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WIDE-BAND TRUE TIME DELAY PHASE SHIFTER DEVICES

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ABSTRACT

Fiber optic links in microwave and millimeter wave region have recently been demonstrated. Integration of these links into systems require the development of fiber optic devices such as novel true time delay devices. Most of the currently available fiber optic time delay components provide for constant, fixed time delays. Many applications on the other hand, such as optically controlled phased arrays, would require variable time delays for phase shifting purposes. This paper is concerned with variable time delay devices and their systems integration.

BACKGROUND

The state of the art in transmitting microwave signals on optical carriers via fibers has reached the stage that one can consider the design of large aperture phased arrays with fiber optic (FO) feed networks. More recently a millimeter wave synchronizing link, using optical injection locking of several Ka-band (40GHz) oscillators, was demonstrated.(1) The possibility of synchronizing a large number of local oscillators, up to the important 60GHz range and beyond, now appears to be within reach. Methods to improve the sensitivity and dynamic range of high speed FO links is also well on its way.(2) Since the FO transmission media is inherently wide band, the question arises if one could introduce time delays in the FO links to produce phase shifts. A novel technique, stretching the fiber by a piezoelectric device (PZT) and thereby producing true time delays, was recently proposed.(3) It was further stipulated that this technique may be utilized in various beam forming applications.(4) In this paper two approaches resulting in wide band time delay components are discussed.

WIDE BAND TRUE TIME DELAY PHASE SHIFTER

Consider a typical FO link used to connect two subsystems at microwave or millimeter wave frequencies. The phase difference between the two ends of the link is directly related to the time of travel which is determined by the length of the fiber and the group velocity of the propagating mode:

$$\delta\phi=2\pi(f\cdot\delta t)=2\pi(f\cdot L/v_g) \quad (1)$$

where

$\delta\phi$=phase difference between the two ends of the link

$\delta\tau$=transit time between the ends of the link

f= frequency of the modulating microwave signal

L= length of the fiber

and

v_g= group velocity of propagating mode.

As seen from eq. (1), a time delay/phase shift may be accomplished by either changing the length of the fiber or by changing the group velocity of the carrier, the light. Both of these approaches are explored.

<u>Time delays by changing the fiber length</u>

The length of fiber optic links may be altered by switching different lengths of fibers into the link(5,6), reminiscent of switched line microwave techniques. This method utilizes integrated optic switches and is capable of producing discrete time delays of 100psec or longer. Shorter time delays may be possible but appear impractical. The main disadvantage of the device is the need to repeatedly transit between the integrated optic circuit and the fiber which results in prohibitive insertion losses.

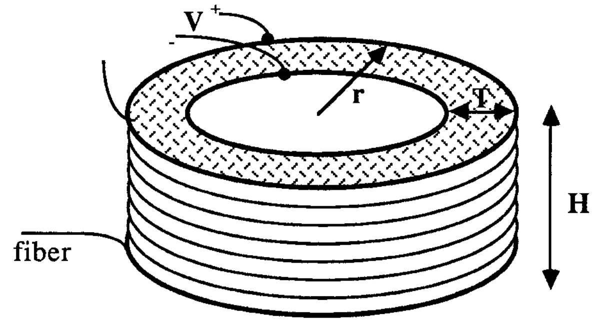

Fig.1 Fiber optic time delay device with PZT stretcher.

An alternate approach is the physical stretching of the fiber. This can be accomplished by wrapping the fiber around a piezoelectric (PZT) ring, as shown in Fig.1, which expands upon the application of an electric field and thus stretches the fiber. The change in phase, $\Delta\Phi$, can be written as:

$$\Delta\Phi=2\pi(f\cdot\Delta t)=2\pi\Delta l/\lambda_g=2\pi Ls/\lambda_g \quad (2)$$

where

Δt= time delay

λ_g=wavelength of modulating signal

Δl= stretched length of the fiber

$s=\Delta l/L$=piezoelectric compliance ratio= $d_{xx}E$

d_{xx}= piezoelectric strain coefficient, (m/V)

E= Aplied electric field (V/m)

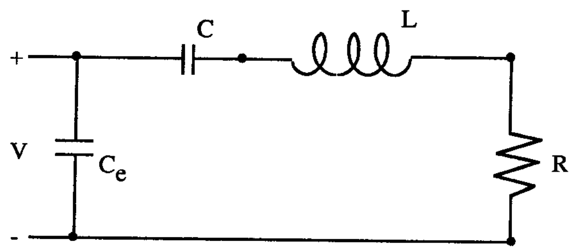

Fig. 4. Simplified equivalent circuit.

where $C=C_m \cdot N^2$, $L=M/N^2$ and $R=Z_r/N^2$. If we assume a ceramic material like PZT-5 (a standard product from Murata Corp.), we obtain the following element values:

