Optically Controlled Phased Array Radar Receiver Using SLM Switched Real Time Delays

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Abstract—**We report the results of a demonstration of a real time delay, optically controlled phased array radar receiver. This implementation employed a free space configuration based upon an optical switching network using liquid crystal spatial light modulators (SLM's). A three-delay unit, two-antenna array receiver was implemented at an optical wavelength of 1.3 μm and demonstrated "squint-free" operation over the entire X-band (8–12 GHz) with an angular accuracy of 1.4°. Finally, a novel configuration for the two-antenna element SLM architecture was proposed and demonstrated equivalent system performance with a reduction in the number of components.**

INTRODUCTION

RECENTLY, there has been considerable interest in employing optical true time delays as a means for optically controlling phased array antennas. Several methods have been proposed to accomplish this task including the use of fiber loops in conjunction with bias switched detector arrays [1], optical heterodyne techniques for generating and sorting delays [2], and bulk optical delay lines using spatial light modulators (SLM's) [3], [4]. In the experiments presented here, we demonstrate an optically controlled phased array radar receiver using the SLM/bulk optics approach. This is the first demonstration using the SLM/bulk optics architecture at an optical wavelength of 1.3 μm that exhibits "squint free" operation over the entire X-band (8–12 GHz). In addition, the use of computer processing techniques on the data collected has resulted in an angular accuracy of 1.4° using only two antenna array elements and three SLM optical delay units. Finally, a novel configuration for the SLM receiver architecture is proposed and demonstrated that can increase the digital resolution from 15 sampled points to 64, improving the angular accuracy of the radar receiver without increasing the number of components.

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Fig. 1 displays the configuration of our optically controlled phased array radar receiver that is based on the spatial light modulator (SLM) architecture previously proposed by Dolfi *et al.* [3]. An X-band horn radiates into the two-element antenna array at an unknown angle, θ. The plane waves emanating from the horn will couple to the antennas at different times, thereby generating a phase difference between the signals at the output of the antennas. This phase difference is given mathematically by $\Delta\varphi_m = (2\pi d/\lambda_m)\sin(\theta)$ where d is the spacing between the antennas, λ_m is the wavelength of the microwave signal from the horn, and θ is the angle of the horn measured with respect to broadside of the antenna array [1]. In our system, we determine the microwave phase difference, $\Delta\varphi_m$, by optical processing techniques and then determine the angle of the horn through this equation.

The antenna array consists of two exponentially tapered coplanar double-strip antennas with constant impedance of 175 Ω over a 5–20 GHz band. The spacing between the antennas was $d = 20$ mm. The signals acquired by the antennas drive two $LiNbO_3$ Mach–Zehnder optical modulators (3 dB RF modulation bandwidths of 10 GHz) which intensity modulates the output from two 1.3 μm distributed feedback (DFB) laser diodes. The DFB lasers were temperature and current stabilized with average output optical powers of 10 mW and linewidths of 10 MHz.

The microwave phase information is now encoded onto the two light beams that traverse through the optical processing network, which consists of three delay units. Each delay unit contains a polarization rotating SLM and polarization beam splitting cubes as shown in Fig. 1. The liquid crystal SLM's can rotate the 1.3 μm optical polarization by 90°, when 16 V are applied, with an extinction ratio of 32 dB. The first delay unit can delay the optical signals by Δt, the second by $2\Delta t$, and the third by $4\Delta t$ units of time. By employing this methodology, one can obtain $2^{(n+1)} - 1$ distinct optical delay combinations where n is the number of delay units. Thus, in our two-antenna, three-delay unit system, we obtain 15 distinct delays.

The optical delay network adds a suitable phase difference, $\Delta\varphi_{\text{delay}}$, between the two microwave signals. The two microwave signals are then extracted from the light beams by two

