

# AN ACOUSTO-OPTICALLY CONTROLLED PHASED ARRAY BEAMSTEERING SYSTEM

by

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## ABSTRACT

A novel acousto-optic beamsteering control system for MMIC-based phased array antennas which utilizes parallel optical signal processing is presented. The approach is compatible with existing MMIC digital phase shifter and gain controller designs and offers several advantages over conventional beamsteering control systems. An overview of the system architecture, comparison to other beamsteering control alternatives, discussion of several key design issues, and experimental results validating the approach are highlighted.

## INTRODUCTION

Active phased array antenna systems are currently under development for modern communication and radar systems. These systems may potentially incorporate thousands of active antenna elements and will require high levels of beam agility in order to satisfy stringent operational requirements. Transmit/Receive (T/R) modules which use MMIC digital phase shifters and gain controllers currently offer the best alternative to achieve these goals. These devices require digital control commands which must be provided in a reliable, efficient, timely, and cost effective manner. Conventionally, a beamsteering controller (BSC) is employed to compute and distribute the necessary beamsteering commands to the array T/R modules in a digital fashion. However, the BSC design becomes difficult for large arrays which may have thousands of active radiating elements with as many as seven bits of phase and/or gain control. The beamsteering controller design is further complicated as the array operating frequency increases, which results in reduced inter-element spacings. In this case, the beamsteering controller must be designed to operate within strict size constraints while avoiding both electrical and physical interference with other array subsystems such as DC, microwave, and cooling manifolds.

A novel beamsteering control technique is described in this paper which employs parallel optical signal processing within an acousto-optic cell to control MMIC digital phase shifters and/or gain controllers. This technique is compared to conventional beamsteering control alternatives followed by an overview of several key design issues. Experimental results are then presented based on a four channel laboratory beamsteering control system. This approach is compatible with existing MMIC phase shifter designs, may be applied to a wide range of phased array systems, and offers compatibility with the rapidly growing field of parallel optical signal processing.

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## DESCRIPTION

The acousto-optic beamsteering control architecture utilizes a combination of digital and optical technology to compute and distribute the beamsteering control information [1]. The system block diagram is shown in Figure 1.

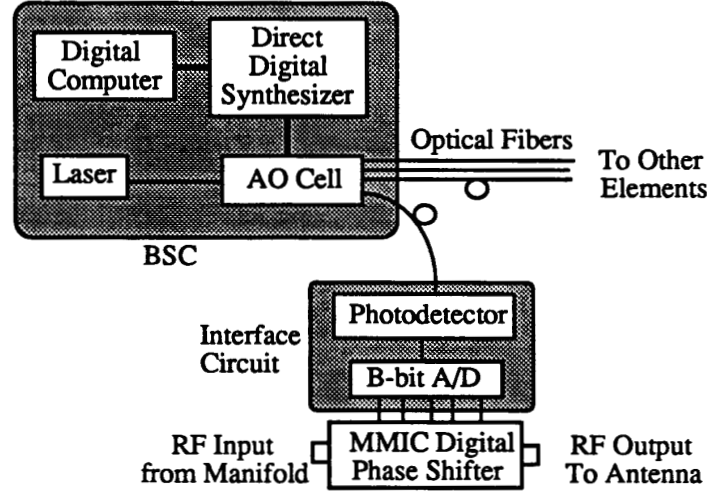


Figure 1. Acousto-Optic Beamsteering Control System Block Diagram

In this approach, a digital computer calculates the required phase and amplitude settings for the array. This information is used to generate a multi-tone AO cell drive signal, consisting of  $M$  frequencies, where the amplitude at each frequency is related to the required phase or amplitude setting of an individual T/R module. The AO cell transducer converts this signal to longitudinal acoustic waves which modulate the AO cell index of refraction,  $n(x,t)$ . This index variation may be expressed by

$$n(x,t) = n_0 + \sum_{m=1}^M n_m \sin[(\omega_m t - K_m x) + \delta_m]$$

where  $n_0$  is the unperturbed index of refraction,  $\omega_m$  and  $K_m$  are the angular frequency and wavenumber of the acoustic signal, and  $n_m$  and  $\delta_m$  are the amplitude and phase of the refractive index modulation of the  $m$ th signal. A laser illuminates an acousto-optic cell at the Bragg angle,  $\theta$ , which is given by

