Performance characteristics of 5-bit optical Receive beamformer

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ABSTRACT

This paper describes implemented methods for characterizing a 5-bit programmable dispersion matrix (PDM) that is built to control a two-channel Receive beamformer in the 1550 nm region. The architecture of the PDM, is based on an array of 5 delay lines each having two spliced fiber Bragg gratings. Phase measurements for 32 possible delay configurations of the PMD are presented. Beam-patterns of this Receive beamformer at RF frequencies of 0.2, 0.5 and 1 GHz agrees well with the theoretical calculations. The main lobe of the beam pattern is shown to be independent of frequency for several target positions thus demonstrating a "squint-free" characteristic of this optical processor.

Keywords: Optical delay lines, Fiber Bragg gratings, Phased-array radar, Optical beamforming.

1. INTRODUCTION

Many RF and microwave systems, such as high-resolution phased-array antennas and signal processing electronics, require true-time delay (TTD) phase shifters. In such systems the individual T/R-element control allows the implementation of beam steering and shaping. In those cases, the antennas are required to have wide scan angles, wide operational bandwidths and multiple simultaneous independent beams. In conventional RF systems, TTD is achieved by switching to different lengths of electrical cable. However, these implementations tend to be bulky, heavy and susceptible to electromagnetic interference. The fiber-optic control systems provide benefits in the above areas.

A variety of optical techniques have been proposed for obtaining TTD capability using fiber-optic systems [1]. In particular, systems using fiber Bragg reflectors for providing time delays have been proposed and demonstrated by Soref [2] and Zmuda et al. [3]. In Ref. [4] a 2-bit transmit/receive module using a fiber Bragg grating matrix has been demonstrated.

In this paper we design and experimentally demonstrate a two-channel true-time delay programmable matrix for controlling a phase array antenna. The wideband processor has a resolution of 5-bit. In section 2 we describe in detail the theory of the beamformer for transmit and receive modes. The experiment is presented and results are discussed in section 3. Concluding remarks are given in section 4

2. THEORY

Figure 1(a) shows a schematic drawing of the beamformer architecture in the transmit mode. Two diode lasers provide optical carriers (channels) with wavelength λ_1 and λ_2. Both channels are multiplexed and externally modulated with an RF signal using an electro-optic modulator (EOM). Modulation of multiplexed channels ensures zero phase delay between the RF components before the optical carrier is processed. The modulated carrier feeds a

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programmable dispersion matrix, which performs the true-time delay processing. For each configuration of PDM λ_1 either leads or lags λ_2 by a time-period. At the output of PDM, where a proper phase difference is set, channels are demultiplexed. Two broadband photo-detectors recover the delayed RF signals that would feed the antenna elements.

The 5-bit architecture of the PDM, which is based on fiber Bragg grating (FBG) arrays, is shown in Figure 2. The N-bit version of two-channel architecture consists of an array of N delay lines. Each delay line is constructed by splicing two FBGs. The center wavelength of each FBG matches one of the multiplexed optical channels. The separation between Bragg reflectors is different for each delay line. Thus, the time delay(s) between channels are proportional to these FBG separations. The separation of two adjacent gratings for the ith line is given by

$$\Delta L_i = 2^{i-1} \Delta L_1 , \tag{1}$$

where ΔL_1 is the minimum separation between gratings that corresponds to line 1. Using Eq. (1) the time delay provided by the ith line can be written as

