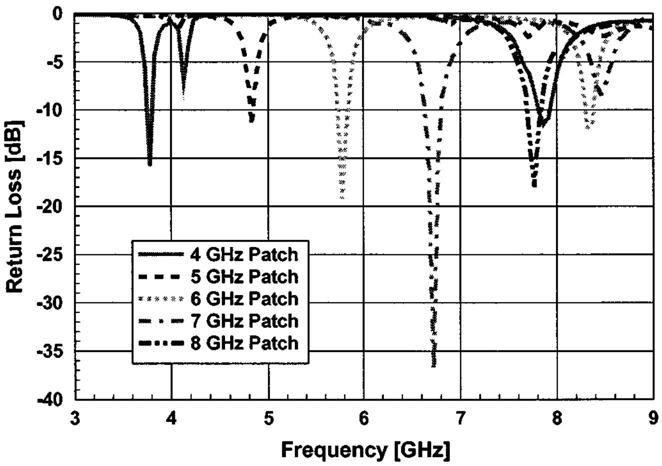

Fig. 4. Return loss of patch-antenna ports. Each curve corresponds to a different patch-antenna port.

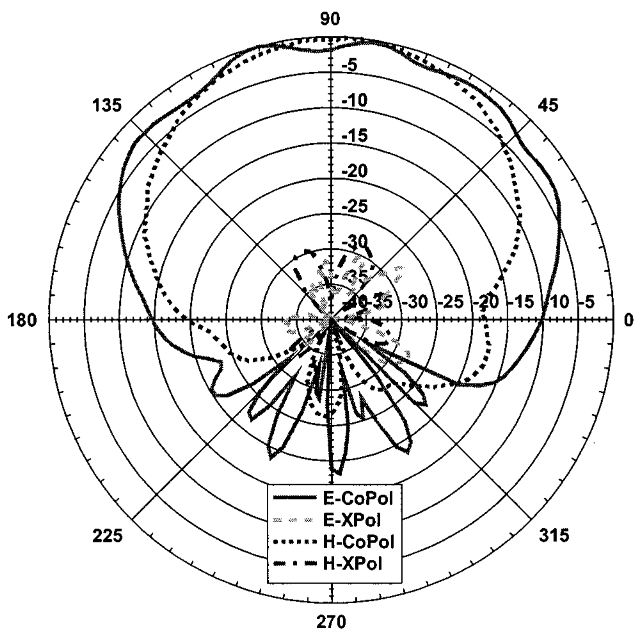

Fig. 5. Radiation patterns of port 6 patch antenna taken at 5.73 GHz.

due to the patch loading effect. The patch loading effect is also evident in the radiation patterns of the patch antennas, as seen in Fig. 5. For brevity, only radiation patterns for the 6-GHz patch are shown. The patch loading effect results in a small ripple in the E-plane of the radiated far-field. Nonetheless, the characteristic broadside radiation patterns of the patch antenna are still well defined, with backlobes below -18 dB and cross-polarization better than -27 dB. Table I summarizes the radiation characteristics for the remaining patch antennas. The results show excellent radiation characteristics at all frequencies, except at 8 GHz. For this frequency, the peak radiation no longer occurs at broadside, but rather at 45° and 135°, resulting in large cross-polarization.

An important parameter in any transmitting or receiving system is the isolation between the different ports. This requirement becomes more paramount in the case of the reconfigurable aperture, where one or more antennas are physically sharing

TABLE I
PATCH-MODE RADIATION CHARACTERISTICS

Port	Resonance	Backlobes	X-Pol
Port 4	3.83 GHz	< -15 dB	< -13 dB
Port 5	4.82 GHz	< -20 dB	< -22 dB
Port 6	5.77 GHz	< -17 dB	< -27 dB
Port 7	6.71 GHz	< -17 dB	< -22 dB
Port 8	7.76 GHz	< -15 dB	< -7 dB