$$2 \sin \theta = \frac{\lambda_o}{n_o \Lambda_s}$$

where  $\lambda_o/n_o$  is the optical wavelength in the AO cell and  $\Lambda_s$  is the acoustic wavelength corresponding AO cell center frequency. Photon-phonon interactions result in an optical output consisting of  $M$  first order diffracted beams where each beam is associated with a separate frequency. Moreover, the intensity of each beam is linearly proportional to the power of it's corresponding tone [2]. Each beam is then coupled to a separate optical

fiber which transmits the optical intensity to an assigned T/R module. An interface circuit at the T/R module, consisting of a photodetector and an A/D converter, converts the optical intensity to an analog voltage which is digitized and interfaced to the T/R module to provide the required digital command to the microwave phase shifter and/or gain controller. In this manner, the intensity level of the incident optical input sets the phase and/or amplitude to the required value.

The laser, AO cell, and driver, which comprise the most complex portion of this beamsteering system, would be located remotely from the array. In addition, the acousto-optic cell and fiber coupling could be realized compactly and reliably in integrated optics [3,4]. Likewise, a direct digital synthesizer (DDS) could be used to drive the AO cell in a precise fashion. The digital interface circuitry at the T/R module is fairly simple and may be designed such that the A/D output is directly compatible with the negative control voltages typically associated with MMIC phase shifters. The A/D requirements are modest, requiring a maximum of six to seven bits for even the most stringent applications. Furthermore, the speed requirements for both the A/D and optical detector are also modest since the digital command is derived from a single analog optical intensity which changes at the beamsteering rate which may be on the order of 200 to 600  $\mu$ s [5]. It is also possible that the entire digital interface circuit may be monolithically integrated such that a single chip development may be used for a wide variety of systems. Alternatively, the interface circuitry may be integrated on the same chip as the MMIC control circuits allowing the MESFET to be used as the optical detector [6].

### COMPARISON OF BEAMSTEERING CONTROL ARCHITECTURES

Conventional beamsteering control techniques are based solely on digital methods to compute and distribute beamsteering commands. The centralized and distributed beamsteering control architectures and are shown in Figure 2.

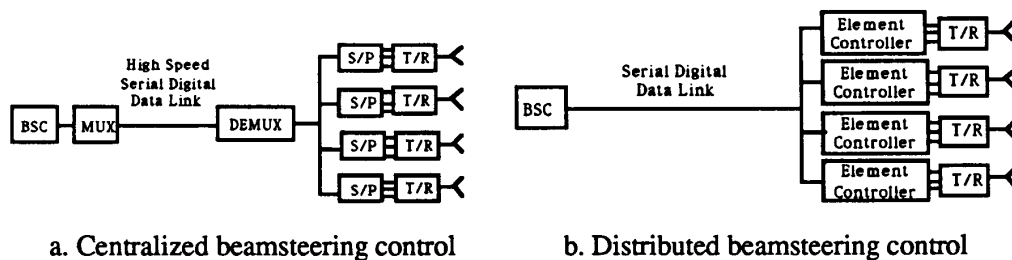


Figure 2. Conventional Beamsteering Control Architectures

In centralized beamsteering, shown in Figure 1a, the BSC calculates the phase and gain settings for every array element based on a desired beamsteering angle. These settings are then mapped into digital control data for the T/R module phase shifters and gain controllers. This data is multiplexed onto a high speed serial digital data link where it is demultiplexed at the array and distributed to the appropriate T/R module. A serial to parallel converter (S/P) then converts the demultiplexed data to a parallel format which is interfaced to the microwave control circuitry.

The distributed beamsteering approach provides a "smart" interface at the T/R module, and is shown in Figure 1b. In this case, a common beamsteering angle command is simultaneously distributed to all of the array T/R modules where a T/R module element controller calculates the required amplitude and phase settings based on the position of

the module in the array lattice. Specific phase shifter and gain controller commands are then derived based on this information.

Table 1 shows a general comparison of the centralized, distributed, and acousto-optic beamsteering control approaches based on an assessment of their relative complexity at three points in the phased array system.