C_e = 1296 pF
C = 1.7 nF
L = 26.5mH
R = 912Ω

at resonance, $f_0 = 1/2\pi(LC)^{1/2} = 27KHz$. Now, the mechanical Q is calculated

$$Q_m = \omega_o M/\rho_o c 2\pi r H = \omega_o r T/\rho_o c = 4.9$$

and finally the electromechanical time constant can be determined

$$\tau = 2Q_m/\omega_o = 57.6\mu s.$$

The value of the elctromechanical time constant can be minimized by: i) reducing C_e (i.e., geometry), ii) placing cylinder in a denser medium (i.e. H_2O) would lower the Q, iii) using a ceramic with a lower material Q, and iv) increasing the inductance (i.e., mass).

The prime power required for driving PZT devices is an important consideration only if the the device is to be driven near its resonant frequency, where the acoustic impedance drops to a minimum. At this point, the capacitive reactance can be less that 1kΩ, and the power handling capacity of the ceramic must be considered, especially under high voltage operation. Materials with low dielectric losses under high electrical drive conditions are therefore desirable.

The theoretical calculations show that time delays of less that 1 ps to over 100 ps are achievable. However, many practical tradeoffs for device performance must be considered. Materials with a high electromechanical conversion constant and low Q are desirable. Fortunately, low Q materials also have the high d_{xx} coefficient necessary for the greatest possible range. Increasing the number of turns of fiber wrapped around a cylinder is one way of achieving a greater range, but too much mechanical stress on the ceramic can result in mechanical depolarization and poor performance. The exact choice of geometry need to be tailored to the particular application.

Alternative geometries employing a "gain" mechanism, e. g., the mechanical advantage produced by a piezoelectric cantelever, might also be investigated if larger motions are required from lower driving voltages; however, these devices have limited stretching capacity. Of course, the higher the frequency of the signal in the fiber, the less stretching is required to achieve a particular phase shift.

Time delays by changing the group velocity

In a step index multimode fiber the different modes travel with different velocities. In particular, lower-order modes, which travel along the center of the fiber, take shorter time to transit the FO link than higher-order modes which are continually reflected at the core-cladding interface, i.e. the optical path is longer for the higher-order modes.

It was also shown that by perturbing the fiber one can introduce mode coupling(7). If a narrow group of lower order modes are launched in a multimode fiber and due to external perturbation they are redistributed to higher order modes, then a time delay is observed. The phase shift can be written, for small angles θ, as:

$$\Delta\Phi = 2\pi(f \cdot \Delta t) \approx \pi(L/\lambda_g)\theta^2 \quad (3)$$

where

θ = angle between the rays of lowest and higher order modes

λ_g=wavelength of the lower order modes

The mode-dependent, programmable time-delay device described here is based upon an idea set forth by Yang, et al (8), who suggested that a local perturbation of the fiber will produce the desired mode coupling. To obtain a switchable time delay, a localized perturber is placed on the fiber at a distance L from the photodiode. Typically, the perturber would be a voltage-controlled piezoelectric microbending device. When actuated, the fiber microbender would convert a fraction of the on-axis light into higher-order modes. After traversing the fiber length L, the time-of-arrival of those higher-order modes would be delayed with respect to the arrival of the low modes. It is best to select a fiber with step index profile, because in such fiber it is relatively easy to restrict the number of modes launched.

We performed a simple proof-of-concept experiment. The FO portion of the experimental setup is shown in Fig. 5. The source (laser) and detector (PIN) were coupled to the microwave network analyzer to measure the phase shift. Restriction to the number of launched modes was acomplished by separating the input fiber from the step index fiber in the mechanical splice I by about 1 cm (see Fig 5). Therefore, only lower order modes were launched into a 3m-long step-index multimode fiber. To acomplish the phase shift, lower order modes were redistributed to higher order modes by locally microbending the fiber. The resultant phase shift, 15^o at 7 GHz, was observed on the HP 8510 network analyzer. The measured phaseshift ΔΦ agreed with the prediction, assuming $\theta = 1.6^o$.

