1996 International Symposium on Phased Array Systems and Technology — *Highlights* —

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INTRODUCTION

The very successful 1996 IEEE International Symposium on Phased Array Systems and Technology was held in the Boston, Massachusetts area, October 15-18, 1996. Over 500 attended and 92 papers were presented by authors from 16 countries. The following sections highlight several exciting papers presented at the symposium. Included are several papers on active MMIC (Monolithic Microwave Integrated Circuit) arrays, and research and development papers on electronically steered laser (optical) beams, digital beamforming (DBF), ferroelectric scanning, RADANT lens, (an electronically rotated and tilted plasma mirror antenna) and finally, a C- to Ku-band multi-user shared aperture MMIC array.

EXCITING NEW ERA OF MMIC PHASED ARRAYS

Electronically scanned phased arrays are entering a new era with the intense development and deployment of active MMIC phase-phase scanned arrays, i.e., arrays that scan in two dimensions. This was well illustrated at the symposium by numerous papers on the subject. I have chosen some of these for discussion.

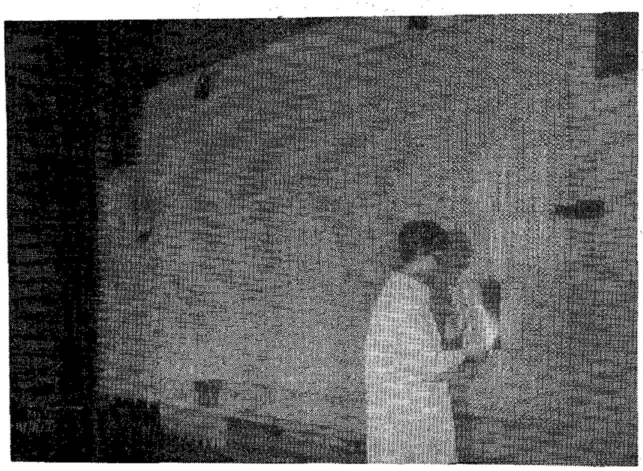

Fig. 1. 25,000 Element X-Band MMIC Array for Theater High Altitude Area Defense (THAAD; Formerly GBR)
Photo Courtesy of Raytheon

THAAD (GBR) MMIC Phased Array

One outstanding paper was given by Sarcione, et. al., [1]. He described the Theater High Altitude Area Defense (THAAD; formerly called GBR) X-band ground based radar which has 25,344 MMIC T/R modules and radiating elements; see Figure 1. Three of these systems have been built. The first was half populated with radiating elements and modules; while the second and third were

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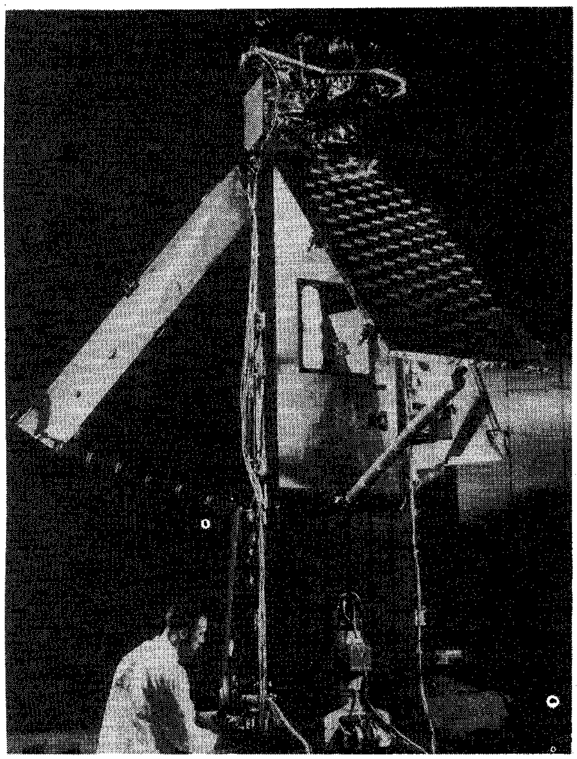