Beamsteering Architectures	Complexity at the Remote BSC	Complexity between the BSC & the T/R Modules	Complexity at the Array Face
Centralized Beamsteering	Medium	High	Medium
Distributed Beamsteering	Low	Low	High
Acousto-optic Beamsteering	High	Low	Low

Table 1 Comparison of Beamsteering Control Alternatives

Centralized beamsteering is conceptually the simplest approach with all beamsteering computation and module calibration data performed and stored at the BSC. Unfortunately, data rates become prohibitively high for large arrays since the communication time from the BSC to the T/R modules linearly with the number of array elements. This which necessitates the use of a dedicated computing element for each row or column of the array [5].

Distributed beamsteering control is attractive since it greatly simplifies the digital interface from the BSC to the T/R modules, reduces communication time from the BSC to the T/R module, and allows module specific calibration data to be stored in the element controller [5]. However, each T/R module requires an element controller which significantly increases the complexity, power requirements, and thermal dissipation at the array face and should be avoided since tight lattice spacings, mutual compatibility with other radar subsystems, and thermal management pose difficult phased array antenna challenges.

The acousto-optic beamsteering control technique offers reduced complexity and communication time between the BSC and the T/R modules (which are associated with distributed control) while also providing minimal complexity at the array face. This is possible since parallel optical signal processing, performed within the AO cell, generates and distributes beamsteering control commands simultaneously to a number of T/R modules. Calibration data would be stored at the BSC as in the centralized beamsteering approach. The interface from the AO cell to the T/R modules is very simple, consisting of a single optical fiber for each module which provides a small, lightweight, and flexible signal distribution medium which is immune from the effects of electromagnetic interference (EMI).

Several aspects of the acousto-optic beamsteering system are highlighted in this section. These include, dynamic range requirements, channel capacity requirement, and the effects of noise on a single channel as well as on the overall phased array antenna system.

### AO BEAMSTEERING PERFORMANCE ISSUES

Unlike the centralized and distributed beamsteering control architectures, the acousto-optically controlled beamsteering technique generates the digital phase shifter commands from the quantization of an analog signal. Therefore, the viability of this technique depends on a number of factors including the precision to which the A/D input voltage can be optically controlled, the number of phase shifters which can be controlled by a single acousto-optic cell, the effects of noise on the ability to correctly issue beamsteering commands.

The optical intensity in each diffracted beam must be controlled such that the input of the A/D is an integer number of quanta as shown below.

$$V_{A/D} = k q \quad ; \quad 0 < k < 2^B - 1$$

where  $q$  is the quantization level of the A/D. The quantization level is given by

$$q = \frac{V_{FS}}{2^B}$$

where  $V_{FS}$  is the full scale unipolar input voltage,  $B$  is the number of A/D bits, and  $2^B$  is the number of discrete voltage levels. Since the intensity of each diffracted beam is linearly proportional to the AO cell drive power and the photodetector current is linearly proportional to the optical intensity, the dynamic range, DR, requirements for the AO cell driver, AO cell, and photodetector is given by

$$DR = 3.01 B \quad (\text{dB})$$

This dynamic range requirement also affects the beamsteering control system channel capacity, which is equal to the number of phase shifters which may be independently controlled using a single AO cell. Typically, the resolution criteria associated with acousto-optic cells is given by the number of spots,  $N$ , which is a measure of the beam deflection angle,  $\Delta\theta$ , to the beam diffraction angle,  $\theta_{\text{diff}}$ , and correspond to the  $e^{-2}$  points of the Gaussian laser beam intensity profile. However, a modified resolution criteria is required to specify the channel capacity for the acousto-optic beamsteering system which takes into account the dynamic range requirement. This results in a channel capacity,  $P$ , which is

$$P = \frac{\Delta\theta}{2\theta_{\text{DR}}} \cong \frac{2.7 w_0}{V_s \sqrt{B}} \Delta\nu$$

where  $w_0$  is the beam waist of the Gaussian laser beam,  $V_s$  is the velocity of sound in the AO crystal, and  $\Delta\nu$  is the bandwidth of the AO device. The effective channel capacity is directly proportional to the AO cell bandwidth and inversely proportional to the square root of the number of phase shifter bits. This may be related to the number of spots,  $N$ , by

$$P = \frac{1.35}{\sqrt{B}} N$$

The number of channels is approximately one half of the number of spots for an application requiring a seven bit phase shifter. However, since commercially available AO cells may provide as many as several hundred spots, many array elements can still be controlled by a single device.

