Practical Impairments in FBG-Based True Time Delays

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Abstract: In this paper we analyze the response of a non-ideal optical beamforming system which employs true-time delays based on fiber Bragg gratings. Effects regarding deviation of the Bragg wavelengths, instabilities of the laser source wavelength and misalignment of the fiber path lengths, were studied. We show how these deviation parameters affect the irradiation pattern of linear phased-array antennas.
OCIS codes: (230.2090) Electro-optical devices; (230.2285) Fiber devices and optical amplifiers; (250.4745) Optical processing devices;

1. Introduction

A phased-array antennas (PAA) consists of a set of antennas located in an orderly manner, one next to the other. Each antenna element of the set is separated by a known distance d, as is shown in Fig. 1 for a linear array of four elements. The phase shift $\Delta\varphi$ required to route the beam to a certain angle θ is equal to

$$\Delta\varphi = \left(2\pi df / c\right)\sin(\theta), \qquad (1)$$

where d is the spacing between elements, f is the frequency of the transmitted signal, θ the steering angle and c is the speed of light in vacuum. Equivalently, the phase delay can be accomplished by performing a time delay Δt between the signals feeding the elements of the array. This time delay is given by

$$\Delta t = \left(d / c\right)\sin(\theta). \qquad (2)$$

Employing Eq. (2) presents the important advantage of producing non frequency dependent delays, in contrast to phase shifters. Thus, optically based true time delay (TTD) beamformers are natural candidates for future PAA due to their squint-free operation, excellent performance over a wide RF bandwidth, immunity to electromagnetic interference (EMI) and low weight and volume [1]. Numerous schemes have been proposed for the implementation of optical TTD beamforming for a PAA. Several architectures have been proposed to implement delay lines based on optics schemes using fiber optic, uniform fiber Bragg grating (FBG) [2-4], tunable laser sources and dispersive components such as high dispersion fibers [5], chirped fiber grating [6] and photonic crystal fibers [7].

In this paper we show the response of an optical beamforming (OBF) employing FBG based TTDs to control the PAA. It is analyzed how the deviation of the Bragg wavelengths of the FBGs, the fiber length and the wavelength of the laser modify the irradiation pattern of the PAA, producing unwanted effects.

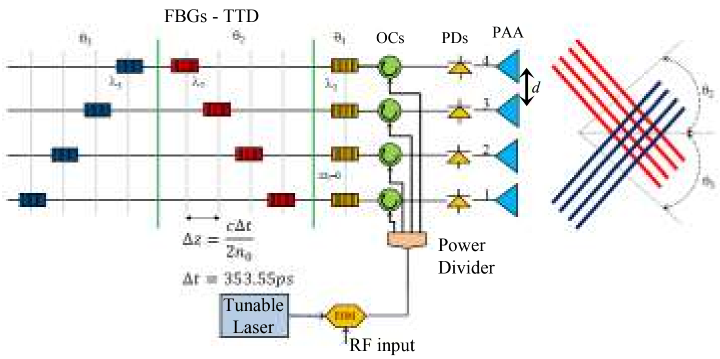
2. System description and numerical simulations

Figure 1 shows the analyzed optical beamformer for the transmit mode operation (it is a simplified version of the one presented in ref.[4]). A tunable laser is externally modulated with an electrooptic modulator (EOM). This signal is splitted by a 1x4 power divider, and addressed to the delay lines through optical circulators (OC). The delay lines are performed with a piece of optical fiber of well defined length and FBG reflectors to determine the time delay of the propagating signal. The spacing between successive FBGs operating at the same wavelength defines the relative time delay required for a particular beam steering angle. On the other side, the technique for selecting between different angles is to employ sets of FBGs with different reflection wavelengths. Thus, using a tunable laser the delays can be determined by choosing the proper wavelength (i.e. the proper set of FBGs). The delayed optical signals reflected by the FBGs are redirected towards the photodetectors (PD) and then to the PAA. Thus, the conformation of an RF beam in a given direction is achieved by combining the signals from each element of the array, which was delayed according to the desired steering angle.