TABLE II
APERTURE ISOLATION TABLE

S_{mn}	1	2	4	5	6	7	8
1	NA	-15.0	-67.2	-62.4	-51.2	-50.9	-46.3
2	-15.0	NA	-72.7	-56.7	-62.4	-36.3	-19.5
4	-12.4	-38.3	NA	-27.5	-38.8	-49.2	-41.2
5	-17.9	-32.6	-38.4	NA	-37.9	-36.0	-46.2
6	-24.7	-20.6	-34.3	-29.3	NA	-20.7	-33.1
7	-26.5	-15.7	-52.0	-27.9	-22.5	NA	-21.6
8	-24.8	-10.5	-34.8	-26.0	-31.2	-16.1	NA

the same aperture. Intuitively, one would think that a system of several antennas sharing the same physical aperture would have no sense of isolation whatsoever. However, the reconfigurable aperture utilizes the unique field profiles of the leaky-wave and patch apertures to provide isolation between the different ports in the various modes of operation. The minimum isolation values between the different ports in the first reconfigurable aperture are summarized in Table II. In Table II, the mth row represents the output port, while the nth column represents the input port. The scattering parameters represent the minimum isolation across the operating band of the input port. For example, S_{52} represents the minimum isolation between ports 5 (5-GHz patch port) and 2 (leaky-wave port 2) across the operating band of the leaky-wave antenna port 2. The shaded cells of Table II indicate measurements where the p-i-n-diode switches were turned off. The results show generally good isolation values between any two aperture ports. The minimum isolation between the two leaky-wave ports is better than 15.0 dB. This isolation is provided by the radiation of the leaky mode as it propagates along the microstrip line to the output leaky-wave port. The smallest isolation values are provided between the leaky-wave ports and the closest corresponding patch-antenna port ($S_{41} = -12.4$ dB and $S_{82} = -10.5$ dB). To ensure isolation better than 15.0 dB between the leaky-wave and patch-antenna ports, a good rule of thumb is to place the patch-antenna ports at least $2\lambda_0$ (at 8.75 GHz) away from the input to the leaky-wave antennas. With only this caveat in mind, the first prototype demonstrates that the patch antenna can be placed almost anywhere along the length of the leaky-wave antenna without much sacrifice in the performance of either the leaky-wave or patch-antenna apertures.

III. TWO-DIMENSIONAL RECONFIGURABILITY

The symmetry of the patch antenna suggests extending the reconfigurable leaky-wave/patch-aperture concept to two dimensions. Such flexibility would enable two-dimensional reconfigurable arrays like the one shown conceptually in Fig. 6. To this

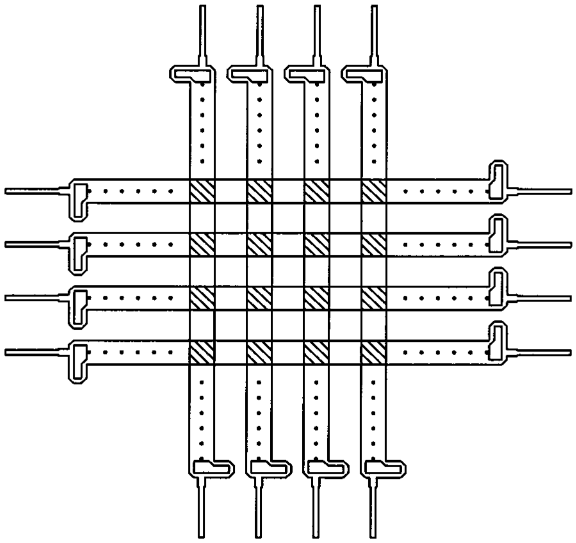

Fig. 6. Proposed two-dimensional reconfigurable leaky-wave/patch cross structure.

