ACOUSTO-OPTIC CONTROL OF MMIC T/R MODULES FOR PHASED ARRAY BEAMSTEERING

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ABSTRACT

A novel beamsteering technique is presented which utilizes parallel optical signal processing within an acousto-optic (AO) cell to distribute phase and/or gain control signals to MMIC T/R modules which utilize digital phase shifters and/or gain controllers. An overview of the basic operating principles are presented along with experimental results which validate the technique.

INTRODUCTION

Phased array beamsteering control is typically accomplished using digital computers to calculate and distribute the phase and gain control commands to MMIC T/R modules [1]. These control commands must be provided in a reliable, efficient, timely, and cost effective manner. However, the beamsteering controller design becomes more difficult for large arrays which may incorporate thousands of active MMIC T/R modules. Digital phase shifters and attenuators currently offer the best alternative for phase and gain control of MMIC T/R modules. However, these devises typically require a control command in the form a B-bit parallel binary word where B is the number of phase shifter or attenuator bits. This mandates a minimum of B separate control lines for each device. Moreover, certain types of digital phase shifters require complementary control lines for each bit, thereby doubling the number of control lines required. This has resulted in a trend toward the chip level integration of drivers and control circuitry on the MMIC circuit [2, 3, 4]. However, the integration of microwave and digital circuitry has a significant impact on power consumption, processing requirements, and overall yield of the hybrid digital/MMIC circuit. Jemison, *et al.* have demonstrated a control technique for digital phase shifters which has the potential to alleviate some of these difficulties by utilizing photonic control of the MMIC circuit [5]. Furthermore, Herczfeld has proposed the use of parallel optical signal processing to control multiple MMIC circuits simultaneously, as well as the merging of MMIC and photonic circuitry at the chip level [6]. This paper describes a novel beamsteering control technique which utilizes parallel optical signal processing within an AO cell to distribute phase and/or gain commands which are then used to optically control MMIC T/R modules. This technique is compatible with existing MMIC phase shifter designs, offers compatibility with optical signal processing as well as hybrid chip level photonic/MMIC circuit integration, and may be applied to a wide range of phased array systems. A four channel beamsteering experiment is described using a 3-bit digital phase shifter at L-band to demonstrate the technique.

DESCRIPTION

The acousto-optic beamsteering control architecture utilizes a combination of digital and optical technology to compute and distribute the beamsteering control information [7]. The system block diagram is shown in Figure 1.

In this approach, a digital computer calculates the required phase and amplitude settings for the array.

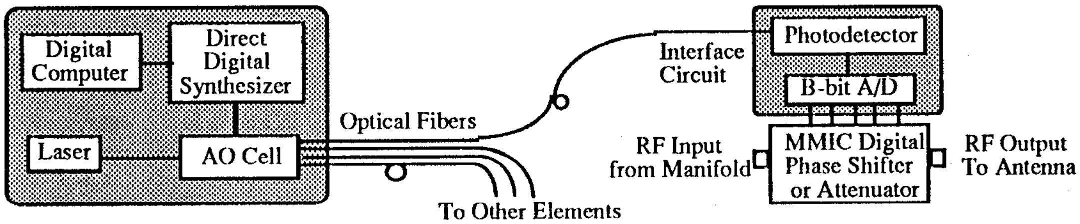

Figure 1. System Block Diagram

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This information is used to command a direct digital synthesizer (DDS) 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

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

where n_0 is the unperturbed index of refraction, ω_m and K_m are the angular frequency and wavenumber of the acoustic signal, and n_m and δ_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, θ, which is given by

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

where λ_0/n_0 is the optical wavelength in the AO cell and Λ_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 [8]. 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 [5]. 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 [9]. 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 μs [1]. 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 [10].

AO BEAMSTEERING PERFORMANCE ISSUES

Unlike traditional beamsteering control architectures [1], 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, and the effects of noise on the ability to correctly issue beamsteering commands. These two issues have been discussed previously [5]. However, there are additional concerns including the beamsteering system dynamic range requirements and the number of phase shifters which can be controlled by a single acousto-optic cell. 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

$$DR = 3.01\ B \quad (dB) \qquad (3)$$

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, Δθ, to the beam diffraction angle, θ_{diff}, and corresponds 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

$$P = \frac{\Delta\theta}{2\theta_{DR}} \cong \frac{2.7\, w_o}{V_s \sqrt{B}} \Delta v = \frac{1.35}{\sqrt{B}} N \qquad (4)$$

where w_0 is the beam waist of the Gaussian laser beam, V_s is the velocity of sound in the AO crystal, and Δv 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. 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.

