

BINARY AND TERNARY ARCHITECTURES FOR A TWO-CHANNEL 5-BIT OPTICAL RECEIVE BEAMFORMER

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Abstract: Binary and ternary 5-bit programmable dispersion matrix is built to control a two-channel receive beamformer at 1550 nm. Phase measurements for the delay configurations along with beam-patterns at RF frequencies 0.2-1 GHz are presented.

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 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 [2,3]. 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 binary and ternary version of a two-channel true-time delay programmable matrix for controlling a phase array antenna. The wideband processor has a resolution of 5-bit.

2- SYSTEM OVERVIEW

The schematic drawing for a receive-mode beamformer is shown in Figure 1. 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 position. The received RF signal at each element separately modulates two individual optical carriers, which are provided by laser diodes with wavelength λ_1 and λ_2 .

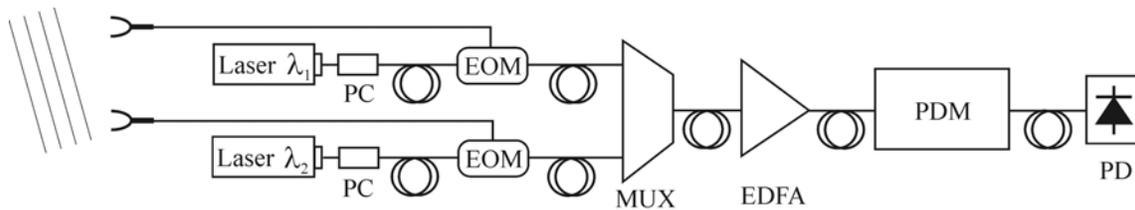


Figure 1: Beamformer setup configuration for receive mode.

The modulation is performed by two Mach-Zender electro-optic modulators (EOM). The multiplexed optical carriers feed a programmable dispersion matrix, which performs the true-time delay processing. The time delay between 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

$$P(\text{dB}) = 10 \log(K_1 + K_2 \cos \Delta\phi), \quad (1)$$

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.

The architecture of a 5-bit programmable dispersion matrix (PMD), 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 i^{th} line is given by

$$\Delta L_i = 2^{i-1} \Delta L_1, \quad (2)$$

where ΔL_1 is the minimum separation between gratings that corresponds to line 1. Using Eq. (2) the time delay provided by the i^{th} line can be written as

$$\tau_i = \frac{2 n_{\text{eff}} \Delta L_i}{c}, \quad (3)$$

where n_{eff} is the effective refractive 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]. 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

$$\theta_m = \arcsin\left(\frac{c m \tau_1}{\Lambda}\right). \quad (4)$$

In the binary approach shown in Figure 2(a), the order of FBGs in the last line is reversed. This inversion allows symmetrical beamforming by obtaining time delays of opposite sign when the last line is combined with the others. Time delays with opposite sign can also be achieved by routing the optical signal to the top end of a delay line. In the ternary PDM shown in Figure 2(b) this approach is used to obtain symmetrically distributed delay configurations.