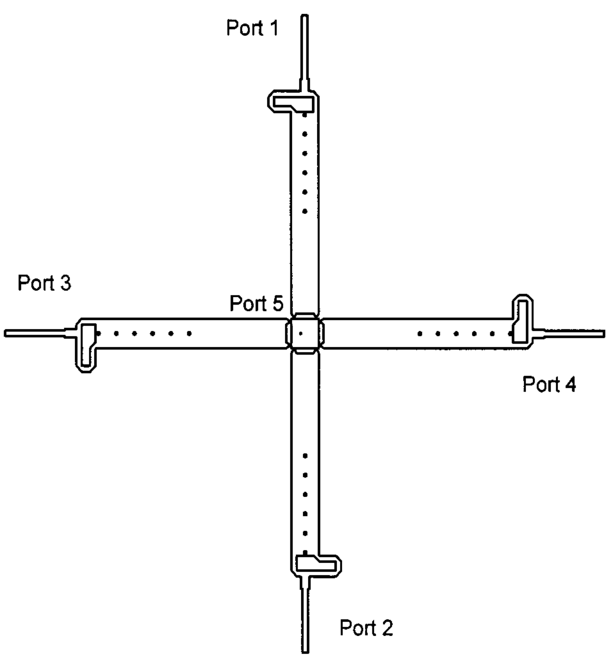

Fig. 7. Mask of multiport reconfigurable leaky-wave/patch cross structure.

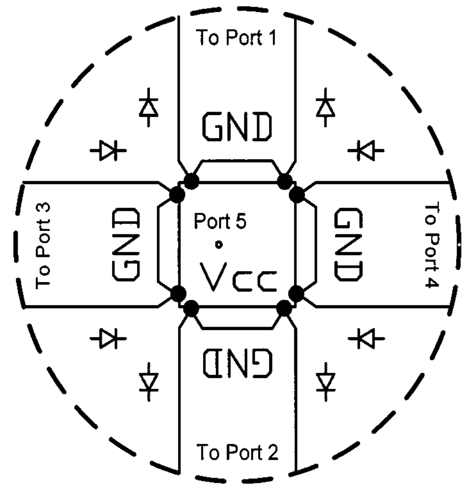

Fig. 8. Enlarged view of central patch section. Diode positions are indicated by the dots and their orientation by the diode symbols.

end, a second reconfigurable leaky-wave/patch-aperture prototype is built, as shown in Fig. 7. In this scheme, two reconfigurable dual-feed leaky-wave antennas are placed perpendicular to each other. The intersection of the two dual-feed leaky-wave antennas forms a probe-fed patch-antenna structure, with the resulting system forming the basis for a multiport antenna aperture. This reconfigurable cross aperture serves two main purposes. First, the structure expands upon our original reconfigurable aperture concept by employing five distinct antennas that are all physically sharing the same radiating aperture. To the author's best knowledge, this is the greatest number of antennas ever demonstrated to all physically share the same radiating aperture. Second, the cross aperture will demonstrate that each patch antenna can be reconfigured and shared with two degrees of freedom. This extends the functionality of the reconfigurable leaky-wave/patch concept, and can potentially be used to form a full two-dimensional reconfigurable leaky-wave/patch phased array.

The second prototype is also built on an RT/Duroid substrate with a dielectric constant 2.33 and a thickness of 31 mil. The multiport aperture is a five-port device, with ports 1–4 designated as the rotationally symmetric leaky-wave ports and port 5 as the probe-fed patch port. An enlargement of the central patch region is shown in Fig. 8. Eight p-i-n-diode switches separate the central patch structure from the four leaky-wave arms. Since shorting vias are used in each of the leaky-wave mode launchers, each of the leaky-wave arms is intrinsically grounded at dc. Due to the arrangement of the p-i-n-diode switches, only two leaky-wave ports can be turned on at any instant. For example, when a positive bias is fed through the patch-antenna port, all the vertically placed p-i-n-diode switches turn on, while the horizontally placed p-i-n-diode switches are off. The opposite occurs when a negative bias is fed through the patch-antenna port. When a ground bias is present, all switches are off and the aperture operates in the patch mode. As we shall see later, this arrangement intrinsically isolates any two leaky-wave arms that are perpendicular to each other. The p-i-n-diode switches that separate the central patch-antenna structure from each of the leaky-wave arms are deliberately placed along the edges of the leaky-wave antenna, where the leaky-mode field profile is maximum. This arrangement ensures minimal insertion loss of the leaky mode when the switches are turned on. Additionally, the metallization surrounding each p-i-n-diode switch has been tapered at the leaky-wave side of the p-i-n-diode switch. This is done so as to improve the isolation across each p-i-n-diode switch, while simultaneously minimizing the loading effects of the surrounding metallization on the central patch antenna. In order to preserve the current profile along the edges of the patch aperture, no tapering is done on the patch side metallization of the p-i-n diodes.