Fig. 2. Three L-Band MMIC Array Panels Deployed on IRIDIUM® Satellite
Photo Courtesy of Motorola

fully populated. A total of over 60,000 MMIC T/R modules have been built for those systems. This program demonstrated that MMIC T/R modules could be manufactured for less than $1,000 each by the end of the production run. It was pointed out in the lead paper by Ellot D. Cohen [2], formerly head of the MIMIC (Microwave and Millimeter Wave Monolithic Integrated Circuits) Program, that the early technology base for the GaAs T/R module was derived from the ARPA/Tri-Service MMIC Program. Many more THAAD systems are planned to be built.

Space Age Telecommunications MMIC Phased Arrays

A second outstanding paper highlighting the development of active MMIC phase-phase electronically scanned arrays is that by Schuss, et al., [3]. He described the revolutionary new IRIDIUM® commercial global satellite personal communication system which uses low orbiting satellite constellation that employ active phased arrays populated with MMIC modules [3]. This commercial communication satellite system is in production and will involve large numbers of phased arrays and MMIC modules. The IRIDIUM® constellation consists of 66 satellites in six circular 700 km altitudes near polar orbits (eleven satellites per orbit). The constellation provides coverage for global communications. Each satellite has three antennas pointed toward the Earth for horizon-to-horizon coverage [3]. The antennas are active L-band (1.6 (GHz) phased arrays using about 100 MMIC T/R modules and patch radiating elements. As a result, there are about 20,000 MMIC T/R modules and radiating elements per constellation. A subscriber holds a hand-held phone (similar to those used for the conventional cellular phone systems) which communicates directly with one of the satellites. In turn, the signal is cross-linked to other satellites for final passage down to the Earth to another subscriber with a hand-held IRIDIUM® phone or to a gateway which directs the call to a conventional telephone user via land lines. Alternately, the signal could be transmitted directly down from the satellite to a user in view of the same satellite as the first user. Figure 2 shows the three L-band active phased arrays mounted on the IRIDIUM® spacecraft bus for testing in an anechoic chamber.

There has been much talk about the transfer of military technology to the commercial world, especially with the end of the cold war. It was pointed out in the Introductory Comments by Brookner [4] that the IRIDIUM® Space Based L-band antenna is derived from the Air Force's and Navy's Space Based Radar Program. The Space Based Radar was originally being developed for surveillance of CONUS or the US Fleets to warn of possible attack by USSR bombers [33]. The lightweight (one ounce) L-band module developed by the Air Force for the SBR Program forms the basis for the IRIDIUM® L-band module. The SBR was never deployed by the Air Force and Navy because of the end of the cold war and also because of the expense of building the system. It is nice to see the IRIDIUM® system taking its place for a total low cost of $3.5 billion dollars, including the cost of satellite, ground stations and software.

Brookner [4] also mentioned that high data rate digital communication systems (like 1 Mbps) for computer to computer and video confronting communications are following on the heels of the IRIDIUM® and other video telephone communication systems. One such system is the Teledesic Low Orbiting Satellite System which plans to use about 840 satellites. One possible implementation of this system would require 120 arrays per satellite, each needing 400 MMIC T/R modules and radiating elements for a total of 40 million MMIC T/R modules and radiating elements for constellation — a phased array engineer's and MMIC engineer's dream. The seed money for the Telsdesic system is being provided by William Gates of Microsoft and Craig McCaw, formerly of McCaw Cellular Communications. The only other system this writer has seen that requires a larger number of MMIC modules is one proposed by an engineer at the Jet Propulsion Lab for voice communications. For this system, each user would have a phased array antenna on top of his head. If each of these antennas required 100 radiating elements and MMIC T/R modules, and one billion of the world's population received one; the total number of MMIC modules and radiating elements that would need to be manufactured is one hundred billion — wishful thinking!