The effects of quantization and noise must be also considered on both the ability to issue a correct phase shifter command and the resulting phased array beam pattern in the event of an incorrect command(s). The ability to correctly control a single phase shifter depends on the A/D input noise level as well as the precision to which the A/D input voltage can be optically controlled at each of the  $2^B$  discrete intensity levels. The A/D input noise contains contributions from various sources including the AO cell driver, laser, and photodetector. Assuming that the A/D input voltage may be controlled within a fraction,  $x$ , of a desired quantization level (ie.  $V_{A/D} = xq$  for each A/D state), and Gaussian noise statistics, the probability of issuing a correct phase shifter command,  $P_C$ , may be expressed as

$$P_C = \frac{1}{2} \left\{ \operatorname{erf} \left[ \frac{q}{\sqrt{2} \sigma_N} (0.5 - x) \right] + \operatorname{erf} \left[ \frac{q}{\sqrt{2} \sigma_N} (0.5 + x) \right] \right\}$$

where  $\operatorname{erf}(z)$  is the error function of  $z$ , and  $\sigma_N$  is the standard deviation of the noise. This expression is plotted in Figure 3 for various ratios of quantization level to noise.

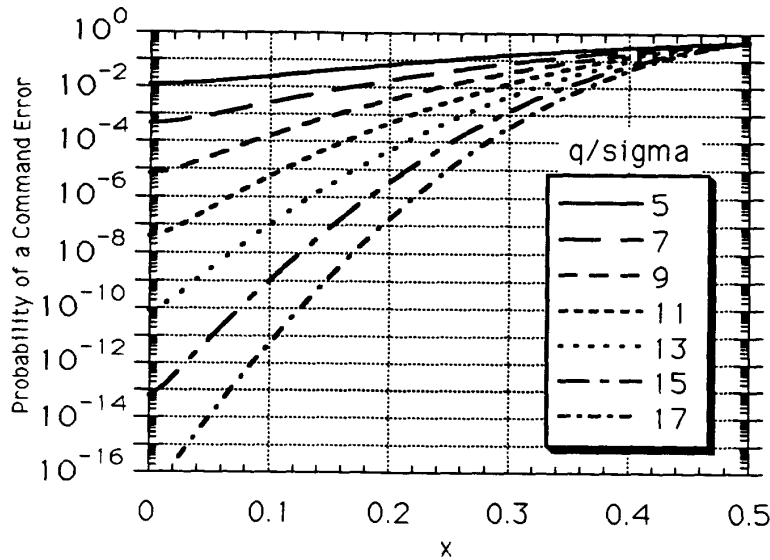


Figure 3. Probability of Obtaining a Correct Phase Shifter Command

As evident from Figure 3, the probability of generating an erroneous command for a given A/D input voltage tolerance decreases with increasing  $q/\sigma_N$  and decreasing  $x$ . For example, if the input voltage can be controlled to within  $\pm q/10$  of the center of a quantization level for  $q/\sigma_N=15$ , the probability of obtaining a command error is  $10^{-9}$ .

The noise performance specification, however, should be determined in the context of overall array operation such that the antenna pattern is not degraded by the acousto-optic beamsteering system. Assuming statistically independent noise at each phase shifter, the probability of setting all of the phase shifters correctly is given by:

$$P_{\text{all}} = \prod_{i=1}^N P_c$$

Likewise, the probability that at least one phase shifter is set incorrectly is given by:

$$P_1 = 1 - \prod_{i=1}^N P_c$$

This expression is plotted vs. the number of array elements,  $N$ , in Figure 4 for the particular case that the input voltage is set to within  $\pm q/10$  of the center of a quantization level ( $x = 0.1$ ).