An investigation of the radiation patterns of the cross aperture demonstrates the effects of the p-i-n-diode switches. When all of the central p-i-n-diode switches of the cross aperture are

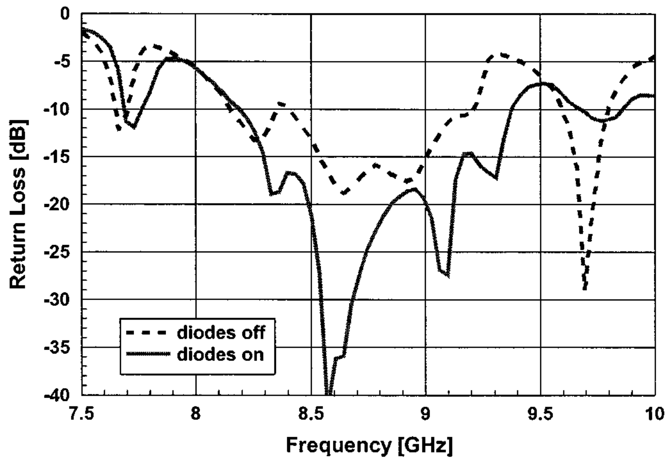

Fig. 9. Effect of p-i-n-diode switches on one leaky-wave arm of cross aperture.

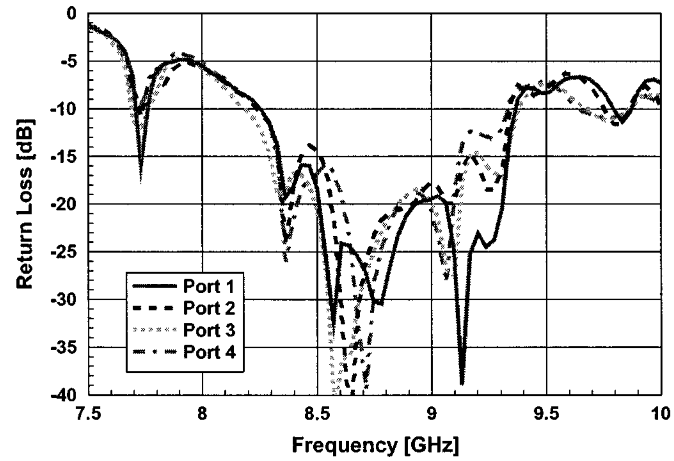

Fig. 10. Measured return loss of leaky-wave arms of reconfigurable cross structure.

TABLE III
CROSS-APERTURE ISOLATION

S_{mn}	1	2	3	4	5
1	NA	-15.0	-20.0	-20.0	-14.6
2	-15.0	NA	-20.0	-20.0	-14.6
3	-20.0	-20.0	NA	-15.0	-20.3
4	-20.0	-20.0	-15.0	NA	-20.3
5	-10.1	-10.1	-20.8	-20.8	NA

turned off, each leaky-wave arm has its effective radiating aperture length cut in half. This causes a strong reflection of the leaky mode, since the wave encounters an open circuit at the first pair of p-i-n-diode switches. As a result, a significant reflected backfire beam (−6 dB) is present in the radiation patterns of the leaky-wave antenna. When the appropriate p-i-n-diode switches are turned on, the effective length of each leaky-wave arm is restored in its entirety, more energy is directed into the forward main beam of the leaky-wave antenna, and the reflected backfire beam is greatly reduced (−17 dB). The operation of the p-i-n-diode switches is further demonstrated in Fig. 9, where the input return loss for one leaky-wave arm of the cross aperture is shown. When the switches are turned on, the input bandwidth at the leaky-wave port increases from 8% to 13% (voltage standing-wave ratio (VSWR) < 2). Additionally, the nulls in the plot are visibly deeper, indicating the input match for the leaky-wave port has improved noticeably.

