Wavelength-Selective True Time Delay for Optical Control of Phased-Array Antenna

S. Yegnanarayanan and B. Jalali

***Abstract*—Performance of an optically controlled phased-array antenna system employing novel single-chip optical wavelength selective true time-delay devices is reported. High-resolution time-delays are demonstrated using integrated delay lines. Extension to two-dimensional (2-D) antenna arrays with independent control of azimuth and elevation by using mid-stage optical wavelength conversion is proposed and demonstrated. An optical true-time-delay steered two-element X-band antenna was assembled to verify the wide instantaneous bandwidth operation.**

***Index Terms*—Optically controlled beam steering, phased-array antenna, true time delay.**

I. INTRODUCTION

PHASED-ARRAY antenna is an enabling technology in modern radar and communication systems. Phased-array antennas offer many advantages including steering without physical movement, increased scan flexibility in two dimensions, precise elemental phase and amplitude control to obtain low spatial sidelobes, the potential for large peak and average power, and the ability to degrade gracefully due to the distributed nature of the array. The use of optical control techniques for phased-array antennas promises to alleviate many of the problems associated with traditional electronic steering systems. The unique properties of optical fiber that are suitable for this application include the ability to store large bandwidth analog signals (10 s of gigahertz) for long times (tens of microseconds), the immunity to electromagnetic interference (EMI) and low mass and volume, which is especially important in airborne applications. In particular, optical techniques are able to provide true time-delay beam steering that is essential for squint-free wide instantaneous bandwidth operation of high-performance radar systems [1]–[3]. A wide variety of optical true-time delay techniques have been proposed, but many are difficult to implement due to their demands for matched components, excessive power loss, specialized element development, component costs, and their inability to easily scale to real-world two-dimensional (2-D) arrays.

Recently, we proposed a key technique to enable optical control of wide-band arrays, using a novel single-chip switchless photonic time-delay device, where the microwave time-delay is selected by the optical wavelength [4], [5]. Since all the optical energy is self routed to the desired time delay, this technique can easily scale to large arrays. Time delays of the order of nanoseconds may be realized with subpicosecond resolution using integrated delay lines on chip while larger delays may be obtained off chip.

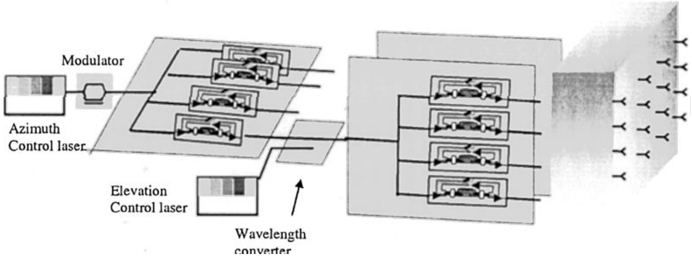

Fig. 1. Optically controlled 2-D beam steering system using a wavelength converter between azimuth and elevation beam-steering units.

In this letter, we propose a novel technique to extend this optical wavelength-selective time-delay device to 2-D arrays while completely eliminating optical-electrical conversion losses. This represents a departure from conventional approaches to optically controlled 2-D beam steering, where the optical signal at the output of the azimuth beam steering unit (BSU) is converted to an electrical signal in a photodetector, followed by an optical modulator to transfer this electrical signal to the elevation BSU. This introduces optical-electrical conversion loss and more importantly adds to the system complexity. The approach we propose for a 2-D optically controlled beam-steering system is shown in Fig. 1. A tunable laser is used to select the time-delay through each stage. Each stage consists of a wavelength-selective time-delay [4]. There is no optical electrical optical conversion between the azimuth and elevation control stages. Typically, one would need a separate photodetector after the first time-delay device, followed by an optical modulator, to transfer the analog signal to the second time delay.

In our technique, however, the broad-band analog signal is transferred from one wavelength to the other using wavelength conversion. This eliminates the optical/electrical/optical conversion loss. Several techniques exist for transferring the analog signal from one wavelength to another including four-wave mixing (FWM), cross-gain modulation (XGM), and cross-phase modulation (XPM). In our particular experimental demonstration, the wavelength conversion is achieved by using cross-gain modulation in a semiconductor optical amplifier (SOA) [6], [7]. Since the gain of the SOA saturates with an increase in optical intensity, an analog signal at λ_1 modulates the gain of the SOA. A CW beam at λ_2 will sample this gain modulation, thereby copying the analog signal from λ_1 to λ_2.