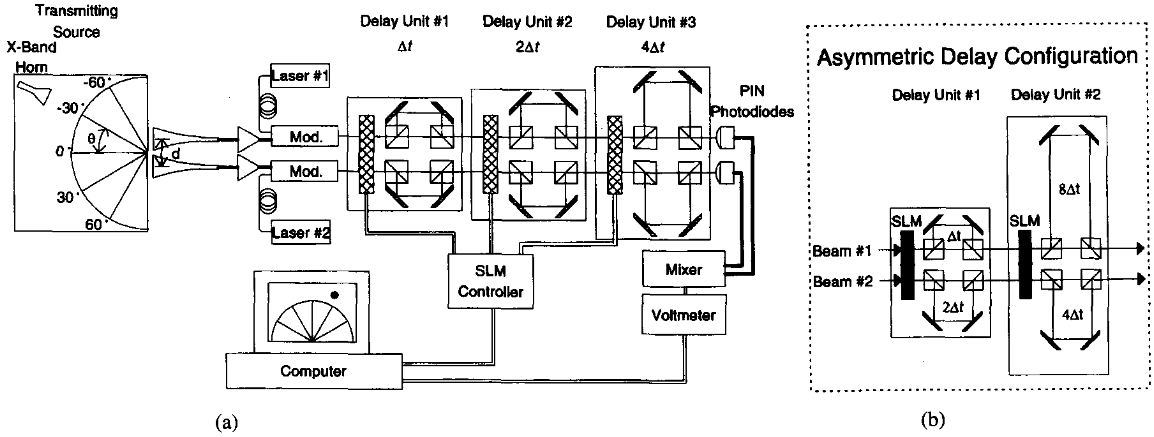

Fig. 1. (a) Schematic of the three-unit optically controlled true time delay phased array radar receiver. Polarization beam splitters and liquid crystal SLM's are used to switch the beams through different optical delay paths. (b) The asymmetric configuration used to increase the angular resolution.

InGaAs/InP p-i-n photodiodes that have 30 GHz bandwidths [5]. The microwave outputs of the two photodiodes are then homodyne mixed in a conventional microwave mixer. From homodyne mixing theory, the output of the mixer contains a dc component given by

$$V_{DC} = A + B\cos[\underbrace{2\pi f_m(p\Delta t)}_{\Delta\varphi_{\text{delay}}} + \Delta\varphi_m]$$

where A and B are constants, f_m is the microwave frequency, and p is an integer in the range $-7 \leq p \leq 7$ for our three delay unit system [6]. From this equation, we find that as we switch through the different optical delay paths the homodyne mixing voltage, V_{DC}, follows a cosine of frequency f_m and phase $\Delta\varphi_m$. Extraction of the phase $\Delta\varphi_m$ from this cosine function then uniquely determines the angle of the source.

We observe that the measured dc voltage from the homodyne mixing will be a maximum when $\Delta\varphi_{\text{delay}} = -\Delta\varphi_m$ and since $\Delta\varphi_{\text{delay}}$ is a known parameter, we can determine the sought after microwave phase difference that was originally incident on the two antennas and thus calculate the angle at which the X-band horn is located. Since $\Delta\varphi_{\text{delay}}$ is discrete our resulting real-space angular accuracy, θ_{res}, is determined by $\theta_{\text{res}} = \arcsin(c\Delta t/d)$ [1]. Given $\Delta t = 5.5$ ps and $d =$ 20 mm, we obtain an angular accuracy of $\theta_{\text{res}} \cong 5°$ for our system. We significantly improved the angular accuracy of our system by determining $\Delta\varphi_m$ using a least squares fit to the discrete set of data [7]. A least squares fit for this data is obtained by minimizing the function $\Pi = \sum_{i=1}^{15} |V_{DCi} - [A + B\cos(\omega_m\tau + \Delta\varphi_m)]|^2$ where A, B, and $\Delta\varphi_m$ are the adjustable parameters. Fig. 2 displays a least squares curve fitting to the 15 sampled points with the horn at a real-space angle of $-25°$ and a microwave frequency of 10.5 GHz. From the least squares fit, we obtain $\Delta\varphi_m = -1.89$ radians, which corresponds to a calculated real-space angle of $-25.98°$.

To determine the angular accuracy of this technique, we calculate the "standard error of the mean" of the data shown in Fig. 2. $\sigma_M = (\sigma/\sqrt{N-1})$ where σ_M is the standard error of the mean, σ is the standard deviation, and N is the number of measurements taken (15 for our system) [8]. The standard error of the mean was calculated to be 0.097 radians, which corresponds to a real-space angular uncertainty of 1.4°. Thus,

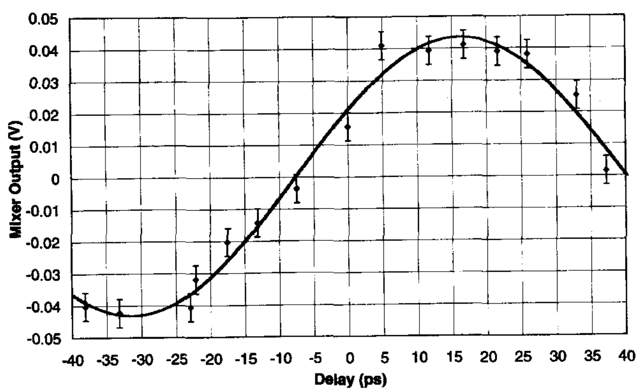

Fig. 2. Homodyne mixing output voltage versus optical delay time at 10.5 GHz with the X-band horn at $-25°$. The least squares fit to the measured data determines the microwave phase delay, $\Delta\varphi_m$, with improved accuracy.

the angular accuracy of our radar receiver has improved from 5 to 1.4°. The angular accuracy can be increased at the rate of $1/\sqrt{N-1}$ by increasing the number of delay units thereby increasing the number of sampled points.