The isolation between any two ports is recorded and presented in Table III for the reconfigurable cross aperture. When a positive or negative turn-on voltage is applied to the patch-antenna port, all the diodes in one direction (either horizontal or vertical only) are turned on, and we measure the isolation between two opposite arms. Similar to our first structure, we have better than 15-dB isolation since most of the excited leaky mode is radiated by the time the wave arrives at the output leaky-wave port. This level of isolation should improve as the length of the leaky-wave aperture is increased. Meanwhile, we expect better isolation between perpendicular arms, since the p-i-n-diode configuration utilized never allows a conducting path between perpendicular arms. This is exactly the case, as isolation is better than 20 dB in the operating band of the leaky-wave antenna between perpendicular arms. Finally, the most susceptible configuration is between any leaky-wave port and the patch-antenna port since the separation distance is the shortest between these two ports. Nonetheless, we see that across the operating band of the leaky-wave arms and in the resonant frequency of the patch antenna, isolation is measured to be better than almost 15 dB for the horizontal arms. This isolation is again possible because of the unique field profiles of the propagating wave. When the input signal is injected from the leaky-wave port, the first higher order odd mode of the microstrip line is launched. Since a null exists along the center line of the microstrip line for the odd mode, very little of the leaky mode is received at the patch port if the patch feed is placed along the null of the microstrip line. Conversely, when the input signal is launched from the patch port, all switches are off and the even resonant patch mode is intrinsically prohibited from propagating back to the leaky-wave ports. Any leakage of the patch mode is further suppressed by the vias of the leaky-mode launcher, which enforce a short circuit along the center line of the microstrip. For the vertical arms, the patch port is no longer in the null of the leaky mode and, consequently, the minimum isolation is poorer, being only better than about 10 dB for ports 1 and 2. It should be noted that these isolation values represent the intrinsic isolation of the antenna aperture itself. In system configurations where isolation requirements are much more stringent, additional switches or filters can be utilized at the input ports for better isolation.

The reconfigurable cross aperture demonstrates the multimode/multifunction characteristics of the reconfigurable leaky-wave/patch-aperture concept. Each of the leaky-wave arms provides moderate bandwidth of about 13% when the diodes are switched for leaky-mode operation, as seen in Fig. 10. An inherent trait of leaky-wave antennas is the ability to frequency scan the tilted main beam with relatively high gain (~12 dB) about the elevation angle. This is demonstrated in Fig. 11, where 25° of scan coverage is achieved about the elevation angle within the operating band of the leaky-wave antennas.

When a ground bias is fed through the probe-fed patch port, all of the p-i-n-diode switches are turned off and the multiport antenna operates solely in the patch mode. This is demonstrated in Fig. 12, where we have achieved an input match of −18 dB

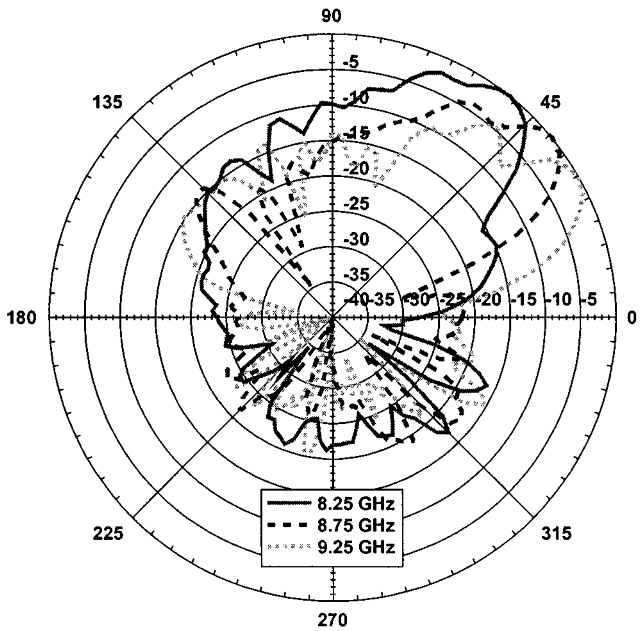

Fig. 11. Frequency scanning with each leaky-wave arm of reconfigurable cross structure.