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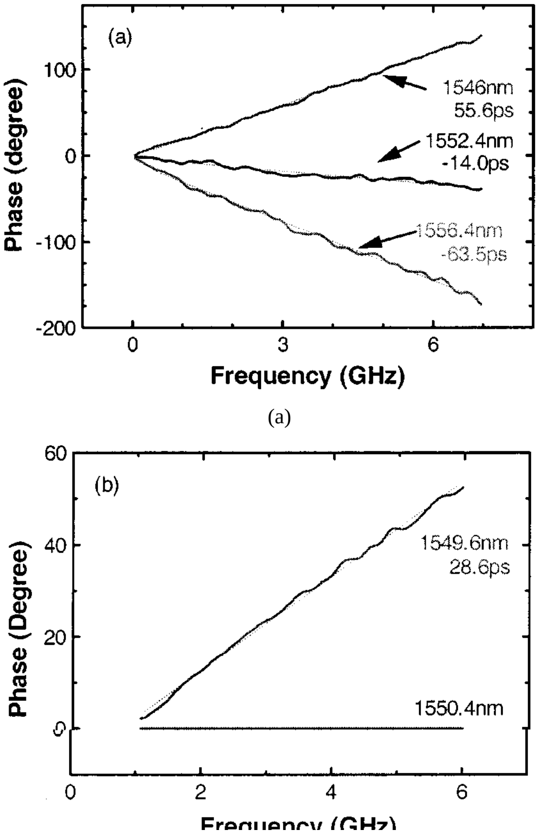

(a)

(b)

Fig. 2. (a) Azimuth laser wavelength tuning (elevation laser set to 1549.6 nm). (b) Elevation laser tuning (azimuth laser set to 1550 nm).

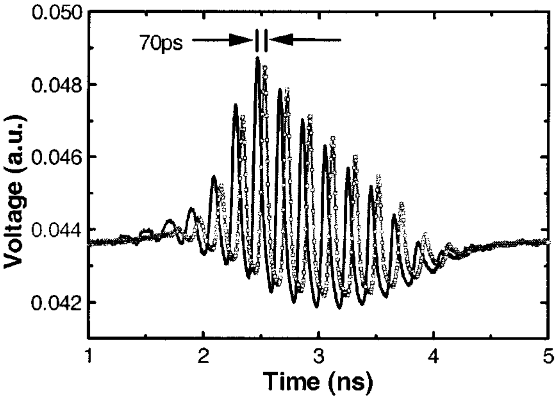

Fig. 3. Time-domain response using 2-ns pulsed 5-GHz carrier. The response shifts by 70 ps when azimuth control wavelength is changed from 1547.6 nm to 1553.2 nm.

The maximum frequency of operation is limited only by the stimulated emission lifetime and wavelength conversion at frequencies as high as 40 GHz has already been demonstrated [8]. Thus, by cascading two individual time-delay devices, each with its own control wavelength, one can set the time delay for the azimuth and elevation to achieve independent 2-D optically controlled beam-steering, as shown in Fig. 1. The analog signal is inverted in the wavelength conversion process, but this is of no consequence in radar applications.

In the experimental setup, the optical carrier is an external cavity tunable semiconductor laser. The RF output is applied to the Mach–Zehnder (MZM) modulator. The amplitude modulated optical signal at λ_1 is fed to a wavelength-selective time-delay chip. This true time-delay generator chip consists of an arrayed waveguide grating (AWG) with recirculating feedback. Tuning the laser wavelength changes the time delay experienced by the microwave signal [4]. The optical signal at the output of the first time-delay stage serves as the pump for the SOA. The second-stage tunable laser at λ_2 serves as the CW probe signal of the SOA. Through wavelength conversion, the broad-band analog signal at λ_1 is transferred to λ_2, while the internal gain in the SOA ensures lossless operation. In order to remove the pump signal after the first time-delay stage without using a cumbersome tracking filter for each feed, we use counterpropagating pump and probe signals. The optical signal at λ_2 is now applied to the second stage wavelength-selective time-delay chip.