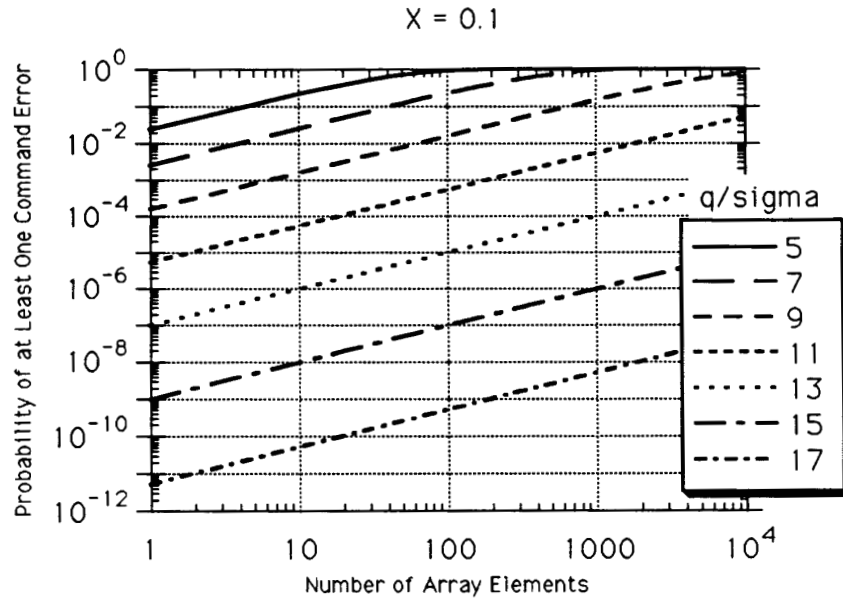


Figure 4. Probability of a Command Error vs. the Number of Array Elements

Clearly, tighter tolerances are required to maintain high levels of command error free performance in large arrays. However, since phase errors at an individual element will have less effect on the overall radiation for large arrays, a tradeoff between beamformer design and antenna performance may be conducted.

## EXPERIMENTAL SETUP AND RESULTS

An experimental acousto-optic beamsteering control system was constructed utilizing commercially available equipment in order to validate this technique. The experimental set-up is shown in Figure 5.