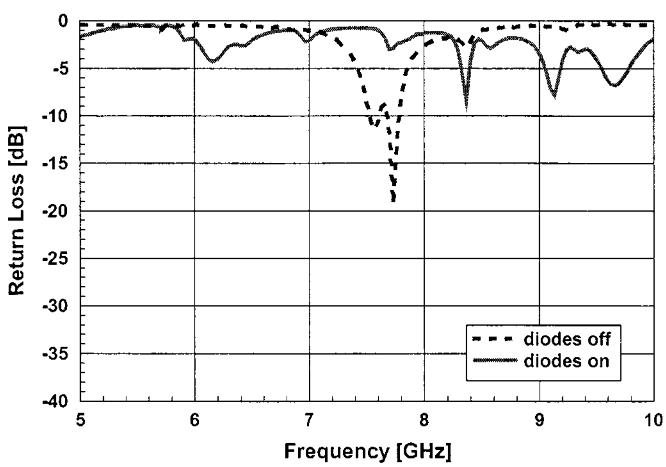

Fig. 12. Return loss of patch-antenna port of reconfigurable cross structure.

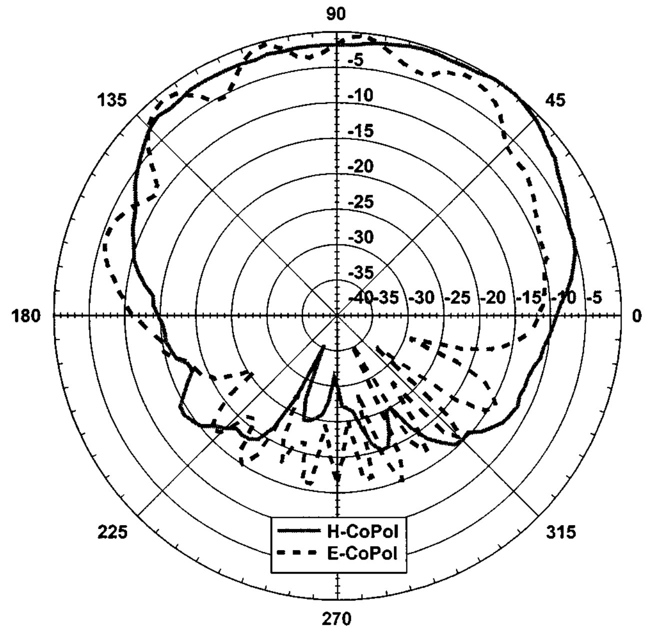

Fig. 13. Measured radiation patterns of reconfigurable cross structure in patch mode.

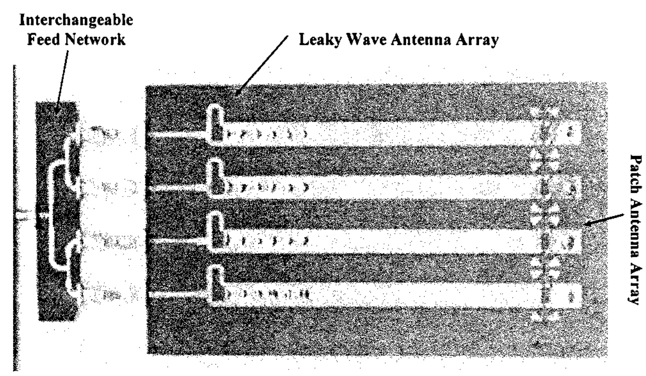

Fig. 14. Array structure used to demonstrate beam-steering capabilities of leaky-wave/patch aperture.

at the resonant frequency. Due to the combined loading effects of the p-i-n-diode switches and the surrounding leaky-wave antenna metallization, the resonant frequency has shifted from the design frequency of 8 GHz to 7.77 GHz. Despite the shift in frequency, the measured radiation patterns in Fig. 13 of the patch antenna are consistent with conventional patch patterns, despite showing a ripple in the E-plane due to the aforementioned loading effects. The resonant patch antenna offers broadside coverage with moderate gain, with backlobes better than -15 dB.