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 2.

A 10 mW linearly polarized HeNe laser was used in conjunction with a TeO_2 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 ±q/10 at each quantization level. 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 [11]. 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 3.

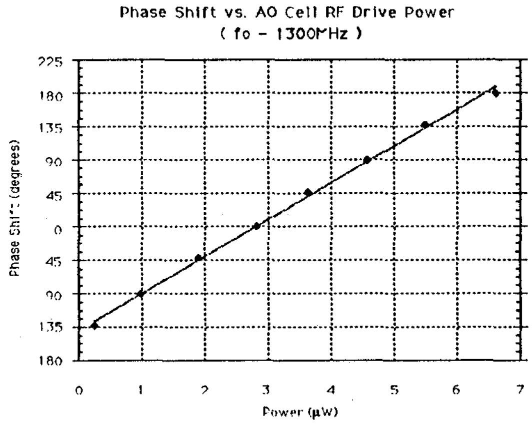

Figure 3. Phase Shift vs. AO Cell RF Drive Power

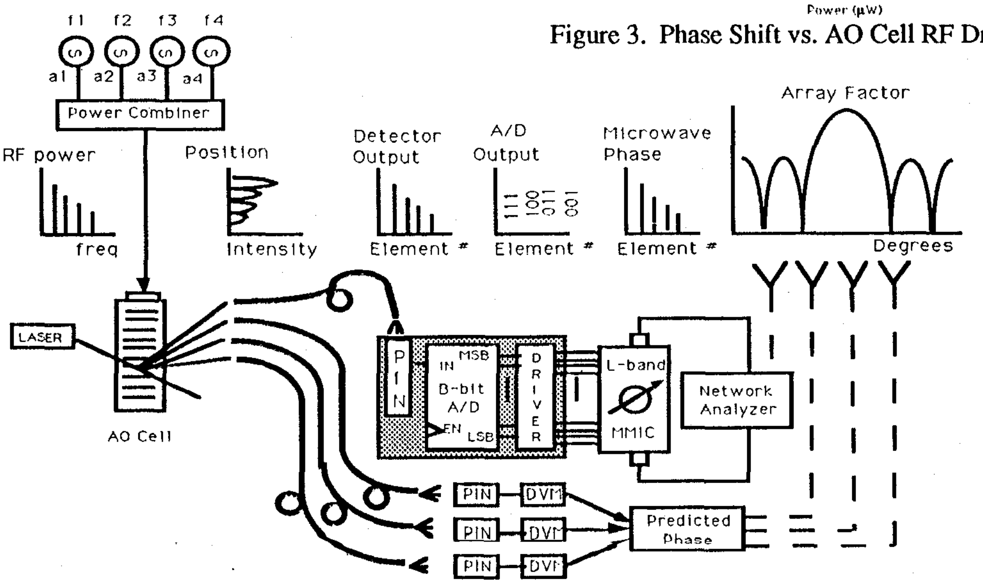

Figure 2. Experimental Set-Up

The measured results, indicated by the diamonds, show the eight possible phase states as a function of the AO cell RF 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, θo, in Figure 4.

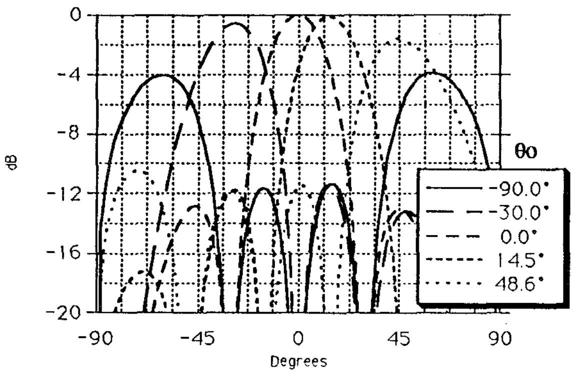

Figure 4. Radiation Patterns Computed from Measured Results

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.

ACKNOWLEDGMENT

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