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True-time-delay optical driving system for phased array antenna beamformers using a single chirped fiber Bragg grating

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Abstract: - In this paper, a new five-element true-time-delay system is presented. To achieve the time delays needed for beamforming, a single chirped fiber grating delay line is used. The chirped fiber grating reflects different optical wavelengths driven into it at different times. These time differences constitute the necessary conditions for the beamforming. The different wavelengths are captured by tunable optical filters. All components of the system are commercially available. The angle resolution obtained is less than five degrees for a beam range of 180^0. The system avoids any special dedicated optical structure or any micro-instrumentation set up for chirped fiber grating tuning or any synchronal tuning control of the tunable light (laser) source and the tunable filters.

Key-Words: - Beamforming, Phased Array Antenna, True Time Delay

1 Introduction

Satellite, aviation modern communications and radar systems require high performance transmitting antennas. Phased-array antennas (PAA) have been mostly used which have the advantage of two dimensional scanning without moving mechanical parts. In order to keep the beamforming direction stable at different microwave frequencies, true-time-delay (TTD) units are employed, which stem from the much promising photonic technique. This technique provides the ability of driving several antenna arrays using either wave-length division multiplexing (WDM) or optical splitters to drive different arrays. Advantages of the photonic technique are, the low loss of optical fibers, the delays are independent of the radio frequencies used, lightweight, very small power consumption, immunity to electromagnetic interference and an enormous bandwidth with a flat response from DC to hundreds of GHz. Several system configurations have been proposed the last few years [2-4], having either complicated structures or difficult controlling and/or synchronizing systems.

In this letter, we propose and demonstrate a new TTD system that uses only a single chirped fiber Bragg grating (CFBG) delay line and five Fiber Fabry-Perot Tunable Filters (FFP-TF) which are tuned by using low control voltage. The FFP-TFs select centre wavelengths, from the C band, equally spaced between adjacent ones. All optical components are commercial ones used in WDM systems.

2 Theory

The system configuration is shown in Fig. 1. The light of the broad band light source (BBLS) is externally modulated by a RF signal through an electro-optic modulator (EOM). A polarization controller (PC) is used between the BBLS and the EOM to control the polarization state. The CFBG is fed by the modulated light through an optical circulator. The modulated light consists of a range of wavelengths. These wavelengths are reflected by the CFBG at different gratings thus giving different time delays, and through the circulator, are propagated to the equally divided by N=5 optical splitter. The outputs of the splitter feed five equal path single-mode channels each including a tunable optical filter, a photodetector (PD), a RF amplifier (RF AMP), and an antenna. The antennas of the array have a distance, d, between adjacent ones. The first FFP-TF is tuned by the constant voltage, V_{cc}=6V, to the wavelength λ_0 corresponding to the middle point of the length of the chirped grating as shown in Fig. 1. The other four FFP-TFs are tuned by applying DC voltages from 0 to 12V [5]. These applied voltages, V_{c1}, V_{c2}, V_{c3} and V_{c4} differ from each other by an integer multiple of the voltage step as explained later. As the voltages increase, the FFP-TFs tune to wavelengths further apart but equally spaced between each other since the relation of λs versus voltage is a linear function [5]. Consequently the time delay differences between adjacent channels will vary according to this control function and they will be equal between channels. When the applied voltages coincide at the V_{cc} point, all the FFP-TFs tune at the wavelength λ_0, thus producing zero time delay differences between adjacent channels and therefore giving the zero beampointing angle. To improve the performance of the system and compensate for the losses, an erbium-doped fiber amplifier (EDFA) is inserted into the system after the circulator. For the TTD system illustrated in Fig.1, the beampointing angle θo, corresponding to the maximum value of the main lobe of the array antenna is equal to

$$\cos\theta_0 = \frac{c\Delta t}{d} \qquad (1)$$

where *d* is the distance between adjacent elements of the array, *c* is the speed of light in the free space, and Δt is the time delay difference between adjacent elements. Since the angle θ_0 is controlled by the factor Δt which comes from the delay produced by the round trip of the wavelengths in the CFBG it will be equal to