Other Ground Based and Airborne MMIC Arrays

The development of active MMIC array systems is not just occurring in the US, it is happening worldwide — as pointed out by Brookner [4], and the papers that followed. One sees that with the development of the COBRA (COunter Battery RAdar) Artillery and Mortar Weapon Locating System by a consortium of Lockheed-Martin (US), Siemens AG (Germany), Thomson-CSF (France), and Thorn EMI (England) [4, 5]. This system has 2,700 MMIC T/R C-band modules and radiating elements in its antenna. Three of these systems have been built.

Other examples are seen in the development by a number of countries of active phased arrays using MMIC T/R modules for fighter aircraft [4]. These are: the USA for the F-22 fighter [4]; Japan for the FSX, [4, 6]; the consortium of France, Germany and the United Kingdom developing the Airborne Multi-Roll Solid-State Active Array Radar (AMSAR) [7]; and finally Sweden, for the Active Electronically Scanned Array Antenna (AESA) [8]. All of these are X-band. It is planned to build 424 F-22 X-band MMIC phased arrays for a total of about a million MMIC T/R modules [4].

Colin [6] described a very aggressive effort wherein MMIC was taken to the point of wafer integration — 4" wafers. Specifically, Thomson-CSF is developing a missile seeker antenna which uses two 4" wafers. One wafer is imprinted with the dipole elements and one bit PIN diode phase shifters. The second 4" wafer contains the driving circuits which are linked to the first wafer through bumps. The antenna has 3,000 elements; the beam width is 2°; and can be steered ±45°. They have reported having obtained low sidelobes.

RESEARCH AND DEVELOPMENT PHASED ARRAY PAPERS

Electronically Steered Phased Array for Laser and Optical Beams

Dorschner, et al., [24] demonstrated an electronically steered phased array for laser and optical beams. This array (which he carries around in a briefcase) represents a major breakthrough in the scanning of laser and optical beams. The technique uses two liquid crystal sheets. One sheet consists of N columns of liquid crystal phase shifters, $\lambda/2$ apart; used to scan the beam in azimuth while the other consists of N rows of liquid crystal phase shifters, again $\lambda/2$ apart; used to steer the beam in elevation. The phase gradient is produced by stopping the voltages across the liquid crystal columns and rows of phases shifters. By using row/column steering; instead of element-by-element steering the number of phase shifters and controls is reduced from N^2 to 2N; a reduction of N/2. Further reduction is achieved by using coarse/fine steering. In production, the cost per phase shifter for an optical phased array would be pennies [24].

Digital Beamforming (DBF)

There were seven fine papers dealing with digital beamforming [12, 14, 25-29]. The excellent paper by Pettersson [25] of Sweden describes a National Defense Research Establishment experimental S-band antenna operating between 2.8 and 3.3 GHz which does digital beamforming using a sampling rate of 25.8 MHz on a 19.35 MHz IF signal. The advantages of using IF frequency sampling rather than baseband sampling is that one does not have to worry about the imbalance between the two channels, that is, the I and Q channels, or the DC offset. They demonstrated that by using digital beamforming they could compensate for amplitude and phase variations that occur from element-to element across angle and across the frequency band. Via a calibration they were able to reduce an element-to element gain variation due to mutual coupling from ±1 dB to about ±0.1 dB. Using equalization, they were also able to reduce a ±0.5 dB variation in the gain over the 5 MHz bandwidth to about a ±0.05 dB variation. With this calibration and equalization, they were able to demonstrate sidelobes of 47 dB peak over a 5 MHz bandwidth. A 50 dB Chebyshev weighting was used. They demonstrated that the calibration was maintained fairly well over a period of two weeks. This work demonstrates the potential power offered by digital beamforming.

Garrod [26] of England described an experimental 13 element array using digital beamforming on transmit as well as on receive. This experimental system uses the Plessey SP2002 chip running at a 400 MHz rate as a digital waveform generator at every element. Doing digital beamforming on transmit allows one to put nulls in the direction of an Arm threat or where there is high clutter.

[12] described the use of a systolic array for DBF while [27] utilized the CORDIC algorithm.