We considered an OBF network as shown in Fig. 1 with the following specifications: 4 in-line elements PAA; an operation frequency of 1 GHz (or equivalently λ = 300 mm); a separation between elements of $\lambda/2$ (d = *150* mm) to minimize the side lobe power, and a beam steering range of 90° given by three discrete angles (-45°, 0 and +45°) independently addressable. According to Eq. (2) given in the previous section, the relative time delay for θ = -45°, 0° and +45°, are Δt = -353.5 ps, 0 ps and 353.5 ps, respectively. The relative time delays are implemented by propagating the optical signals in a specific length of optical fiber for each FBG operating on the same wavelength. The length can be calculated as

$$\Delta z = c\Delta t / 2n\,, \qquad (3)$$

where n is the group refraction index. By replacing in Eq. (3) the corresponding lengths are -36 mm, 0 mm and +36 mm.



Bragg wavelengths:
λ_1 = 1550 nm, λ_2 = 1551 nm, λ_3 = 1552 nm
FBG bandwidth: 0.2 nm
Reflectivity: 99%
Laser power: 10 mW
Laser line width: 0.1 MHz

Fig. 1. Optical beamforming system in transmit mode operation which includes 4 in-line elements PAA, 3 programmable true time delays based-on FBGs.

The aim of this paper is to determine the effect over the steering angle and the irradiation pattern, produced by some imperfections in the generation of the delays through the photonic processor. Three error sources were considered: deviations of the FBGs Bragg wavelengths, the lengths of optical fibers which generate the relative delays and the wavelengths of the laser source. Each of these mismatches was evaluated in order to determine the irradiation pattern deterioration of the PAA for a steering angle of +45°, which corresponds to a wavelength λ_3 = 1550 nm.

For the Bragg wavelength mismatch were assumed a total of 20 realizations normally distributed with 1550 nm mean and standard deviation 0.2 nm / 3 = 0.066 nm (so that interference with neighboring FBG may be neglected since they are separated 1 nm). Figure 2 (a) and (b) show the polar and linear graphic respectively. The former depicts the 20 realizations and the latter shows the ideal irradiation pattern and the interval around it for the standard deviation values.

The second case corresponds to the length deviation of the optical fiber that produces the propagation time delay. Again, 20 realizations were considered with normally distributed statistics, having a mean of 36 mm and a standard deviation of 1 mm. Figure 2 (c) and (d) show the obtained results in polar and linear scales. It can be seen that the irradiation pattern shape was not considerably modified.

Finally, we considered 20 realizations of the laser wavelength with normal distribution, a mean of 1550 nm and a standard deviation of 0.05 nm. The numerical results are shown in Fig. 2 (e) and (f) for polar and linear scales. In the same way as in the previous case, it can be seen that the pattern shape was not considerably modified.

All polar figures show 360° so both, the desirable irradiation pattern (i.e. 45°) and the mirror image (i.e. 135°) appear in the graphs.

3. Conclusions

An OBF network including FBGs-based TTDs to control the beam steering of a PAA was numerically simulated. Three main impairments were analyzed in order to determine its dependence over the irradiation pattern. These impairments were the deviations of the Bragg wavelength, the length of the optical fiber needed to adjust the propagation delays and the wavelength of the laser source. All these parameters mismatches were considered with normal statistics and typical values for the mean and standard deviation. Two different graphs were displayed for each analysis: a polar figure with the 20 realizations and a linear figure showing the curve of the ideal irradiation pattern and the mean squared error above and below it. From these simulations, it can be seen that an error in the Bragg wavelength having a standard deviation of 0.066 nm (one third of the bandwidth) produces the highest distortion in the irradiation pattern while the other parameters mismatches do not have much influence for the typical values considered. Taking into account this fact, special care should be taken when fabricating the FBGs which will be used in the system, in order to have an irradiation pattern closer to the ideal.