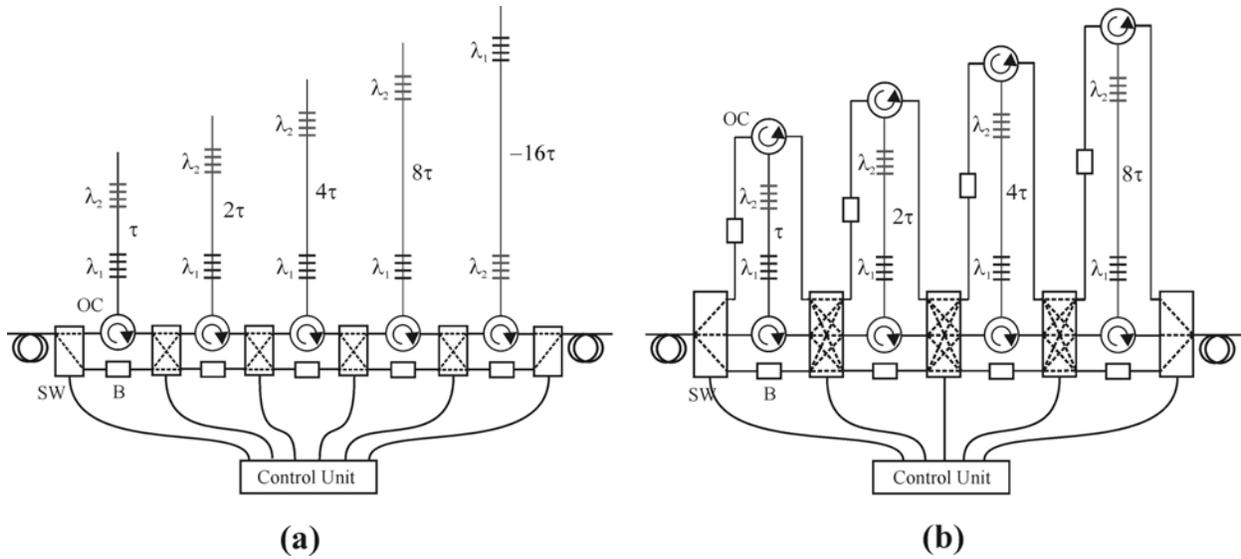


Figure 2: Two-channel 5-bit programmable dispersion matrix for: (a) Binary switching configuration; (b) Ternary switching configuration. SW: optical switch, B: optical balancer, OC: optical circulator.

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. According with figure 2(a) the order of FBGs for line 5, in the binary version, is reversed in order to obtain symmetrical beamforming. Hence the 32 possible delay configurations are

$$\tau_m = m \tau_1, \quad m = -16, \dots, 15. \quad (5)$$

The minimum separation between FBG is $\Delta L_1 = 0.02$ m corresponding to the line 1. Separations for successive lines are: $\Delta L = 0.04$ m, 0.08 m, 0.16 m, and 0.32 m. The theoretical minimum time delay of the PDM, calculated from Eq. (2), is $\tau_1 = 195.8$ ps. Optical circulators are used to route the signals to/from the lines. In the binary version (Figure 2a),

two 1x2 and four 2x2 optical switches are programmed in order to obtain all the delay configurations. However, for the ternary system (Figure 2b) two 1x3 and three 3x3 optical switches are used to set the delay configurations. In both approaches optical switches are controlled by means of an Agilent 34970A data acquisition unit. The optical 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 the PDM. Due to optical losses over the system, an IPG Photonics erbium doped fiber amplifier (EDFA) with 25 dB gain is inserted to improve the dynamic range of the network.

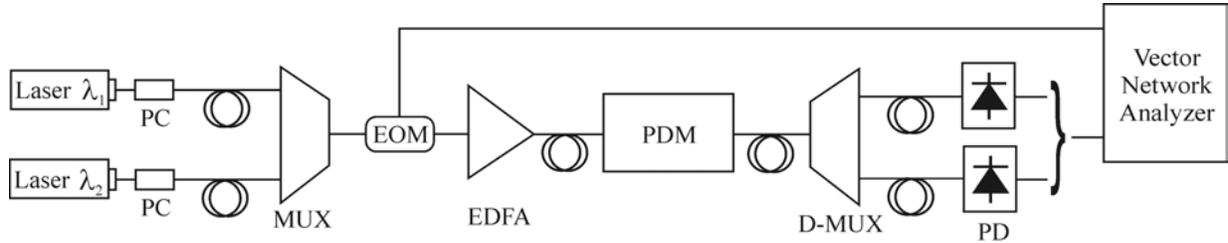


Figure 3: System configuration for measuring time delays.

Time delay characterization: The setup shown in Figure 3 is used to characterize the time delay lines. 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

$$\Delta\phi_m = \phi_0 + 2\pi\nu_{RF} \tau_m, \quad (6)$$

where $\Delta\phi_m$ is the phase difference for the m^{th} delay configuration, ν_{RF} is the RF frequency, and ϕ_0 is an arbitrary constant phase. Figure 4(a) shows the unwrapped phase difference between channels for switching configurations involving: no delay and individual delay lines 1 to 5.

