Optical fiber beamformer for processing two independent simultaneous RF beams

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ABSTRACT

We propose a novel architecture for an optical programmable dispersion matrix (PDM) able to process simultaneous independent RF beams. The proposal is demonstrated by processing the transmission of two independent RF signals in two-channels with a resolution of 3-bit. The optical beamformer processes two independent RF-beams, for eight different angular directions, and it is based on a binary array of three delay lines. Each delay line is composed of four fiber Bragg gratings whose center wavelengths are channels 30 to 33 of the ITU grid. Beampatterns are characterized in transmit mode for two simultaneous RF beams in 0.6-1.5 GHz frequency range and azimuth angles from 0^o to 70^o.

Keywords: Optical beamforming, True-time delay, Fiber Bragg gratings, RF-photonics, Phased array antennas.

1. INTRODUCTION

Phased-array antennas with beamforming networks for controlling individual T/R elements are used widely in radar and satellite communication. The use of photonic processing techniques for such antennas compares favorably with conventional electronics in terms of instantaneous bandwidth, weight, size and isolation for electromagnetic interference.

Several 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 [2-7]. Non-TTD beamforming is possible by using two-dimensional Fourier transform techniques. This approach is used to design optical processors to drive a multibeam antenna array in transmit mode [8] as well as in receive mode [9].

In the present paper, we propose a novel architecture for a programmable dispersion matrix (PDM) able to process simultaneous independent RF beams. The proposal is demonstrated by processing the transmission of two independent RF signals in two-channels with a resolution of 3-bit.

2. SYSTEM OVERVIEW

Figure 1 shows a schematic drawing of the two-beam beamformer in transmit mode. The optical beamforming network can control an antenna array with two radiating elements. Four diode lasers provide optical carriers with wavelengths ë$_1$ to ë$_4$ (channels). The even wavelength channels (ë$_2$ and ë$_4$) and odd wavelength channels (ë$_1$ and ë$_3$) are multiplexed together by using 1x2 fiber couplers. The combined even and odd channels are then separately modulated with two different RF-signals using electro-optic modulators (EOM). Modulation of multiplexed channels ensures zero phase delay between the RF-signals before the optical carriers are processed. The modulated optical carriers feed a programmable dispersion matrix (PDM), which performs the true-time delay processing.

The PDM is capable of providing independent time delays between the even and odd wavelength channels. For each configuration of the PDM, ë$_2$ lag ë$_4$ and ë$_1$ lag ë$_3$ by an independent time-period. Each pair of carriers processes

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the information for one RF-beam. At the output of the PDM, after the proper phase difference is set between the even/odd optical carriers, the optical signals are demultiplexed. Four broadband photo-detectors recover the delayed RF signals that are linearly combined to feed the antenna T/R elements.
The transmit beampatterns are characterized for a far-field observer located at broadside, when the main lobe of the RF-beam is steered by changing the time-delay configuration of the PDM. Assuming isotropic radiating elements the theoretical beampattern can be calculated from power variations given by

$$P(dB) = 20 \cdot \log(p \cdot f_{RF} \cdot t) + K, \tag{1}$$

where K is a proportionality constant, $\hat{o}$ the introduced time delay between the even respectively odd optical carriers and f_{RF} is the frequency of the transmitted RF-signal.

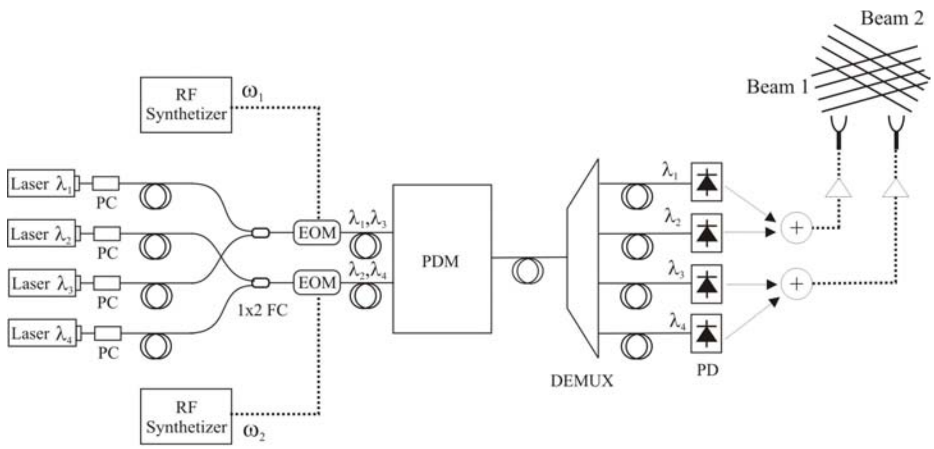

Figure 1: Beamformer setup for transmit mode operation. Even and odd channels process the information of separate RF-beams. PC: Polarization Controller, PD: Photodiode, FC: Fiber Coupler