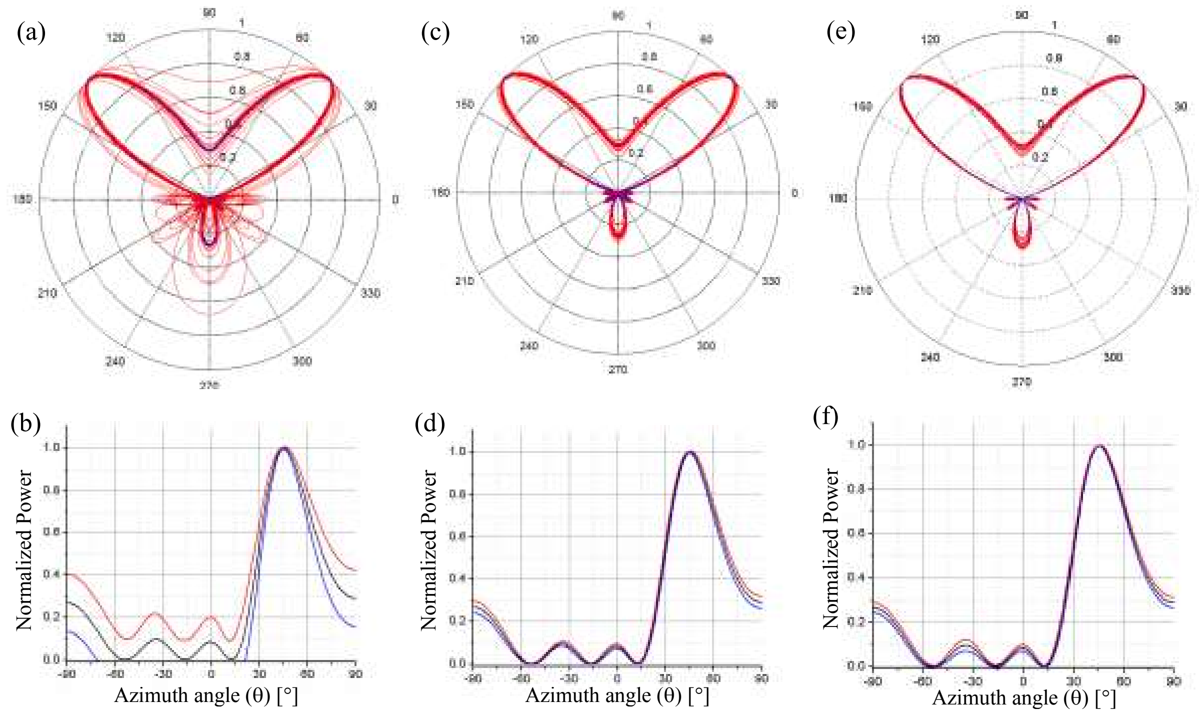


Fig. 2. Simulated irradiation patterns considering errors in the Bragg wavelength in (a) and (b), the length of the optical fiber in (c) and (d), and wavelength of the laser source in (e) and (f). All patterns correspond to a steering angle of +45° (associated to λ_3 = 1550nm). (a), (c) and (e) display the 20 realizations while (b), (d) and (f) show the ideal irradiation pattern and the mean squared error curves around it.

This work was partially supported by CONICET (PIP 112-200801-01769), Facultad de Ingeniería Universidad Nacional de La Plata (Project I128) and ANPCyT (PICT 0378/08 and 38289/05).

4. References

[1] H. Zmuda and E. H. Toughlian*, Photonic Aspects of Modern Radar*. Norwood, MA: Artech House, 1994.

[2] H. Zmuda, R. A. Soref, P. Payson, S. Johns, and E. N. Toughlian, “Photonic beamformer for phased array antennas using a fiber grating prism,” *IEEE Photon. Technol. Lett.*, vol. 9, no. 2, pp. 241–243, Feb. 1997.

[3] Byung-Min Jung, and Jianping Yao, “A Two-Dimensional Optical True Time-Delay Beamformer Consisting of a Fiber Bragg Grating Prism and Switch-Based Fiber-Optic Delay Lines,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 10, May 15, 2009.

[4] Pablo A. Costanzo Caso, Lureano A. Bulus Rossini, R. Duchowicz, and E. Sicre, “Photonic signal processing applied to optical beamforming,”(in Spanish) in Proc. Reunión de Procesamiento de la Información y Control (RPIC), Argentina, Oct. 2011, pp.1-6.

[5] S. Blanc, M. Alouini, K. Garenaux, M. Queguiner, and T. Merlet, “Optical multibeamforming network based on WDM and dispersion fiber in receive mode,” IEEE Trans. Microw. Theory Tech., vol. 54, no. 1, pp. 402–411, Jan. 2006.

[6] P. Q. Thai, A. Alphones, and D. R. Lim, “Optical dual-beam beamformer employing multichannel chirped fiber grating,” in Proc. Photonics Global Conference. Singapore (IPGC), Dec. 2008, pp. 1–4.

[7] M. Y. Chen, H. Subbaraman, and R. T. Chen, “Photonic crystal fiber beamformer for multiple-band phased-array antenna transmissions,” IEEE Photon. Technol. Lett., vol. 20, no. 5, pp. 375–377, Mar. 1, 2008.