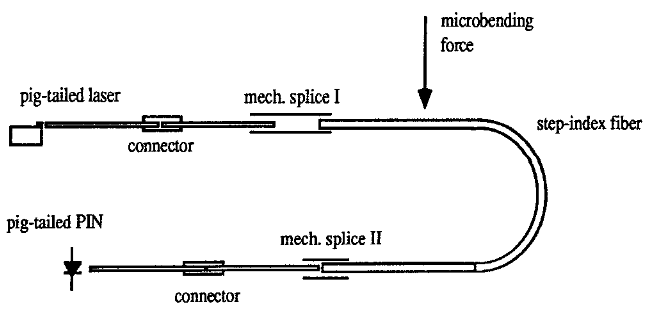

Fig.5. Experimental setup for mode-switching-induced phase shift measurement

The experimental setup used to measure the phase shift is shown in Fig.2. The BH laser diode from Ortel is modulated by the amplified signal from port 1 of the HP8510 network analyzer. The modulated optical signal is transmitted through 100m of multimode (50/125μm) optical fiber which is wrapped around a PZT cylinder. The modulated optical signal is detected by a high-speed photodiode, amplified and coupled to port 2 of the network analyzer. Then, transmission phase shift introduced by the PZT is recorded directly on the network analyzer.

First the phase of the transmission S-parameter (S_{21}) was measured with zero dc biasing to the PZT, to establish a reference phase. Then, upon application of dc voltage, the phase of S_{21} was measured and was compared to the reference phase. The results of the phase shifter measurements are presented in Table I. A phase shift of 20^o at 10GHz is obtained which corresponds to a time delay of 5.55psec, or the stretching the fiber by approximately 1.11mm. These results are in agreement with theoretical calculations for the particular PZT utilized. When the dc bias was reset to zero, the initial phase was recovered. The device showed good repeatability and linearity and no hysterisis effects.

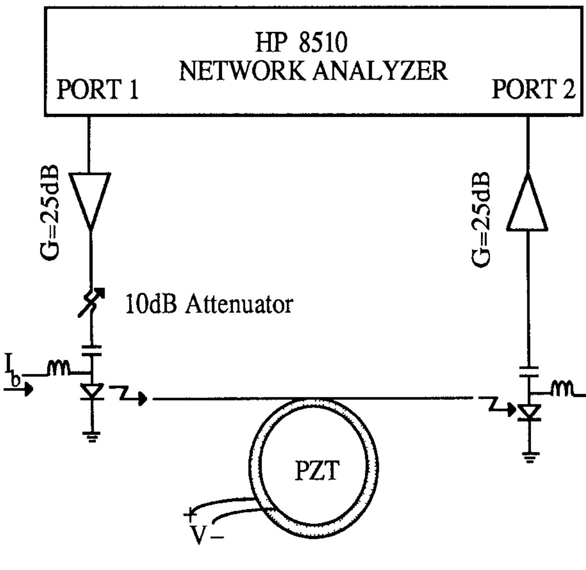

Fig. 2. Experimental set up for true time delay phase shifter.

These initial investigations were conducted using a standard PZT ring that was not designed for this type of application. The results revealed that the performance of the device in various applications is primarily determined by four parameters, namely: range, dynamics, power requirement and size. Some of these issues were theoreticaly analyzed for a cylindrical transducer. This geometry may not be optimal, but it provides a practical means for stretching the fiber since any number of turns can be wrapped around its circumference. It also provides a realistic starting point for the analysis and subsequent optimization.

The range refers to the minimum and maximum time delays that may be introduced, which of course also defines the range of phase shifts at a particular frequency. The range, determined by the achievable stretching, is limited by the PZT device; the fiber itself can be stretched to several percent of its length. The cylinder, shown in Fig.1, has an outside radius r and thickness T, and the ceramic is polarized so that only the thickness is expanded by $\Delta T = d_{33}E$.

For a ceramic cylinder with a strain coefficient of $d_{33}=200\times10^{-12}$m/V, and with the dimensions of r=20mm, H=30mm and T=6mm, an applied electric field of E=100 kV/m (or 600V) would produce an expansion of 0.125mm in the circumference. This suggests that 100 turns of fiber (12.5m) would yield a time delay of about 63psec. The above calculations were based on a standard ceramic type of piezoelectric material. It is evident that choosing a ceramic material with a higher piezoelectric strain coefficient would produce a greater ΔT and therefore a longer delay for the same applied field. Materials with a coefficient twice as large exist, and there are proprietary polymer based materials that promise significantly higher values. Increasing the applied voltage would also increase the range of delay but may be impractical since at very high potentials, some ceramics become depolarized and lose their electro-mechanical transformation efficiency.

Another important consideration is the time response of the device. The analysis is based on an equivalent circuit model for the transducer taking into consideration its geometry and material properties. From the circuit model, the resonant frequency (ω_o) and the mechanical Q (Q_m) can be calculated. Then, the time constant for a step input voltage is given by $\tau=2Q_m / \omega_o$.

