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Compact high frequency true-time-delay beamformer using bidirectional reflectance of the fiber gratings

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ABSTRACT

A compact high frequency true time delay (TTD) beamformer using bidirectional reflectance of the fiber gratings (FGs) is proposed. The FGs can be a set of fiber Bragg gratings (FBGs) or chirped fiber gratings (CFGs). The number and the length of the time delay lines are greatly reduced compared to the previous systems. A phase array antennas system using this TTD beamformer has many advantages including being compact, low requirement on the bandwidth of the tunable laser source and working at high microwave frequency. The proof-of-concept experiment results demonstrated the feasibility of the proposed scheme.

1. Introduction

Phased-array antennas (PAAs) system is required in many fields [1,2], such as radar or communication system. One of the essential parts of the PAAs system is the time delay (TTD) beamformer. Although the electrical time delay schemes have been proposed for a long time, some drawbacks still have to be overcome, for instance their bulky hardware and bandwidth limitation. To solve the problem of the bandwidth limitation, the optical TTD techniques were proposed, which could provide stable time delay for wide frequency band [3,4]. Together with the advantages such as lightweight, immunity to electromagnetic interference, low loss, small size, and the optical TTD beamformer has become a promising technique for the wideband PAAs system.

An optical TTD beamformer can be constructed by integrated-optic switch delay lines [5], dispersive-fiber prism [6], discrete fiber Bragg gratings (FBGs) [7–9] or/and chirped fiber gratings (CFGs) [10–14], piezoelectric fiber stretchers [15], photonic crystal fiber [16], superstructure fiber Bragg grating [17], dispersion compensating fiber and a multi-wavelength laser [18], etc. Among these schemes, those based on the fiber gratings (FGs), including FBGs and CFGs, attracted more attention because of the well developed FGs techniques. In 1996, Soref theoretically proposed, for the first time, the TTD beamsteerer based on the prism-shaped arrays of FBGs [7]. Short time later, the feasibility of this system is experimentally shown [8]. Nevertheless, it cannot operate at the frequency beyond 3 GHz because the minimum time delay increment is about 10 ps [11,19]. In order to achieve smaller time delay increment, several improved methods were proposed [10–14]. Some of them use the CFGs instead of the FBGs. Some of them adopt the combination of the FBGs and the CFGs. Since the CFG has inevitable time delay jitter [20,21], the time delay resolution and thus the minimum time delay increment still could not be made small enough.

In this paper, we propose a compact high frequency TTD beamformer using bidirectional reflectance of the FGs, in which the time delays are created by the reflections from the two opposite directions of the FGs. Consequently, the system structure is much more compact than previous ones and the requirement on the bandwidth of the tunable laser source reduced. Besides, the PAAs beam forming system using the proposed TTD system can work at high microwave frequency. The proof-of-concept experiment results demonstrated the feasibility of the proposed scheme.

2. Theoretical analysis and the system design

2.1. Basic idea of the proposed system

The structure of a traditional TTD beamformer based on the FG array is schematically shown in Fig. 1. It consists of a group of time delay lines made of FGs. The FGs can be a set of fiber Bragg gratings, chirped fiber gratings or other kinds of fiber gratings. Light with a certain wavelength generated by the tunable laser source (TLS) firstly passes through a polarization controller (PC) to reduce the polarization dependent loss and then is modulated by the

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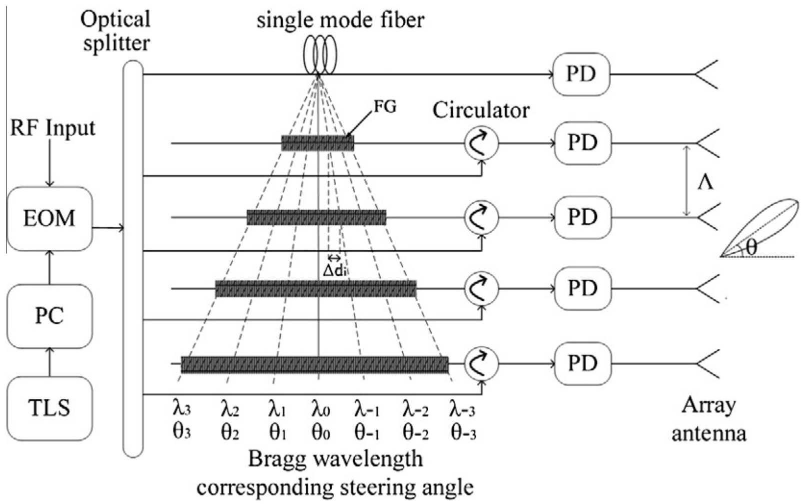

Fig. 1. The traditional configuration of the PAAs beam forming system based on the FG.

microwave RF signal through the electro-optic modulator (EOM). The modulated light feeds a 1:N equal path optical splitter, then the split lights are directed to N FGs by optical circulators. Then the light in each delay line will be reflected from different positions in different time delay lines and produce different round trip time delays, the dashed lines in Fig. 1 schematically show the reflection positions, each dashed line corresponds to a wavelength. After that, the photodetectors (PDs) recover the time delayed RF signals, which are amplified and sent to the antenna radiator elements.