As was mentioned, one of the primary motivations for using a true time delay processing system for a phased array radar receiver is that it exhibits "squint free" behavior, resulting in wide instantaneous bandwidths [1]. If one were to use conventional microwave phase shifters in place of our optical true time delay network, the determination of the angle of the incoming radar signal from the target would be $\theta = \arcsin[c \cdot \Delta\varphi_{\text{phase}}/(2\pi d \cdot f_m)]$ and is a function of frequency [1]. Thus, as the frequency of the radar changes, the target angle appears to shift. This undesirable "beam squint" behavior can be eliminated by replacing the microwave phase shifters with the optical true time delay network of Fig. 1. When using a true time delay system the target angle is given by $\theta = \arcsin(c \cdot \tau/d)$ and is independent of frequency [1].

In making our measurements over a broad range of frequencies, deviations of several degrees attributed to mutual coupling [9] were observed at some frequencies and angles. Our data is corrected for these effects, using a digital sampling oscilloscope for calibration, and plotted as a function of frequency in Fig. 3. Squint free operation is shown over a 8–12 GHz band which is a ±20% bandwidth around the center

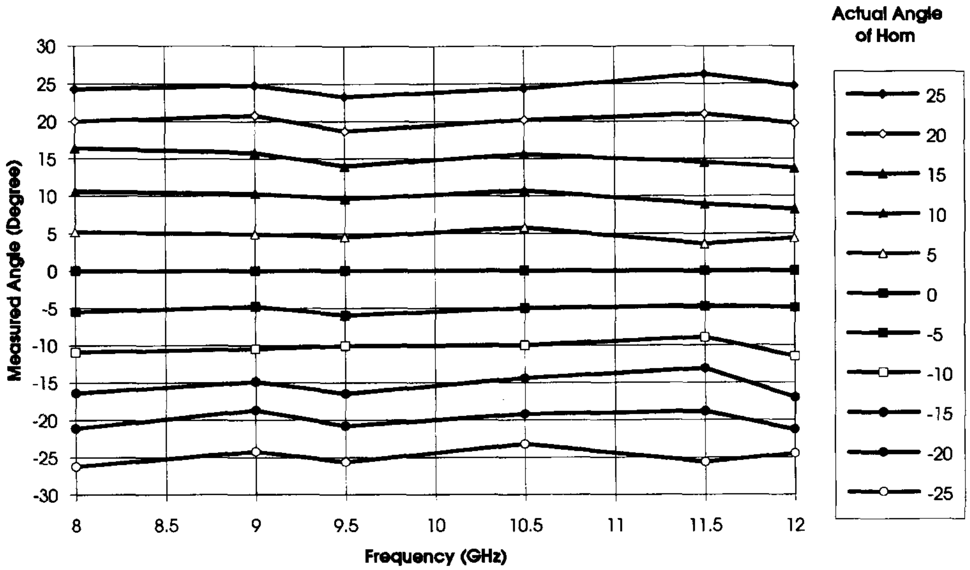

Fig. 3. Measured angle from −25–25° over an 8–12 GHz band exhibiting "squint free" operation measured in the symmetric configuration. Deviations of the measurements from the actual angle of the horn are attributed to random phase shifts in the cables, amplifiers, and mixers. Comparable data was achieved using the asymmetric system.

frequency of 10.5 GHz. The standard deviation of the angular error is $<1.1°$ at all frequencies, which is within our specified angular accuracy. The maximum deviations from the actual angle are approximately 2° and are attributed to random phase shifts in the cables, amplifiers, and mixers.

The angular accuracy of the system can be improved by increasing the number of delay units. The angular accuracy of this system can also be significantly increased without increasing the number of delay units by noticing that the use of symmetric delays for both light beams as shown in Fig. 1 is an inefficient configuration for obtaining different combinations of optical delay. For example, we found that the three delay unit system in Fig. 1 could provide 15 different combinations of optical delay given by the formula $2^{(n+1)} - 1$ where $n = 3$ delay units. There are, however, 49 other possible combinations in the three-unit system that are degenerate in that they reproduce one of the aforementioned 15 optical delays. If one could design the optical delay network such that this degeneracy were removed, one could obtain 2^{2n} distinct optical delay combinations.

We demonstrate this concept using the asymmetric two-delay unit system shown in the inset of Fig. 1, which gives 16 optical delay combinations yielding approximately the same angular accuracy as the previously presented symmetric three-delay unit configuration. The standard deviation of the angular error for this configuration was measured to be 1.2° at 10.5 GHz displaying the same angular accuracy of the symmetric three-delay unit system. This concept can be extended to higher number of antenna elements by joining the two element subarrays in combinations to form large phased array apertures [1].

In summary, the first demonstration of an optically controlled true time delay phased array radar receiver using the SLM/bulk optics approach at an optical wavelength of 1.3 μm has been described and a real-space angular accuracy of 1.4° was obtained. The system operated with "squint free" behavior over the entire X-band (8–12 GHz) demonstrating a wide instantaneous bandwidth. Furthermore, a new SLM-based architecture was proposed and demonstrated a large angular accuracy with a reduced number of system components. The simplicity and high performance of this system suggests its applicability to realistic phased array radar applications.

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