$$\tau_i = \frac{2 \, n_{eff} \, \Delta L_i}{c} , \tag{2}$$

where n_{eff} is the effective refraction index of the fiber and c is the speed of light. Each of the 2^N delay configurations of the PDM is an integer multiple, m, of minimum time delay τ_1. The minimum time delay, associated with line 1, is directly related with the angular resolution and the minimum steering angle of any beamformer [5].
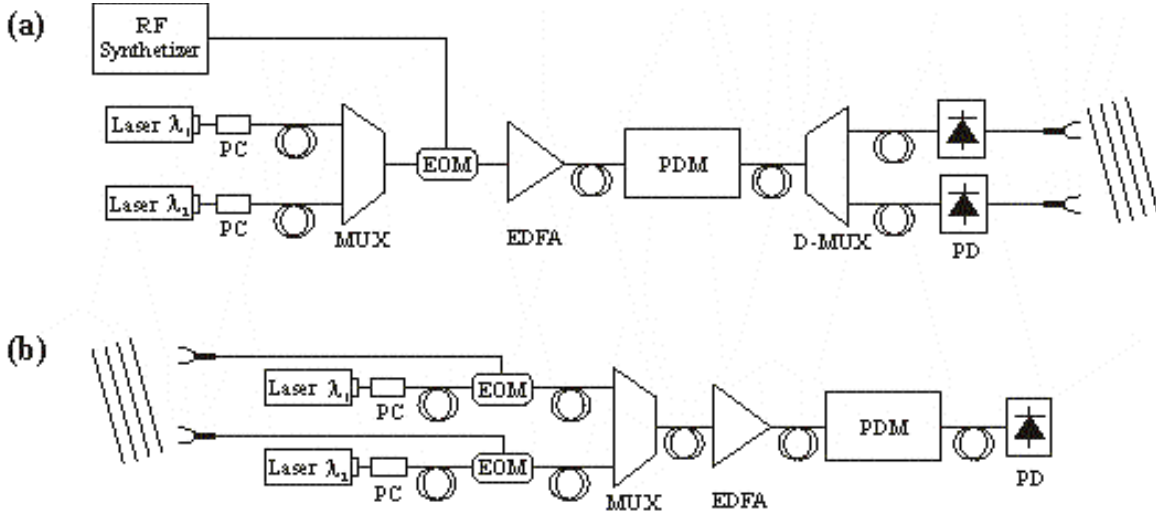

Figure 1: Beamformer setup configuration for: **(a)** Transmit mode. **(b)** Receive mode.

The steered angle θ_m is related to a characteristic parameter of the PDM, that is τ_1, and a geometrical parameter of the antenna, the T/R element spacing Λ, by

$$\theta_m = \arcsin\left(\frac{c \, m \, \tau_1}{\Lambda}\right). \tag{3}$$

In Figure 1(b) the schematic for a receive-mode is shown. An incoming RF signal from a target is received by the two antenna array elements. The phase difference at the antenna elements depends on the target angle. The received RF signal at each element separately modulates two individual optical carriers. The time delay between the multiplexed optical channels is corrected by the PDM and detected with a single photodetector. The output power of the photodetector is a function of the corrected phase difference between the two RF signals

$$P(dB) = 10 \log\left(K_1 + K_2 \cos \Delta\phi\right), \tag{4}$$

where $\Delta\phi$ is the phase difference and K_1, K_2 are the proportionality constants. Thus, the output power is related to the target angular position via this phase difference. When the PDM corrects for the phase difference at the antenna elements a maximum power will be detected for the target position.
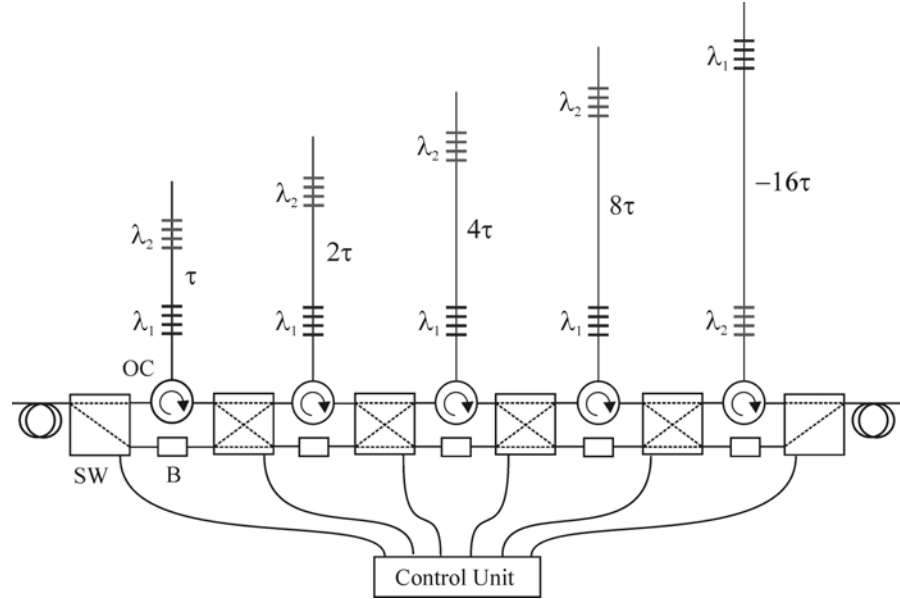

Figure 2: Two-channel 5-bit programmable dispersion matrix. SW: optical switch, B: optical balancer, OC: optical circulator.