The reflection positions of λ_0 are designed to achieve equal time delays in all the time delay lines. The first single mode fiber provides a fixed time delay for all wavelengths, which is equal to the time delay caused by λ_0. The difference of reflection positions of λ_i at adjacent fibers is noted by Δd_i. It can be seen that light of a specific wavelength λ_i can create N different roundtrip time delays in N delay lines and the time delay increment $\Delta\tau_i$ between adjacent delay lines is a constant:

$$\Delta\tau_i = \frac{2n\Delta d_i}{c} \tag{1}$$

where c is the light speed, n is the effective refractive index of the fiber core.

It can be derived by the wave interference theory that the RF signals radiated from the array antenna will collectively form a radiation in a specific direction. In order to avoid the high order radiations, the separation of adjacent antennas, λ, should be half the wavelength of the RF signal. In this case, the steering angle of the radiation, θ_i, satisfies:

$$\sin\theta_i = 2f_m\Delta\tau_i \tag{2}$$

where f_m is the frequency of the RF signal.

It can be seen that in the TTD unit of Fig. 1, all lights enter the time delay lines from right are reflected leftward. We propose a new TTD scheme that could produce the time delays by the reflections from the two opposite directions of the FG. As an example, a 5-channel system based on the FBG prism is shown in Fig. 2. An optical switch together with an optical circulator is introduced in the left of each time delay line. Light from the optical splitter could enter the time delay line from either left or right by adjusting the optical switch to bar or cross state.

Suppose when lights enter the time delay lines from the right group of circulators, the time delay increment is $\Delta\tau_i$, then it will be $-\Delta\tau_i$ when lights enter from the left group of circulators. This means that light with a specific wavelength can achieve the time delay increments for two steering angles, one is positive and the other is negative as noted at the bottom of Fig. 2. Consequently, the size of the TTD system is reduced by half and the requirement for the bandwidth of the tunable laser source is greatly reduced.

2.2. Channel extending of the proposed system

The 5-channel beam forming structure in Fig. 2 can be extended to a 9-channel one without increasing time delay lines as shown in Fig. 3. The 1:5 equal path optical splitter is replaced by a 1:9 one. For the convenience of description, all the fibers connected with the splitter are labeled by a serial number j.

The first single mode fiber labeled $j = 1$ send the light straightforwardly to the central element of the array antenna. Other eight fibers direct the lights to the time delay lines through the circulators at the two ends. Lights that propagate in the fibers labeled $j = 2, 4, 6, 8$ are coupled in or out of the time delay lines via the left circulators, while those propagate in the fibers labeled $j = 3, 5, 7, 9$ are coupled in or out of the time delay lines by the right circulators. These eight paths of lights will get different round trip time delays by the reflections of the FGs from the two opposite directions. When all the optical switches are in bar states, the time delayed lights coming out of the left group of circulators are directed to the upper four antennas, while those coming out of the right group of circulators are sent to the bottom four antennas. When the states of all the optical switches change from bar to cross, the sequence of the time delayed signals in the array antenna will reverse. The label j at the right side of the array antenna indicates where the time delayed signals come from. The cables that connect PDs and antennas in all channels are designed to be equal in path, therefore no time delay difference between adjacent channels is created in this part of the system.

The lengths of the single mode fibers labeled $j = 1, 2, 4, 6, 8$ are designed to guarantee that all the time delays created by λ_0 are equal. Therefore the time delay corresponding to λ_0 in all the nine channels are same, and the corresponding steering angle of the radiated RF signal is zero. The time delays created by other wavelength λ_i are determined by the positions of the corresponding gratings and the light propagating directions, which can be described by the time delay curves as shown in Fig. 4. Each FG time delay line has two time delay curves corresponding to the light entering from left and right. The central horizontal curve in Fig. 4 represents the time delay of the first signal mode fiber ($j = 1$).

It can be seen from Fig. 4 that for a given wavelength λ_i, the time delay values change monotonously from top to bottom and the time delay increment is a constant. This is because that Δd_i is a