Row/Column Ferroelectric Scanned Array

Rao, et al., [30] (of the Naval Research Laboratory, NRL) describes a technique for achieving a low cost phase-phase steered array at microwave frequencies by using row/column phase shifters just as was done at optical frequencies by Dorschner, et al., [24] above. Instead of rows and columns of liquid-crystal phase shifters, rows and columns of ferroelectric phase shifters are used. The dielectric constants of the rows and columns of the ferroelectric phase shifters are determined by the voltages placed across these rows and columns of ferroelectric material. Consequently, by applying an appropriate stepping of this voltage, a phase gradient is generated to steer the beam in elevation and azimuth just as done for the optical phased array scanner. Considerable work is necessary before a practical ferroelectric phased array is produced. This work is presently ongoing at NRL.

Low Cost Hybrid Row/Column Scanned Array and the RADANT Lens

Rao, et al., [30] described work on a hybrid technique for achieving row/column steering. This is an antenna that uses an array of columns of slotted waveguides having one phase shifter per column in order to steer the beam in azimuth ±60°. Following the slotted waveguide antenna is a RADANT lens antenna for steering the beam in elevation. The RADANT antenna consists of diodes sandwiched between parallel horizontal conducting plates. The velocity of propagation between each horizontal pair of conducting plates is dependent on the number of diodes switched on or off in the direction of propagation. By controlling this number, a phase gradient is produced in the vertical diffraction for steering the beam in elevation ±45°.

Colin [5] indicated that Thomson-CSF has developed a RADANT antenna for the DASSAULT Aviation RAFALE Multi-Roll Combat Aircraft. This system uses two RADANT lens antennas in cascade in order to steer the beam in azimuth and elevation.

Electronically Steerable Plasma Mirrors Antenna

Matthew [31] of NRL described a 50 cm × 60 cm plasma mirror that can be electronically rotated and tilted so as to steer a beam in azimuth and elevation.

C- to Ku-Band Multi-User Shared Aperture MMIC Array

Hemmi, et al., [32] of the Naval Air Weapons Center (NAWC) and Texas Instruments described their development work for a phased array for a strike/fighter aircraft that could be shared by many users. Specifically they are developing a broadband array having continuous coverage from C-band through Ku-band that would share the functions of radar, passive ESM (Electronics Support Measures), active ECM (Electronic Counter Measures) and communications. To achieve this wide bandwidth, a flared notch radiating element is used. Cross notches are used so that horizontal, vertical or circular polarization can be obtained. They have built a solid state T/R module that provides coverage over this wide band from C-band to Ku-band, continuously. The module has a power output of 2 to 4 W per element over the band; a noise figure between 6.5 and 9 dB over the band; and a power efficiency between 5.5 and 10% over the band. A 10 × 10 element scanned array having eight active T/R modules was built for test purposes. A typical full-up array would be approximately 29" wide by 13" high. With this type of array, it would, ultimately, be possible to use, simultaneously, part of the array as a radar, part of the array for ESM, part of the array for ECM and part of the array for communications. The parts used for each function would change dynamically depending on the need. Also these parts could be non-overlapping or overlapping, depending on the need.

SURVEY PAPERS AND SYSTEM PAPERS FROM AROUND THE WORLD

There were many excellent survey papers from around the world, covering the work on phased arrays in the county from which the authors came — Italy by Palumbo [9]; Japan by Rai, et al., [6] and by Samejima [10] (see also [11-16]); Russia by Skobelev [17]; and by Corey [18] (see also [19]); China by Guangyi [20]; France by Colin [5]; and Australia by Founkis [21]. Dryer, et al., [22] of Israel presented a paper on Tactical Ballistic Missile L-band solid state active array system; Smolders [23] of The Netherlands presented a paper on 4096-element X-band phased array intended for use as a four-faced active solid state array on-board ships.

CONCLUSION

There were many other excellent papers. The reader is referred to *Symposium Proceedings* for more detailed coverage of the many papers that were presented. The organizers and contributing authors of this symposium are congratulated on a job well done. Everyone looks forward to another International Phased Array Symposium in the near future.

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