3. EXPERIMENT AND RESULTS

Two 15 mW semiconductor lasers, Alcatel model A1905LMI, with wavelengths of 1551.7 nm and 1550.9 nm provide optical carriers. Two in-fiber polarization controllers set proper polarization at the input of the 10 GHz SDL EOMs. The experiment is performed over a 5-bit PDM that provide 32 delay configurations. The central wavelengths of the fiber Bragg gratings match ITU frequency channels 32 and 33 (100 GHz spacing). All the gratings have reflectivity from 94.8% to 99.3% and FWHM of 0.3nm. For lines 1 to 4 the first FBG reflects light of channel ITU 32 meanwhile the second FBG reflects light of channel ITU 33. In the last line of the array the order of FBG is reversed to obtain time delays of opposite sign. Reversal of the gratings for the last delay line permits channel 32 to both lead and lag channel 33 thus allowing symmetrical beamforming. Hence the 32 possible delay configurations are

$$\tau_m = m\tau_1, \quad m = -16,\dots,15. \tag{5}$$

The minimum separation between FBG is $\Delta L_1 = 0.02\,\mathrm{m}$ corresponding to the line 1. Separations for successive lines are: $\Delta L = 0.04\,\mathrm{m}$, 0.08 m, 0.16 m, and 0.32 m. The theoretical minimum time delay of the PDM, calculated from Eq. (2), is $\tau_1 = 195.8\,\mathrm{ps}$. Optical circulators are used to route the signals to/from the lines. In order to get all the delay configurations, two 1X2 and four 2X2 Hitachi optical switches are programmed. The switches are controlled by means of an Agilent 34970A data acquisition unit. The insertion loss of the system is approximately 26 dB. The main sources of loss are the EOM biased on quadrature (6-8 dB) and the connectors in PDM. Due to the losses over the system, an IPG Photonics erbium doped fiber amplifier (EDFA) with 25 dB gain is present to improve the dynamic range of the network.

3.1 Transmit mode characterization

In order to characterize the network in its transmit mode the configuration in Figure 1 is used. The modulator is fed with an RF signal out of port #1 of a Vector Network Analyzer. Port #2 detects the RF signal out of the Thorlabs DC400FC photodetectors, one at a time. Therefore, the phase and magnitude of s-parameter S_{21} are

measured for each channel. For a given frequency, the time delay introduced by the PDM can be obtained by subtracting the phase values associated with the parameter S_{21} for the two channels

$$\Delta\phi_m = \phi_0 + 360\nu_{RF}\,\tau_m,\tag{6}$$

where $\Delta\phi_m$ is the phase difference for the mth delay configuration, ν_{RF} is the RF frequency, and ϕ_0 is an arbitrary constant phase shift. Figure 3(a) shows the unwrapped phase difference between channels for switching configurations involving: no delay and each of the five delay lines.
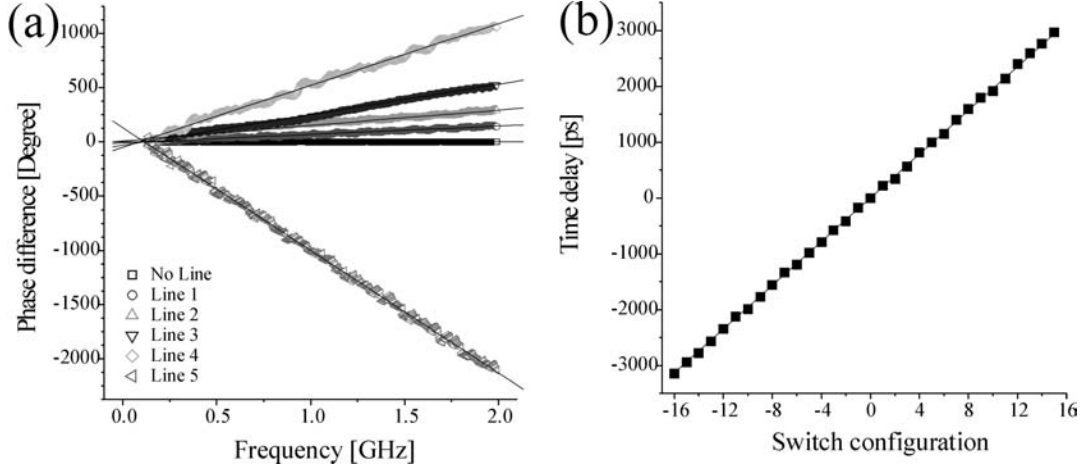

Figure 3: (a) Phase difference vs. RF frequency for: no delay and delay lines 1-5.
(b) Time delay versus switch configuration (parameter m) for all the possible delays in PDM.