2.1 PDM in binary architecture

The architecture of a binary 3-bit two-beam PDM, which is based on fiber Bragg grating (FBG) arrays, is shown in Figure 2. The N-bit version of the two-beam binary architecture consists of an array of N delay lines. Each delay line is constructed by splicing four FBGs. The center wavelength of each FBG matches the wavelengths of the multiplexed optical channels. The separation between FBGs with center wavelengths corresponding to the even/odd channels is increased in multiples of two from delay line to delay line. Thus, time delays between channels are proportional to these FBG separations. The separation of two adjacent gratings with central wavelengths corresponding to the even respectively odd channels of the ith line is given by:

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

where ÄL_1 is either the minimum separations between the gratings which correspond to the even/odd channels of delay line one. Using equation (2) the time delay provided by the ith delay line for the even/odd channels can be calculated to:

$$t_i = \frac{2 \cdot n_{eff} \cdot \Delta L_i}{c}, \tag{3}$$

where n_{eff} is the effective refraction index of the fiber and c is the speed of light.

The programmable switch units are able to route the even and odd wavelength channels independently from each other through the PDM. Each switch unit consists of two 1x2 switches and two 1x2 couplers. The upper switch routes the odd channels either to the delay line for introducing a time delay between the channels, or to bypass the

delay line. The lower switch has the analogous function for the even wavelength channels. The 1x2 couplers are used to combine the outputs from both switches going either to the delay or bypass line. Figure 2 shows also the four possible switch configurations for each switch unit. Optical circulators route the optical channels to and from the delay lines. A 1x3 fiber coupler is used to combine the optical signals coming from the delay line and the bypass line. After the first 1x3 coupler, the four optical channels are amplified with an erbium doped fiber amplifier (EDFA) to compensate for the losses of the PDM. After the amplification an optical interleaver is used to separate the four multiplexed channels again into even and odd channels. The optical interleaver is followed by the next switch unit and delay line. This structure repeats itself until the 1x3 coupler after the last delay line is reached.
For the 3-bit version eight different delay configurations between the even/odd optical channels are possible. The time delays between the even/odd optical carriers increase linearly with the delay configuration (parameter m) of the PDM:

$$t_m = t_1 \cdot m \quad . \tag{4}$$

The steering angles f_m for the two RF-beams are related to the introduced time delay between the even/odd optical carriers:

$$f_m = \arcsin \frac{c \cdot m \cdot t_1}{d} , \tag{5}$$

where d = 33 cm is the assumed separation between the T\R elements of the antenna array.

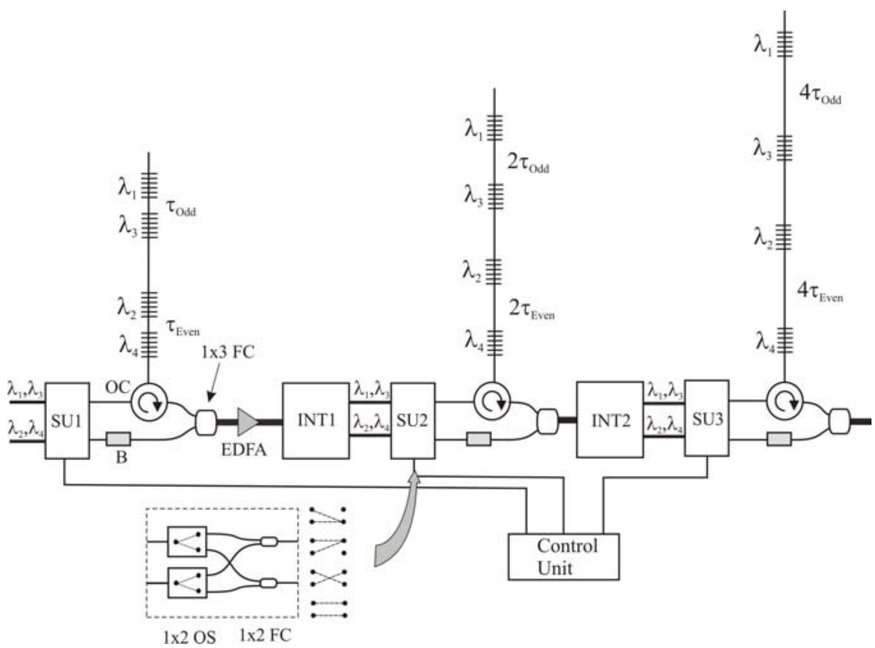

Figure 2: Two-beam two-channel 3-bit programmable dispersion matrix (PDM) in binary configuration. SU: Switch Unit, OS: Optical Switch, B: Optical Balancer, INT: Optical Interleaver, OC: Optical Circulator, FC: Fiber Coupler.