$$\Delta t = \frac{2n\Delta x}{c} \qquad (2)$$

where n=1.5 is the effective refractive index of the CFBG, and Δx is the distance difference on the CFBG formed between the adjacent reflected channels, measured from the centre one (λ_0). The selection of the channels is done by tuning the FFP-TFs. From (1) and (2) we have

$$\cos\theta_0 = \frac{2n\Delta x}{d} \qquad (3)$$

One can see that the angle θ_0 is determined by the distance Δx and is independent of the RF frequency. So the optical system using fiber gratings is a TTD beamformer and is used for wideband applications.

3 Simulation and Discussion

Using an RF of 5 GHz the distance d of the array antenna was set to half the RF wavelength, i.e. d=30 mm, in order to avoid the existence of more than one main lobes in the radiation pattern [1]. To ensure beampointing angles $-\pi<\theta_0<\pi$ a chirped fiber Bragg grating of a length equal to 100 mm was chosen, with a range Δλ=50nm in the C band, reflectivity of more than 95%, central wavelength 1550.12 nm, channel space 0.4 nm and a reflection bandwidth FWHM 0.14 nm. The FFP-TF was chosen with a finesse of 627, a bandwidth at FWHM 0.0247 nm, and a free spectral range (FSR) 60 nm. It is thermally stable, and fast tuning. The simulation results were taken by tuning the FFP-TFs at voltage increments equal to mΔV, where ΔV=0.1 volts is the step voltage, and m is an incremental integer which advances the tuning to channels equally spaced between adjacent ones and covers all the FSR. Fig. 2 shows the tuning of the filters, the first tuned at λ_0=1550.12 nm and the rest at wavelengths advanced by 0.4 nm.