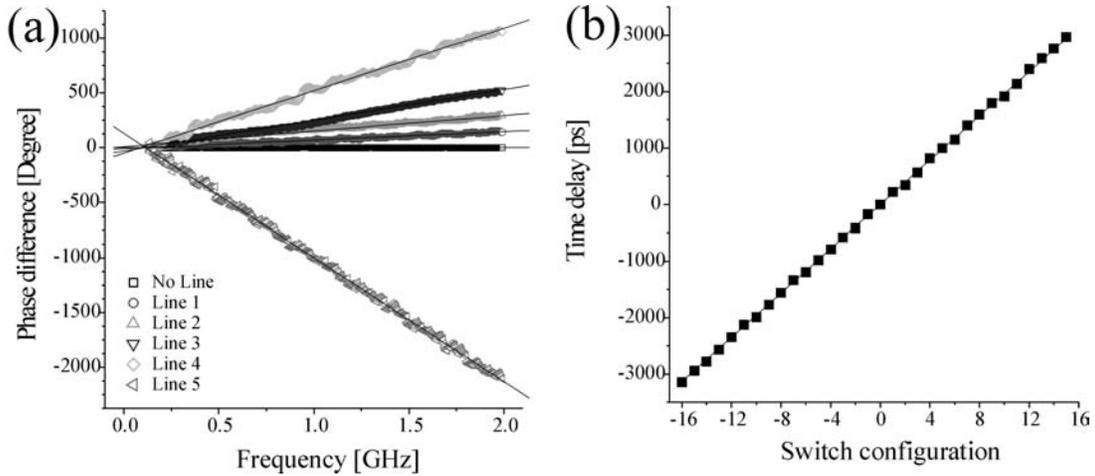


Figure 4: (a) Phase difference vs. RF frequency for: no delay and delay lines 1-5. (b) Time delay versus switch configuration (parameter m) for all the possible delays in PDM.

The experimental data is obtained by sweeping the RF signal from 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 4(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.

Receive mode beam pattern 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. 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 each FBG is different the optical output 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.

Beam patterns are measured for RF frequencies between 0.1 and 1.3 GHz. Figure 5 shows beam pattern measurements for RF frequencies of 0.2, 0.5 and 1 GHz. Figure 5(a) correspond to zero delay, that is the optical carriers do not pass through any of the FBG lines. Hence a target is detected at the broadside position. While Figure 5(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 a target at angular position of 28.02° . For all the above figures, experimental data are fit to Eq. (1) combined with Eq. (4) for $\Lambda = 1$ m. 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, the upper limit is set by our phase shifter, which has a bandwidth of 2GHz.

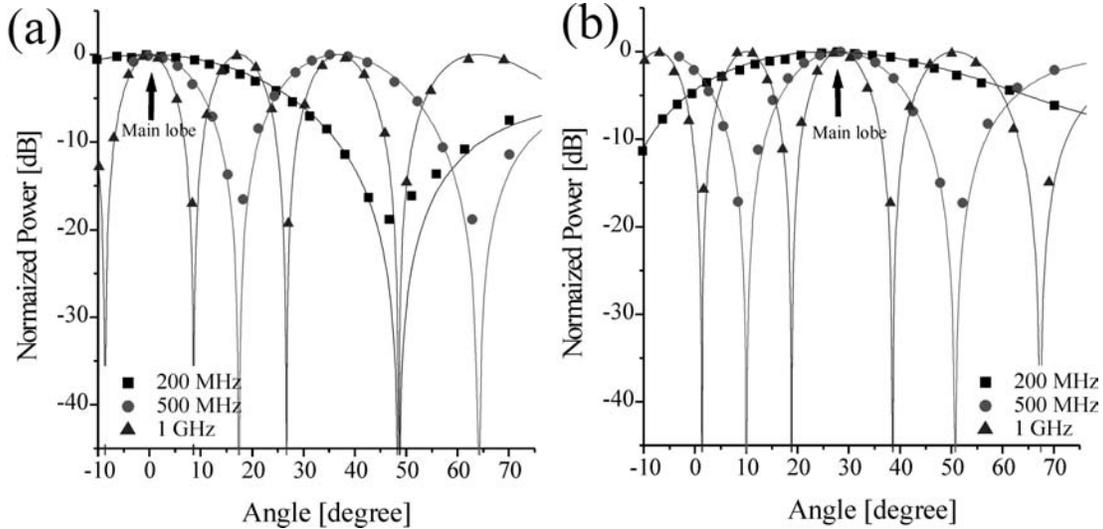


Figure 5: Beam patterns measurement for Receive mode at 0.2, 0.5 and 1 GHz frequencies for: (a) target at broad side position and (b) target at angular position of 28.02° .

4- DISCUSSION AND CONCLUSIONS

In conclusion, we have analyzed and characterized a 2-channel 5-bit optical beamformer system operating at 1550nm using a binary and ternary 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 0.1-1.3 GHz frequency range. These beam patterns are obtained for target positions at broad side and 28.02° for steering angles of $\pm 70^\circ$. Our optical beamformer exhibits squint-free radiation pattern in RF band of 0.2-1.0 GHz.

The use of FBG and WDM architecture to produce time delay for each antenna element can be extended to process multiple simultaneous beams. A simple prototype for processing two independent simultaneous beams in a 3-bit 2-channel beamformer is currently under investigation and its development and preliminary results will be presented at the conference.

ACKNOWLEDGMENTS

The authors would like to thank Dan Purdy of Office of Naval Research for his support of this project under the contract number N00014-00-1-0782.

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