Acoustooptically Controlled True Time Delays

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Abstract—**A novel microwave true time delay system is proposed that uses an acoustooptic cell to address the desired time delay. The system is compatible with high speed optical intensity modulation techniques and will therefore support microwave modulation frequencies into the millimeter wave range. The number of possible delays is a function of the acoustooptic cell properties and the desired isolation between delay paths. A 7-bit true time delay system appears feasible based on an assessment of commercially available acoustooptic cell technology.**

I. Introduction

PROGRAMMABLE microwave time delay networks are required for large phased array antenna systems in order to achieve adequate instantaneous bandwidth. Unfortunately, conventional microwave time delay elements are both heavy and bulky and are not a practical solution, particularly for airborne systems. The use of photonic techniques, however, offers the potential to realize compact, lightweight, and high-performance microwave time delay networks compatible with advanced radar and communications phased array systems. Several photonic techniques have already been proposed to provide true time delay operation including the use of switched fiber networks using optical crossbar switches [1], as well as the use integrated optic-tapped delay lines [2]. Frequency-dependent phase compensation has also been proposed to generate time delays [3], [4]. However, this technique does not adequately account for energy storage over the delay time. Experimentally observed time delays, therefore, must result due to a different physical mechanism, such as imaging into an acousto-optic cell [5]. Photonic time delays have also been proposed by applying a microwave path delay in one arm of a laser heterodyne system [6]. A modification of this heterodyne technique has also been proposed for nonheterodyne systems [7]. This letter describes an alternate photonic true time delay technique that utilizes an acoustooptic beam deflector in conjunction with optical intensity modulation to address different optical delay lines. This approach is compatible with high-frequency microwave modulation, uses a single control command, provides excellent isolation between delay paths, and is amenable to integrated optics.

II. Description

The block diagram of the proposed time delay system is shown in Fig. 1. In this approach, the optical carrier is intensity modulated at the desired microwave or millimeter-wave frequency. This may be accomplished using either direct modulation of a high-frequency laser diode, or by an external electrooptic modulator (external modulation is shown in the figure). Modulation frequencies as high as 23.5 GHz and 40 GHz have been reported using direct and external modulation respectively [8], [9]. The following discussion will assume external modulation via a Mach–Zender interferometer. The optical input signal to the external modulator, $E_1(t)$, may be expressed as

$$E_1(t) = E_0 \cos \omega_o t, \tag{1}$$

where E_0 is the incident electric field amplitude and ω_0 is the optical angular frequency. This signal is split into two equal amplitude components in the Mach–Zender interferometer where the phase of one component is modulated relative to the other via the voltage dependent linear electrooptic effect. Therefore, the electric field at the output of the interferometer, $E_2(t)$, is given by

$$E_2(t, V) = \frac{E_0}{\sqrt{2}}\{\cos \omega_o t + \cos [\omega_o t + \varphi(V)]\}, \tag{2}$$

where $\varphi(V)$ is the phase difference between the two branches of the interferometer. Next, this signal is applied to an acoustooptic (AO) cell, operated in the Bragg regime. The AO cell is driven by an RF signal which launches a traveling acoustic wave into the AO crystal. Photon-phonon interactions deflect the optical beam and induce a single sideband Doppler shift of the optical carrier which is equal to RF drive frequency. This results in an electric field distribution at the output of the AO cell given by the following equation

$$\begin{aligned} E_3(t, V, \theta) = & K_1 \frac{E_0}{\sqrt{2}}\Big\{\cos (\omega_o + \omega_{\mathrm{RF}})t \\ & + \cos [(\omega_o + \omega_{\mathrm{RF}})t + \varphi(V)]\Big\}, \end{aligned} \tag{3}$$

where ω_{RF} is the RF drive frequency and K_1 is a loss term related to the AO cell diffraction efficiency, and θ is the deflection angle. The optical intensity at the output of the AO cell is given by the squared electric field averaged over several optical cycles. Since $\omega_{\mathrm{RF}} << \omega_0$, the resulting intensity distribution is

$$I_3(V, \theta) = K_1^2 \frac{E_o^2}{2} \cos^2\left(\frac{\varphi(V)}{2}\right). \tag{4}$$

This is the intensity transfer function of a Mach–Zender interferometer [10]. Under small signal conditions at the appropriate bias point, the intensity may be normalized and expressed as