Swept frequency measurement of the RF phase versus RF frequency is shown in Fig. 2. The slope of each curve corresponds to the selected RF time- delay. Azimuth laser (λ_1) and elevation laser (λ_2) wavelengths are tuned to select individual time-delays in Fig. 2(a) and 2(b). As expected, the time-delay is independent of the microwave frequency over the measured frequency range of 0–6 GHz. Deviations from linear phase are introduced by optical crosstalk at output of AWG. In Fig. 2(b), the phase curve at 1550.4 nm is perfectly linear as it is the phase reference.

In order to verify the wide instantaneous bandwidth of this optical control technique, we performed time-domain measurements at the output of the wavelength converter using an electrical RF pulse generated by switching a 5-GHz carrier with a 2-ns pulse. Time-delay increments of 10 ps with wide instantaneous bandwidths were obtained using integrated delay lines. In order to easily observe the waveform, the time-domain data in Fig. 3, shows one pulse delayed by 70 ps with respect to the other. The small peak-to-peak amplitude in Fig. 3 was due to the fact that the applied pulse width was short compared to the switching time of the RF switch.

To further verify the wide instantaneous bandwidth, we performed a transmitter experiment. We assembled a two-element transmitter antenna array that is driven by an optically controlled time-delay device. Angular and radial field patterns are obtained by using a horn antenna as a receiver inside a compact test range. The measured beam position is steered by tuning the optical wavelength as shown in Fig. 4. Null depth of 20 dB was obtained over 8–12 GHz bandwidth while steering the null over ±40°. No measurable variation in the null position was observed over the 8–12 GHz bandwidth at each beam-steering angle.

Wavelength conversion can be performed using either XGM or XPM in the SOA. An important issue is the linearity. In the low-frequency limit, the variation of the complex electric field amplitude $A(z)$ along the length of the SOA is given by

$$\frac{dA(z)}{dz} = \frac{1}{2}(1 - i\beta_c)g(z)A(z)$$

where $g(z)$ is the power gain coefficient and β_c is the linewidth enhancement factor. A two-tone linearity analysis, performed after including gain saturation, shows that for an unsaturated

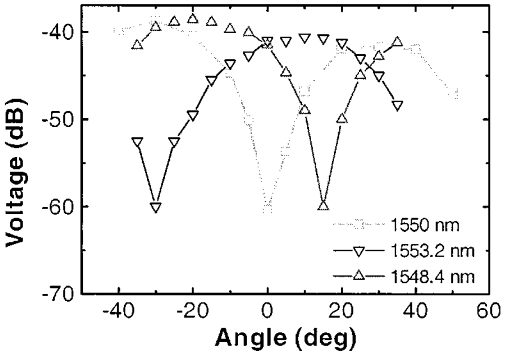

Fig. 4. Angular beam pattern measurements for two-element X-band antenna from 8 to 12 GHz. True time-delay beam steering by tuning optical wavelength is shown.

gain of 10 dB and $\beta_c = 5.0$, the XPM scheme offers a spurious-free dynamic range (SFDR) improvement of 7 dB over the cross-gain wavelength converter. We attribute this to the large β_c in SOA's and the smoother cosine transfer function. The dynamic range in XGM wavelength converters in SOA exhibits a strong dependence on several parameters including the average pump and probe powers and the unsaturated gain and typically degrades when operated in gain-saturation.

Other applications of this technique to transfer analog signals in the optical domain include the ability to extend the total number of discrete time delays. In any wavelength selective time-delay technique the spectral tuning range of the tunable laser source limits the number of different delays that can be obtained. However, by cascading m N-channel time-delay stages with wavelength conversion, we now obtain N^m different delays.

Another application is the ability to realize digitally controlled time-delays. An m-stage cascade with binary delay in each stage can be used to realize 2^m independent delays, which can be set by an m-bit parallel control word. The first time-delay stage would be used to realize the most significant bit (MSB) while the successive time-delay stages will represent the less significant bits.

In conclusion, we have proposed and demonstrated a new optical technique to achieve low-loss independent control of 2-D array transmitters while providing a wide instantaneous bandwidth.

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