The experimental data is obtained by sweeping the RF signal of the vector network analyzer between 130 MHz and 2 GHz. The time delay is calculated from the slope of the linear fit to the data using Eq (6). Figure 3(b) shows the time delays for all the possible configurations of the PDM. The minimum time delay corresponding to line 1 is calculated to be 219.3 ps. The linear behavior of the curve shows a good agreement with Eq. (5). Measurement errors are less than 10% and are attributed to grating spacing errors and random phase changes in the RF cables. Figure 4 shows a beam pattern at 500 MHz calculated using Eq. (4) and the experimental values from time delays given in Figure 3(b). The plots are obtained for beam steering of approximately -70° to +70°, using $\Lambda = 1$ m as element spacing of the antenna-array.
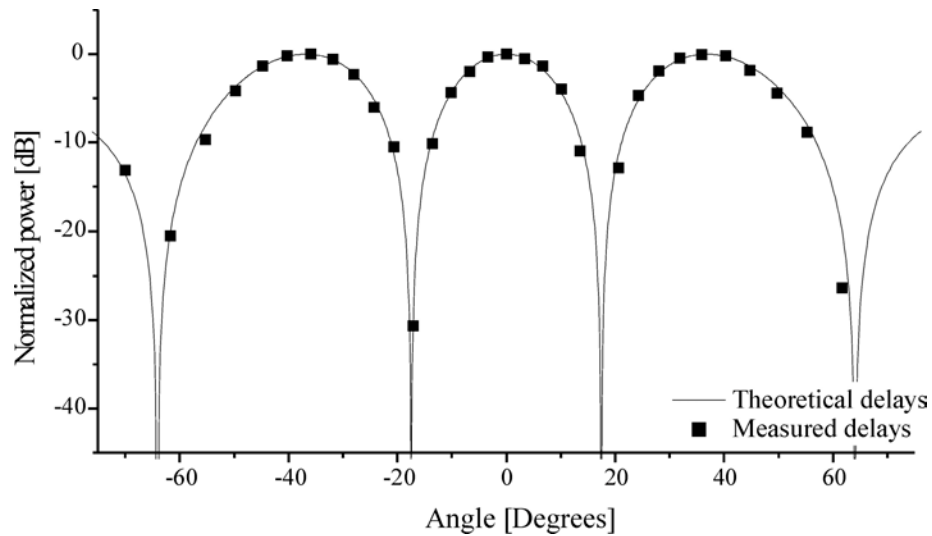

Figure 4: Beam pattern at 500 MHz calculated using Eq. (4) from: theoretical time delays (solid line), and experimental time delays (squares).

3.2 Receive mode characterization

An HP model 83650A RF synthesizer simulates an incoming RF signal from a target. The output of the RF synthesizer is split and sent to optical modulators shown in Figure 1(b). To simulate the phase difference between two antenna elements due to a moving target an RF phase shifter is introduced before one of the modulators. Since the reflectivity of FBGs is different the optical power out of the network changes with each delay configuration. To compensate for this change one of the lasers is coupled to an EXFO FVA3100 programmable optical attenuator. Beam patterns are constructed by sweeping the RF phase shifter and measuring the RF output power from the single photodetector using a Tektronix 2782 RF spectrum analyzer.
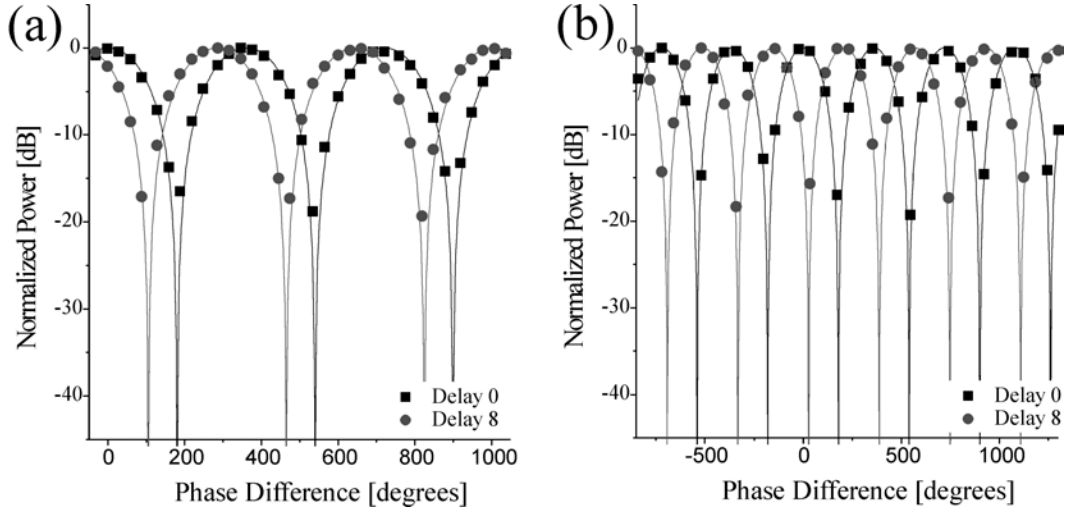