2. RESULTS

The even wavelength channels (ITU-frequency channels 30 and 32) and odd wavelength channels (ITU frequency channels 31 and 33) are provided by four 15 mW semiconductor lasers. Four in-fiber polarization controllers set proper polarization at the input of the 10GHz bandwidth EOMs. The central wavelength of the FBGs match ITU frequency channels 30 to 33. All gratings have reflectivity from 98.6% to 99.8 % and FWHM-bandwidths from 0.38 to 0.69 nm. The minimum separation between the FBGs with central wavelengths, which match the even (odd) ITU channels, is ÄL = 1.4 cm (1.5cm). Separations for successive lines are: ÄL = 2.8 cm (3.0 cm) and 5.6 cm (6.0 cm). The theoretical minimum delay between the even (odd) wavelength channels, calculated from Eq. (3), is $ô_1$=137 ps (147 ps).

Six 1x3 optical switches are used to route the optical signals through the PDM. The optical switches are controlled using an Agilent 34970A data acquisition unit. Note that the optical signals will undergo different levels of attenuation depending on upon the delay configuration, because the number of the components is different for each path. Thus, as the insertion loss of the PDM is path dependent, spurious power variations for different delay configurations can affect the measurements. In order to balance to the optical power in the PDM, in-fiber air gap attenuators are placed in each bypass path. The optical insertion loss of the PDM is approximately 42 dB. The main sources of the losses are the 1x3 fiber couplers with 5.5 dB loss and the 1x2 couplers with 3.6 dB loss. Due to the optical losses over the PDM, an EDFA with approximately 37 dB gain is inserted to improve the dynamic range of the optical beamforming network.

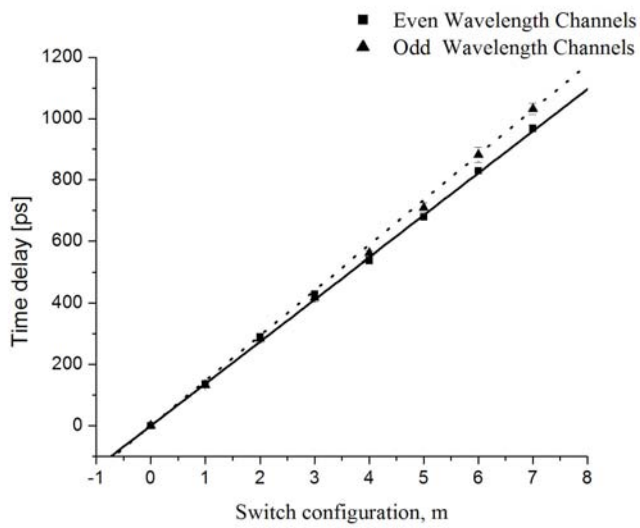

Figure 3: Time delay between even/odd channels versus switch configuration (parameter *m*) for all possible time-delays in PDM.

3.1 Time-delay measurements

In order to characterize the delay-lines a slightly modified version of the setup shown in Figure 1 is used. The modulator for the even/odd wavelength channels is fed with an RF-signal out of port #1 of a Vector Network Analyzer. Port #2 detects the RF-signals out of the two photo detectors (used for the even/odd wavelength channels) one at a time. Therefore, phase and magnitude values for the 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 S_{21} for both channels as,

$$\Delta f_m = f_0 + 2p\, f_{RF}\, t_m \,, \tag{6}$$

where Δf_m is the phase difference for the m^{th} delay configuration, f_{RF} is the signal frequency and f_0 is an arbitrary constant phase. Experimental data is obtained by sweeping the RF-signal between 0.2 GHz and 1.6 GHz. The time delay is calculated from the linear fit to Eq. (6). Figure 3 shows the time-delays between the even and odd wavelength channels for all configurations of the PDM. The minimum delay between the even (odd) channels is

135.9 ps (132.2 ps). The linear behavior of the curves shows a good agreement with Eq. (4). Measurement errors are less than 10% and are attributed to grating spacing errors and phase noise.

3.2 Transmit mode beampattern characterization

For the transmit mode beam pattern characterization, the configuration shown in Figure 1 is modified. The four optical carriers are detected by a single photodetector and an RF Spectrum Analyzer at the output of the PDM. Thus, output RF powers for both beams are measured simultaneously for all the switching configurations.

Power levels of the two transmitted RF-signals depend on the time delay introduced by the PDM as shown in Eq. (1). Therefore, transmit beampattern is obtained by steeping the PDM through each possible time-delay configuration. In order to demonstrate that both RF-beams can be processed independently with the beamformer, both RF-beams are steered in opposite directions. Figure 4 shows the experimental and theoretical beam patterns for the transmission of two RF-signals at 0.6 GHz and 1.5 GHz. The theoretical curves (solid lines) are plotted using Eq. (1). RF-Beam (a) is processed with the even channels and RF-beam (b) with the odd channels. The spectral power profiles of the transmitted RF-signals measured with the spectrum analyzer are also shown in Figure 4. Figure 5 shows the normalized transmit beampatterns for RF-signals at 1.3 GHz and 1.4 GHz. Our measurements are limited to 1.5 GHz in order to obtain a reasonable number of data points per beam lobe.