$$I_3(t, \theta) \approx I_o(1 + m \cos \omega_{\mu w} t), \tag{5}$$

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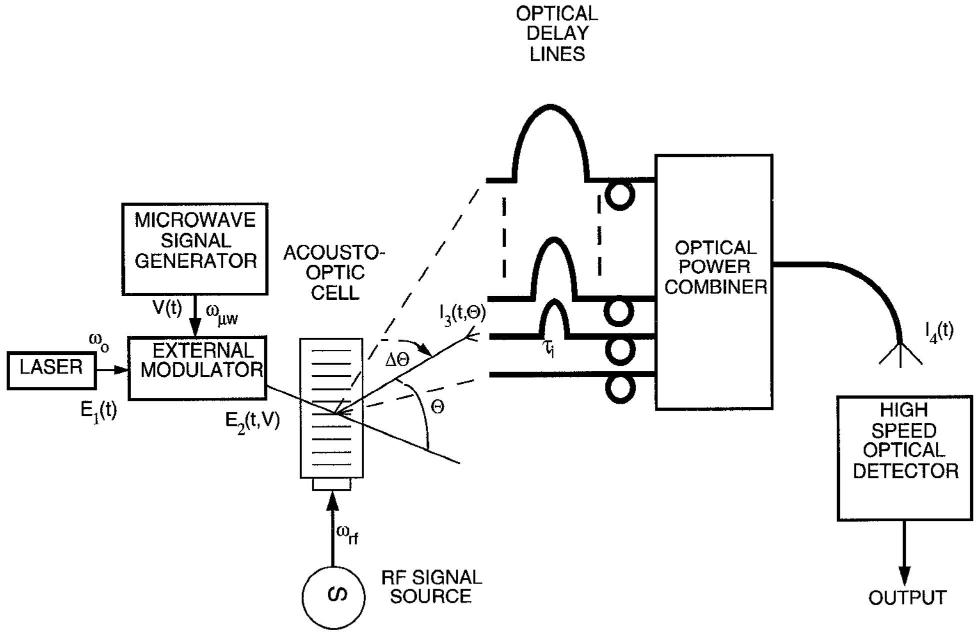

Fig. 1. True time delay system block diagram.

where a microwave signal $V(t) = A\cos(\omega_{\mu w}t)$ has been applied to modulate the phase within the external modulator, and m is the modulation index that is related to amplitude of the applied microwave signal and the physical properties of the external modulator.

An array of optical fibers or integrated optic waveguides, which provides the delay medium, is placed at the output of the AO deflector. The appropriate selection of the AO cell RF drive frequency can change the deflection angle by an amount $\Delta\theta$, which is given by the following:

$$\Delta\theta = \frac{\lambda}{nV_s}\Delta\nu, \tag{6}$$

where λ is the optical wavelength, n is the index of refraction, V_s is the acoustic velocity, and $\Delta\nu$ is the change in the AO cell drive frequency. In this manner the AO cell deflects the intensity modulated light into the ith fiber or waveguide which corresponds to a desired time delay, τ_i. Finally, the fibers or waveguides are combined via an integrated optic power combiner whose output illuminates a high speed photodetector. The expression for the optical intensity at the output of the power combiner is given by

$$I_4(t) = L_c I_o(1 + m\cos\omega_{\mu w}(t - \tau_i)), \tag{7}$$

where τ_i , corresponds the delay of the ith fiber, and the constant L_c is associated with the waveguide coupling and combiner loss. Therefore, the application of a microwave signal $V(t)$ at the external modulator will result in a signal at the output of a high speed photodetector that, with the exception of a dc component, is a replica of the input signal delayed by τ_i.

The overall insertion loss of the system is dependent on a number of factors including the proper impedance matching of the laser transmitter and detector, as well as the diffraction efficiency of the AO cell, coupling efficiency into the fiber, and combiner losses. Assuming a diffraction efficiency and coupling efficiency of 40% and 50%, respectively, the overall insertion loss may be conservatively estimated at 6–10 dB. Furthermore, the number of delays is dependent on the AO deflector characteristics and the desired isolation between delay paths. Typically, AO cell resolution is specified by the number of spots, N, which is a measure of the total beam deflection to beam diffraction

$$N = \frac{\Delta\theta}{\theta_{\text{diff}}}. \tag{8}$$

However, a different resolution criteria, which takes into account the optical isolation between adjacent delay paths, is more appropriate for this application. Assuming Gaussian laser beam characteristics, the number of individual delay paths, P, can be derived and is given by the following equation where C_{opt} is the desired optical isolation in decibels

$$P \cong \frac{4.6N}{\sqrt{C_{\text{opt}}}}. \tag{9}$$

Since the number of spots obtainable from commercial AO cells is on the order of one hundred, the equivalent of six to seven bit true time delay networks appears feasible with 25–30 dB of isolation between delays.

III. Conclusion

A novel microwave true time delay system has been proposed using an acoustooptic cell to address the desired time delay. This approach is compatible with either high-speed direct or external intensity modulation and will therefore support microwave modulation frequencies into the millimeter-wave range. The control circuitry is very simple, consisting of a single tunable oscillator. The number of delays is dependent on the AO cell characteristics as well as the desired optical isolation. An expression has been given for the number of delays as a function of the number of spots, a typical AO cell specification, and desired optical isolation. Based on this expression and typical performance of commercially available AO cells, it is projected that a 7-bit true time delay network is feasible with greater than 25 dB of isolation between delay paths and less than 10 dB of insertion loss. Furthermore, this technique is fully compatible with an integrated optics implementation since the AO cell and fiber coupling may be done in either $LiNbO_3$ or GaAs [11], [12]. Experimental work is currently in progress to demonstrate this technique. This approach also has application to microwave transversal filters which will be discussed in the near future.

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