IV. Phased-Array Capabilities

We have already seen the flexibility of the reconfigurable leaky-wave/patch-aperture system. The combination of the frequency scannable leaky-wave antenna in conjunction with the broadside resonant patch antenna allows for excellent coverage about the elevation angle. The flexibility of the reconfigurable leaky-wave/patch aperture is further enhanced by the ability to phase scan both the leaky-wave antennas about

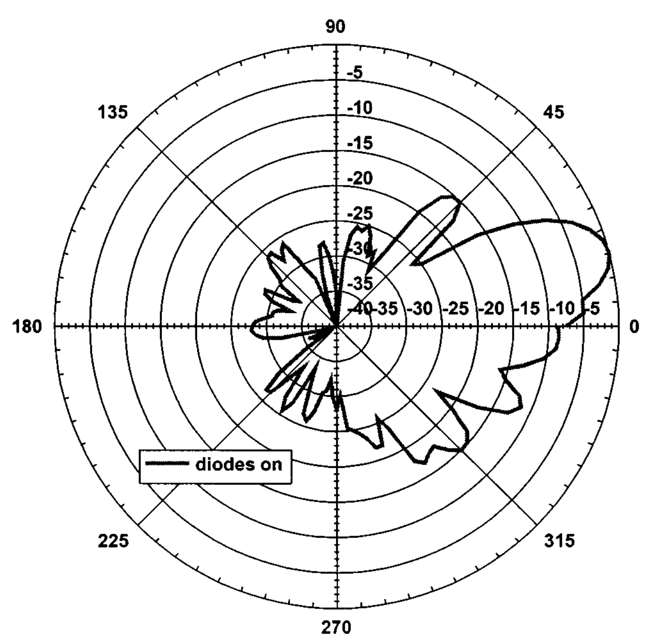

Fig. 15. Beam steering in elevated E-plane of leaky-wave array about azimuth angle.

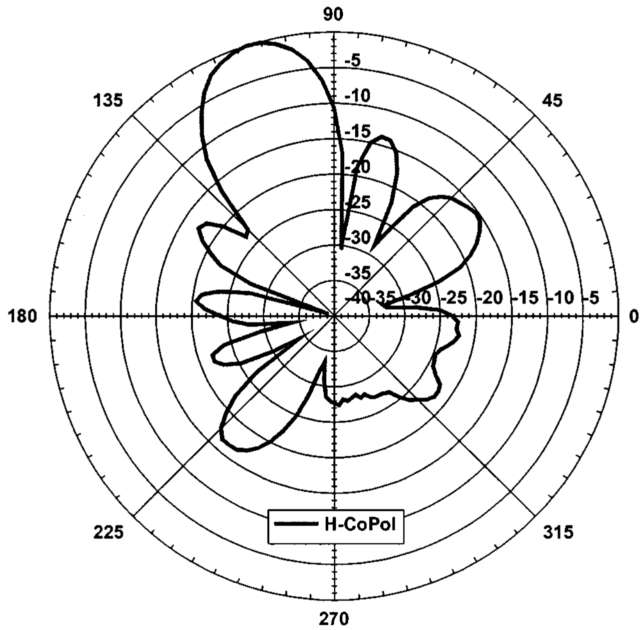

Fig. 16. Beam steering about broadside utilizing patch-antenna array.

the azimuth angle and the patch antennas about broadside. To demonstrate these abilities, a third and final test structure, as shown in Fig. 14, is built. In this scheme, four leaky-wave antennas form a linear array with an element spacing of $d = 0.79\lambda$ spacing. The ends of the leaky-wave antennas have been reconfigured into a patch-antenna array. For this proof-of-concept demonstration, an interchangeable feed network consisting of microstrip delay lines will be used to demonstrate the phase-scanning capabilities of the reconfigurable leaky-wave/patch-aperture array. The broad radiation pattern of the leaky-wave antenna's elevated E-plane lends itself as an excellent antenna array element candidate. When an equal-phase feed network is employed, the leaky-wave array forms a narrower main beam with a 30° 3-dB beamwidth and sidelobes remaining at least 15 dB down from the peak. By using a progressive phase shift, we can phase scan the main beam to obtain a 15° beam steer about the azimuth angle while keeping sidelobes better than 12 dB down from the peak, as seen in Fig. 15. The same beam scanning capabilities are also available through the patch-antenna array. The radiation patterns of the patch array using a progressive phase feed network are shown in Fig. 16. The patch array can be steered 20° about broadside while maintaining sidelobes that are at least 14 dB down from the peak. Finally, by employing the appropriate 180° phase shifts, difference patterns for radar applications can be obtained by both the leaky-wave and patch arrays.