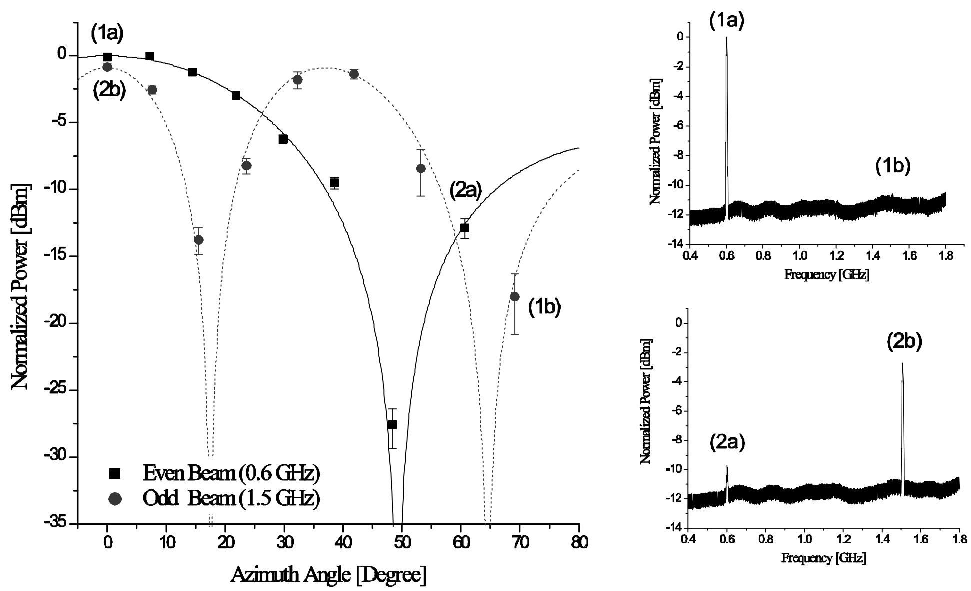

Figure 4: Beampattern obtained in transmit mode with 8 delay configurations. The frequencies of the transmitted RF-signals are 0.6 GHz and 1.5 GHz.

4. DISCUSSION AND CONCLUSIONS

In conclusion, we have analyzed and characterized a two-beam two-channel 3-bit optical beamformer system operating at 1550 nm using a binary PDM. The beamformer prototype is used to demonstrate time-delay and transmit beampattern measurements for two RF-signals in the 0.6 GHz to 1.5 GHz frequency range. The RF-beams can be steered simultaneously and independent from each other. Beampatterns are obtained for steering angles between 0 and approximately 70 .

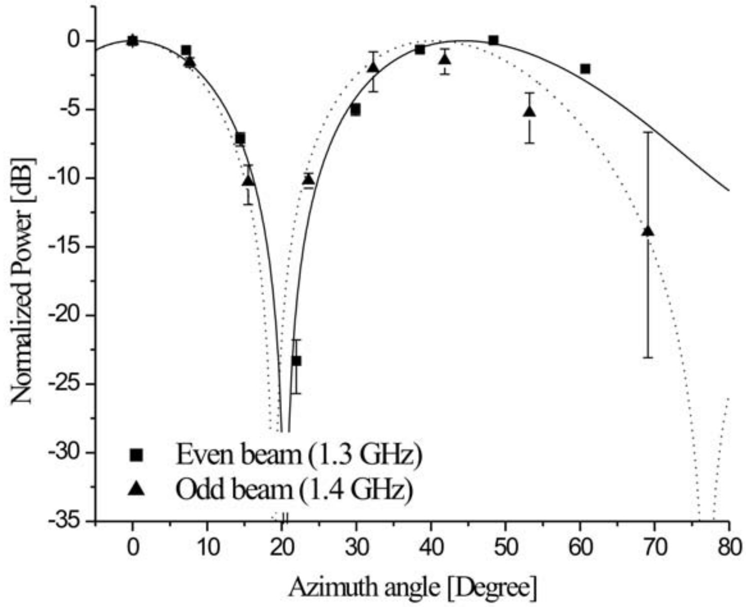

Figure 5: Beampatterns obtained in transmit mode. Frequencies of transmitted RF-signals are 1.3 GHz and 1.4 GHz.

ACKNOWLEDGMENTS

This work was supported by the U.S. Office of Naval Research under the contract number N00014-00-0782.

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