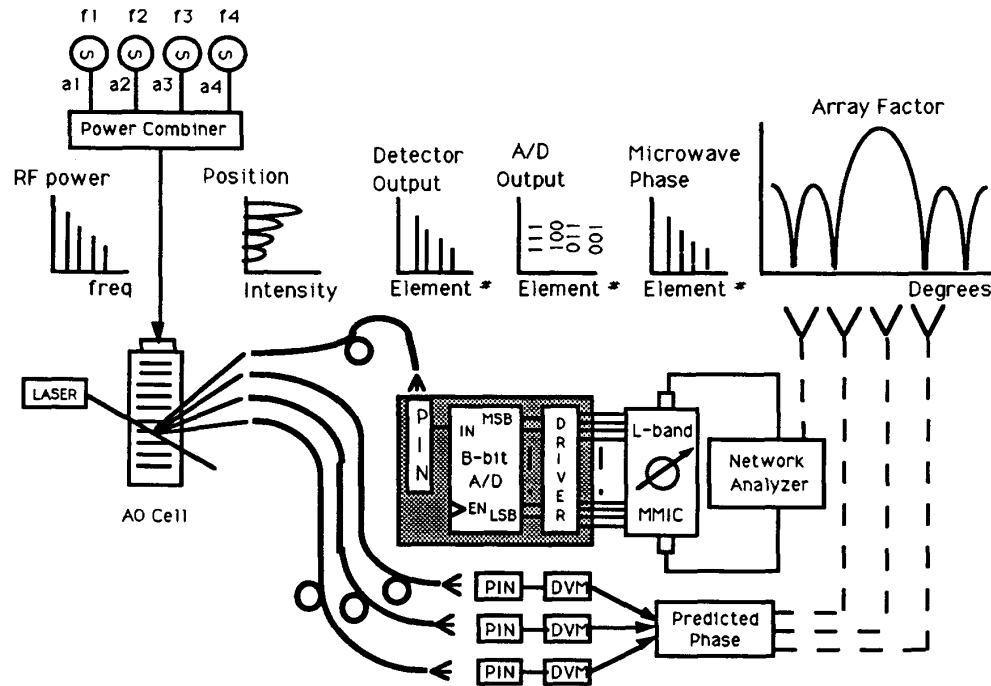


Figure 5. Experimental Setup

A 10 mW linearly polarized HeNe laser was used in conjunction with a TeO<sub>2</sub> acousto-optic cell manufactured by Brimrose Corporation. The AO cell has a center frequency of 290 MHz and an associated bandwidth of 100 MHz. Four microwave frequency synthesizers, whose outputs may be individually controlled, at 240 MHz, 270 MHz, 300 MHz, and 330 MHz are combined to provide the AO cell drive signal. The output of the AO cell is coupled to four 1 mm plastic optical fibers which were selected to provide easy optical coupling. The output of each fiber illuminates a separate p-i-n diode photodetector. The p-i-n diode output of the first channel drives an A/D converter with an effective quantization level of 550 mV with a quantization level to noise ratio of approximately 15. Furthermore, the system was calibrated such that the A/D input voltage was maintained to within  $\pm q/10$  at each quantization level ( $x = 0.1$ ). The A/D converter output is then interfaced to an L-band MMIC phase shifter. This phase shifter consists of three fixed bits followed by a 90° vector modulator to give continuously variable 360° performance [7]. However, only the three digital bits of this device were used in the experiment. The microwave performance of the phase shifter was monitored on an HP 8410 network analyzer. Only a single phase shifter was used in the experiments due to equipment limitations, however, the outputs of the remaining three detectors were monitored by digital volt meters to insure that their response was correct. The entire experimental set-up, including control of the frequency synthesizers, data collection for microwave phase measurement, and the monitoring of the other three



channels was conducted under PC computer control via the GPIB interface. The measured results for the first channel, indicated by the diamonds, show the eight possible phase shifter states at 1.3 GHz as a function of the AO cell drive power in Figure 6.

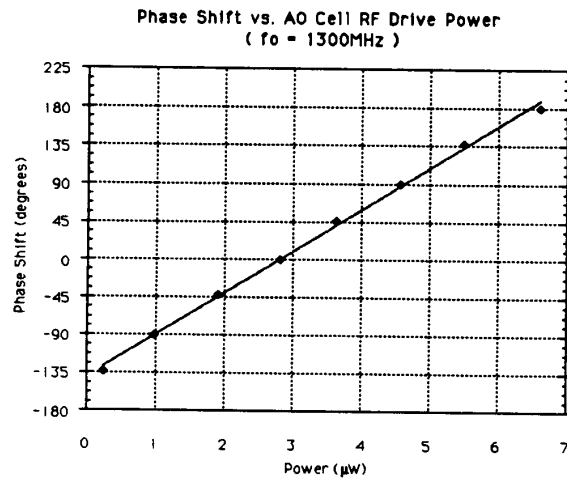


Figure 6. Phase Shift vs. AO Cell Drive Power

This data, along with the data obtained from the other three channels is used to compute a four element array radiation pattern for a number of beamsteering angles,  $\theta_0$ , in Figure 7.

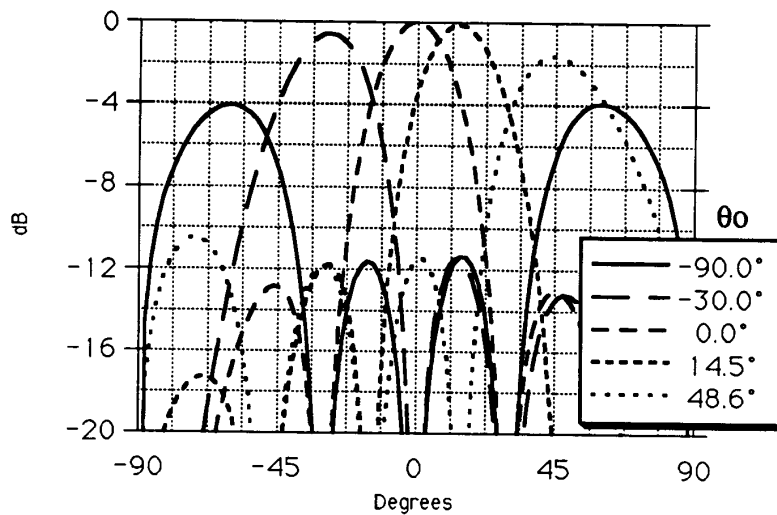


Figure 7. Radiation Patterns Computed from Experimental Data

## CONCLUSIONS

A novel acousto-optically controlled beamsteering control system has been presented which offers several advantages over conventional beamsteering control techniques including reduced complexity at the array face and a small, lightweight, and flexible signal distribution medium. The theory of operation and various design issues are well understood, and a small scale laboratory system has successfully been demonstrated. This beamsteering approach, given further development in the areas of integrated optic implementation of the AO cell and fiber coupling, and the monolithic implementation of the T/R module interface circuitry, offers the potential to reduce the beamsteering control problem associated with large phased array antennas.

## ACKNOWLEDGMENTS

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