Figure 5: Beam patterns obtained in Receive mode for no delay and delay line 4 at frequencies: **(a)** 500 MHz. **(b)** 1 GHz.
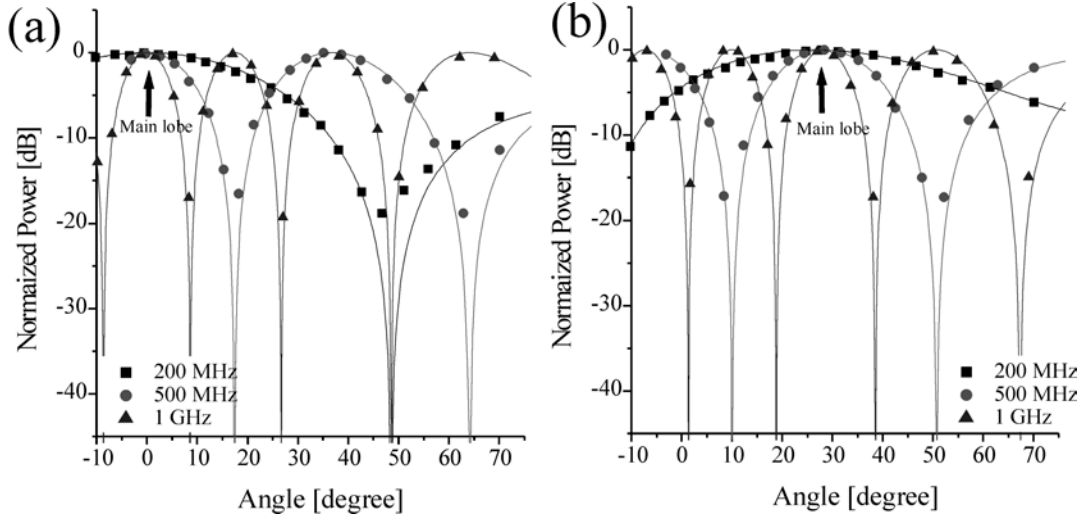

Figure 6: Beam patterns measurement for Receive mode at 0.2, 0.5 and 1 GHz frequencies for: **(a)** target at broad side position and **(b)** target at angular position of 28.02°.

Figure 5(a) and (b) illustrate beam patterns measured for RF frequencies of 0.5 and 1 GHz respectively. In each case, beam patterns are shown for two PDM delay configurations: zero and $8\tau_1$. Figure 6 shows beam pattern measurements for RF frequencies of 0.2, 0.5 and 1 GHz. Figure 6(a) correspond to zero delay, that is the optical carriers do not pass through any of the FBG. Hence the target is detected at the broadside position. While Figure 6(b) the carriers pass through the 4th delay line to provide a delay of $8\tau_1$. In this case, the PDM is programmed for detecting the target at angular position of 28.02°. For all the above figures, the experimental data are fit to Eq. (4) by using a nonlinear curve-fit routine. Notice that the antenna steering-angle is a function of phase delay and separation

of antenna elements but it is not a function of the RF frequency. The position of the main lobe in Figure 5 is shown to be independent of frequencies between 0.2 and 1 GHz demonstrating the "squint-free" characteristic of the processor.

Our measurements are limited to 1 GHz in order to obtain a reasonable number of data points per beam lobe. Otherwise, for the receive mode, the upper limit is set by the phase shifter, which had a bandwidth of 2GHz. In the transmit mode, the readings are limited by the photo-detector, which has a bandwidth of 2 GHz.

3. CONCLUSIONS

In conclusion, we have analyzed and characterized a 2-channel 5-bit optical beamformer system operating at 1550nm using a symmetric programmable dispersion matrix. The working prototype is used to demonstrate time-delay measurements in the transmit mode and beam pattern measurements in the receive mode for the RF 0.1-1.2 GHz frequency range. These beam patterns are obtained for target positions at broad side and $28.02°$ for steering angles of $\pm 70°$. Our optical beamformer exhibits squint-free radiation pattern in RF band of 0.2-1.0 GHz.

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