The electromechanical equivalent circuit takes the following form:

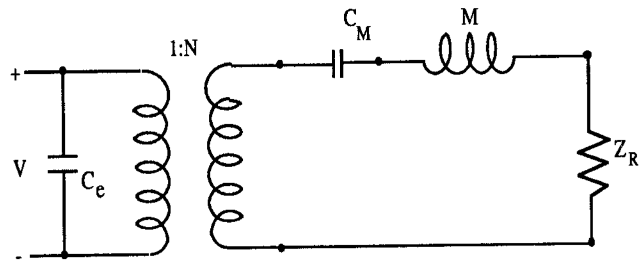

Fig.3 Equivalent circuit for the PZT device.

In Fig. 3 the terms are defined by:

C_e = Electrical Capacitance (F)= $2\pi\varepsilon_o\varepsilon_r T / \ln[r/(r-T)]$

N = Linear Tranf. Ratio (Coul./m)=$(4g_{33}/k_{33})(2\pi rH/T)$

g_{33}=Voltage Output Coefficient (V/m)

k_{33} = Electro-mechanical Coupling Coefficient

M = Effective Mass (kg) = $\rho \cdot V$

Z_r = Mechanical Radiation Resistance (kg/sec)= $\rho_0 c 2\pi rH$

C_m= Compliance (m/Newton)= $(4/\pi Y)\{T/\ln[r/(r-T)]\}$

Y= Young's modulus

$\rho_0 c=1.5\cdot10^6$kg/m^2/s (for air)

The equivalent electrical circuit values (see Fig.4) are obtained by adjusting each of the electromechanical elements by the transformation ratio N^2.

Multiple time delays may be accomplished by placing independent microbenders at selected locations, $L_1, L_2, L_3, ... L_N$ on the step index fiber and thereby obtaining N independent time delays $\Delta t_1, \Delta t_2, \Delta t_3, ... \Delta t_N$. The fiber could be coiled and the N perturbers could be grouped on the coil form. Each local perturbation would occupy only a few mm of the fiber. Note that large amplitude deformations of the fiber are not required here because the microbends do not have to be deep enough to produce core-to-cladding conversion of the light, that is, the light always remains within the fiber core in this time delay device. For electromechanical deformers, the switching time required to alter the delay from Δt_1 to Δt_k is estimated to be 1 to 10 millisec. This implies that the pointing direction of radiation beam from an optically controlled phased-array antenna could be changed (in random-access fashion) in a few ms with fiber devices of this kind.

To increase the response time an all-electronic mode switching mechanism, with switching speeds in the ns to µs range, may be employed. It has been shown that an "active cladding" placed locally on the core of a multimode fiber converts low-order mode light into higher-order modes.(9) The desired mode conversion is produced by a refractive -index discontinuity in the optical transmission line due to the differing "on" and "off" states of the active cladding segment. (The active cladding off state index is matched to the inactive cladding index.) Verification of this mode redistribution principle has been obtained with nematic liquid-crystal cladding.(9)

SYSTEM CONSIDERATIONS

Introducing time delays in the optical domain can lead to novel beamsteering, thus reducing the need for complex beam control methods.(4) Let us consider, for the purpose of illustration, an eight element linear array which is pointing to a certain direction in azimuth coordinate. A progressive phase shift (i.e. ϕ_o, $2\phi_o$, $3\phi_o$,... $8\phi_o$) are introduced by a linear time delay (t_o, $2t_o$, $3t_o$,... $8t_o$) in the respective feed lines. The time delay t_o determines the direction of the constructed beam. By changing time delay, t_o to t_1, the beam is steered to a different direction . Clearly, as the time delay is continuously varied, the beam is scanned.

Implementation of this beam scanning technique is in principle simple. Once again considering the previous example of the eight element linear array the beam can be constructed and steered using a PZT ring. The fiber linking the first element is wrapped around the PZT N times, the fiber to the second element 2N times,... the fiber to the eighth element is wrapped around 8N times. As the potential is applied to the piezo-electric ring it expands, stretches the fiber and introduces progressive time delays in the successive elements. These variable time delays control the beam direction. The advantage of this technique is that a single analog signal applied to the ring steers the entire sub-array.

Two additional points are in order. First, the above described procedure can be extended to steer in two dimension an 8 by 8 rectangular subarray. This would of course require several identical PZT devices. Secondly, by cascading the PZT devices in a systematic manner, not only the sub-arrays, but the entire large aperture array may be controlled by the PZT devices.

CONCLUSION

Two types FO based true time delay phase shifter devices were presented. The system application of these devices was explored.

ACKNOWLEDMENT

The authors wish to acknowledge RADC/EAC and the Ben Franklin partnership of the state of Pennsylvania for their support.

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DC Biasing Voltage (KV)	0	1.6	2.4	3.2	4.2
$\angle S_{21}$ Phase shift	Reference	-7^o	-12^o	-16^o	-20^o

Table II. The transmission phase shift ΔS_{21} as afunction of dc biasing.