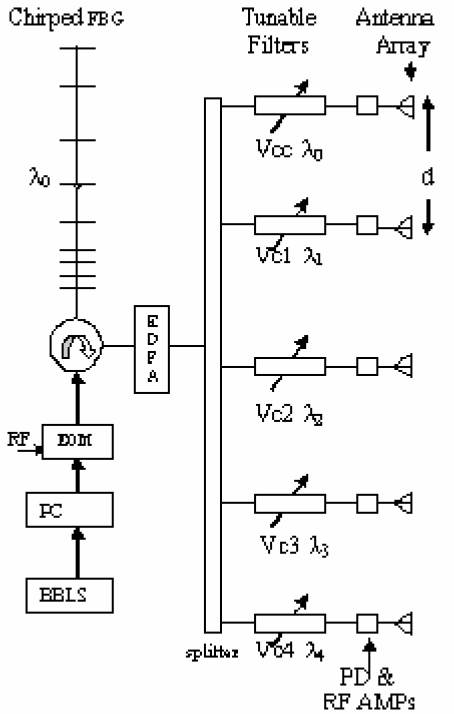

Fig. 1. Photonics driven PAA system

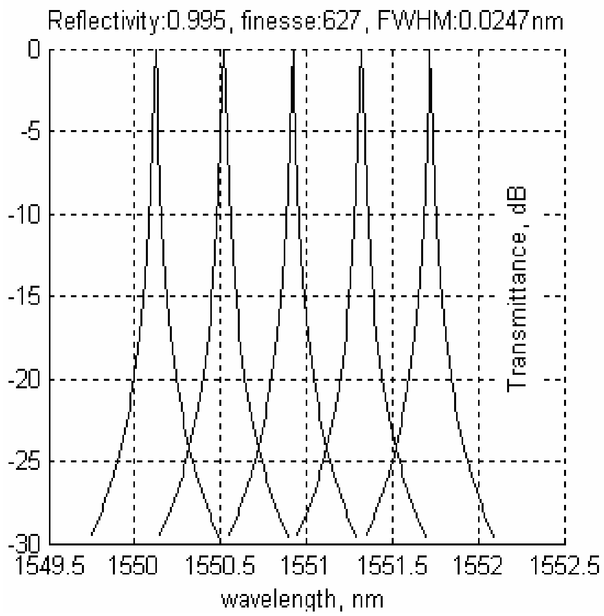

Fig. 2. Responses of the tunable filters

The CFBG accommodates 125 channels. The distance difference Δx, for the channel spaces is 0.8 mm. This distance gives a step time-delay difference of 8 ps (eq.2) and an angle resolution $\Delta\theta = 4.59^0$ (eq.3). The array factor (AF) pattern showing the angle resolution is illustrated in Fig. 3, which is considered a very good one for a scanning process. Any RF higher than 5 GHz and up to 10 GHz can be handled by the CFBG, with an angle resolution of $\Delta\theta = 9.2^0$ and a range of 180^0 corresponding to 10 GHz. The proposed system can be extended to more than five-element array antenna by simply adding extra equal path channels. Caution should be taken when constructing the system, especially when cutting and assembling the length of the paths. They should be equal with high accuracy, because half a millimeter difference causes an extra delay of 2.5 ps. A way of surpassing this difficulty is to use microwave techniques. The simulation results shown were taken assuming ideal conditions. In other words Δx's were taken between central wavelengths at filter tunings. In practice, since the responses of the filters have a certain bandwidth, a number of wavelengths located on either side of the central one are modulated by the RF signal. These side wavelengths, having smaller amplitudes than the central one, offer extra distance differences. Therefore a number of radiation patterns appear as variations to the central AF. The total array factor pattern is the sum of the individual ones each multiplied by its own amplitude.

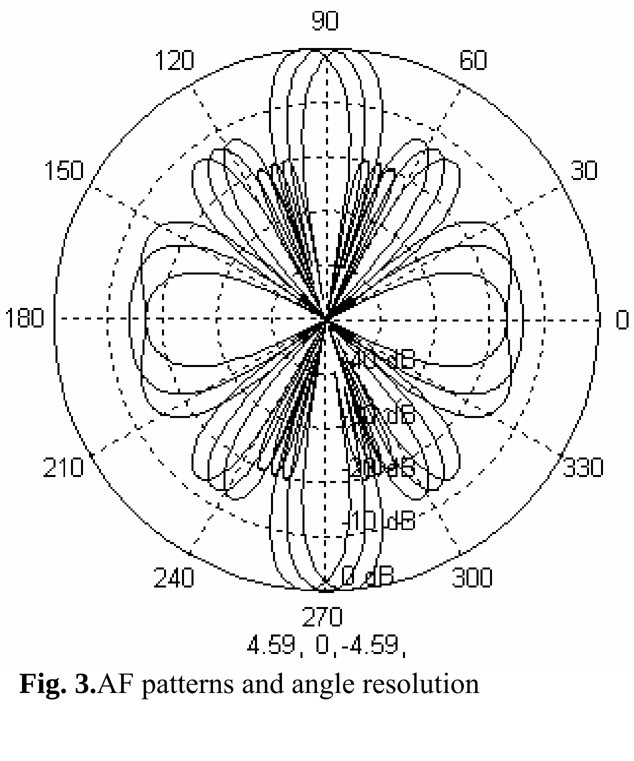

Fig. 3.AF patterns and angle resolution

4 Conclusion

We demonstrated a new TTD system with five-element array antenna that uses a single CFBG delay line for a wideband beamforming. The system is very simple, it uses commercial and modular type components, and it avoids any special dedicated structure or any micro-instrumentation set up for CFG tuning or any synchronal tuning control of the tunable laser source and the tunable bandpass filters. The time delays were achieved by simply tuning the FFP-TFs by a simple voltage control scheme. This control scheme can be a programmable unit, which can guide the beampointing angle to any desired position. The system can be easily extended to more than five-element array antenna and can be used for RF frequencies more than 5 GHz. Also by using an extra splitter, just after the circulator, we can feed so many five-element array antennas as the outputs of the inserted splitter.

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