V. Conclusion

A reconfigurable leaky-wave/patch microstrip aperture is presented and characterized. Inherent design issues associated with the aperture such as leaky-mode excitation and reflection, patch loading, and aperture port isolation have been investigated. Radiation patterns in each of the different states of the reconfigurable aperture are comparable to standard leaky-wave and patch radiation patterns. Each of the leaky-wave arms offers high gain, moderate bandwidth, and frequency scanning about the elevation angle, while the patch antenna offers broadside coverage and moderate gain. Combined together, the reconfigurable leaky-wave/patch aperture is a multimodal system that can operate at multiple frequency bands and provide excellent scan coverage at a reduced weight and size when compared to platforms utilizing multiple individual antennas.

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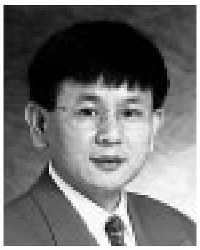
James Sor (S'00) was born in Battambang, Cambodia, in 1976. He received the B.S. and M.S. degrees in electrical engineering from the University of California at Los Angeles, in 1999 and 2000, respectively, and is currently working toward the Ph.D. degree in electrical engineering at the University of California at Los Angeles.

His research interests include leaky-waves, novel antenna structures, and periodic structures.

Chin-Chang Chang (S'00) received the B.S. and M.S. degrees in communication engineering from the National Chiao-Tung University, Hsinchu, Taiwan, R.O.C., in 1991 and 1993, respectively, and is currently working toward the Ph.D. degree in electrical engineering at the University of California at Los Angeles.

From 1996 to 1998, he was with Microelectronics Technology Inc., Hsinchu, Taiwan, R.O.C., as an Electrical Engineer, involved with the design of microwave frequency synthesizers and phase-locked oscillators. He was also engaged in the testing and development of very small aperture terminal (VSAT) transceivers for satellite communications. His current interests include microwave/millimeter-wave circuits and devices.



Yongxi Qian (S'91–M'93–SM'00) was born in Shanghai, China, in 1965. He received the B.E. degree from Tsinghua University, Beijing, China, in 1987, and the M.E. and Ph.D. degrees from the University of Electro-Communications, Tokyo, Japan, in 1990 and 1993, respectively, all in electrical engineering.

From 1993 to 1996, he was an Assistant Professor at the University of Electro-Communications. From April 1996 to January 2001, he was a Post-Doctoral Fellow, Assistant Research Engineer, and Lecturer in the Electrical Engineering Department, University of California at Los Angeles (UCLA). In February 2001, he joined the MicroWaveSys Division, Microsemi Corporation, Santa Ana, CA, where he is currently Director of Technology and Applications with a focus on advanced heterojunction bipolar transistors (HBT) integrated circuits (ICs) for third-generation (3G) wireless LAN and high-speed fiber-optic applications. His research interests have included numerical techniques for microwave and millimeter-wave circuits and antennas, generation and transmission of picosecond electrical pulses, crosstalk problems in high-density monolithic microwave integrated circuits (MMICs), miniature circuits for mobile communications, 60-GHz millimeter-wave focal plane imaging array, broad-band planar antennas, smart antennas and arrays for wireless communications, high-efficiency microwave power amplifiers, RF interconnect for mixed-signal silicon MMICs, quasi-optical power combining, photonic bandgap (PBG) structures, active integrated antennas for indoor LANs, and high-power broad-band RF photonic devices for millimeter and submillimeter-wave photomixing. He has authored or co-authored over 200 refereed journal and conference papers, two books, and several book chapters.

Dr. Qian was the recipient of the 1998 Japan Microwave Prize presented at the Asia–Pacific Microwave Conference, the 1999 Best Student Paper presented at the 29th European Microwave Conference, and the 2000 ISAP Paper Award presented at the International Symposium on Antennas and Propagations.

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 with 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 Microwave Theory and Techniques Society (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 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.