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A high-resolution compact optical true-time delay beamformer using fiber Bragg grating and highly dispersive fiber

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ABSTRACT

A high resolution optical true-time delay (OTTD) beamformer constructed by fiber Bragg grating (FBG) and highly dispersive fiber (HDF) is presented. It can produce the true time delay with the resolution of 1 ps. Besides the proposed system has compact structure and light weight even when a large number of antenna elements are present in a practical antenna array, this is because the used FBG fibers and HDFs are short and independent of the antenna element number. Theoretical analysis and numerical simulations are made. Proof-of-concept experiment results that demonstrate the feasibility of the system are presented.

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1. Introduction

Optical true time delay (OTTD) beamformer can overcome the intrinsic narrowband nature of the traditional electrical phase-shifter. Therefore the OTTD beamforming is a promising technique for the phased-array antenna (PAA) system, which is required in many fields such as electronic warfare systems and broadband wireless communication networks. Many OTTD schemes have been proposed including the dispersive fiber technique [1–5], fiber Bragg grating (FBG) prism [6,7] or/and chirped fiber grating (CFG) [8–11] techniques, substrate guided wave techniques [12,13], integrated-optic switch delay lines [14,15], piezoelectric fiber stretchers [16], multitudinous white cells [17], polarization–domain interferometers [18], etc. Most of them suffer from one or more problems such as the bulky structure or heavy weight, limited resolution due to the time delay jitter and wavelength conversion disturbance. How to realize the time delay resolution of 1 ps is a problem of great concern.

In this paper, we propose a novel OTTD beamformer based on the combination of the FBG and the HDF. It is known that both the traditional FBG prism [6,7] and the reported HDFs OTTD systems [1–3] have the advantage of jitter free which is essential for high resolution time delay. Nevertheless, the time delay resolution of the FBG prism is limited by the manufacturing precision of FBG, and for the HDF system, the length of the HDF becomes extremely long when a large number of antenna elements are present in a practical antenna array. The proposed system in this paper takes the advantage of these two systems and overcome their limitations by combing them elegantly. It can provide the true time delay with resolution of 1 ps. In addition, comparing to other systems, the proposed system is more compact and easier to be integrated especially when a large number of antenna elements are present in a practical antenna array.

2. Theoretical analysis

The structure of the proposed OTTD beamformer is schematically shown in Fig. 1. Where, the OTTD unit is a combination of an FBG prism and a group of identical HDF arrays.

The HDF array is constructed by connecting varying amounts of HDFs and common single mode fibers (SMF). Light emitting from the tunable laser source (TLS) is externally modulated by an electro-optic modulator (EOM), then feeds N channels of the FBG prism through an 1:N optic splitter. For given light wavelength λ_i, the time delay difference caused by adjacent FBG fibers is

$$\Delta\tau_{FBG,\lambda_i} = \frac{2n_{eff}\Delta d_i}{c} \tag{1}$$

where Δd_i is the position difference between the FBGs with the same Bragg wavelength λ_i at adjacent FBG fibers, c is the light speed, and n_{eff} is the effective refractive index of fiber core. The time delayed light coming out of each FBG fiber enters a HDF array through an equal-path 1:M optic splitter and get additional M

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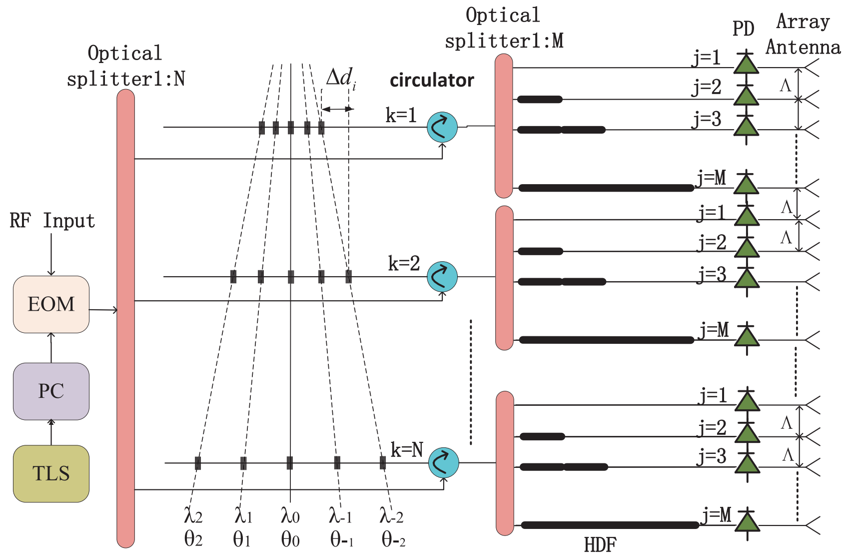

Fig. 1. The structure of the OTTD beamformer based on the FBGs and HDFs.

different time delays, $j \cdot \Delta\tau_{HDF,\lambda_i}$, with $j = 0, 1, 2, \ldots, M-1$. The lengths of the HDFs are 0, L_0, $2L_0, \ldots, (M-1)L_0$. While, the lengths of the SMFs are $(M-1)L_{SMF}$, $(M-2)L_{SMF}, \ldots, L_{SMF}$. The length of the longest HDF is determined by M and not related to the total number of the antenna elements, thus the system is much more compact compared to the traditional dispersive fibers OTTD beamformer. The values of L_0 and L_{SMF} are designed to make all the time delays for λ_0 are matched. Then,

$$\Delta\tau_{HDF,\lambda_i} = L_0 \int_{\lambda_0}^{\lambda_i} D_{HDF}(\lambda) d\lambda \tag{2}$$

where $D_{HDF}(\lambda)$ is the dispersion of the HDF, the dispersion of SMF is neglected because it is much smaller than D_{HDF}. Thus, each λ_i associates with $N \times M$ different time delays:

$$\tau^0_{FBG,\lambda_i} + (k-1) \cdot \Delta\tau_{FBG,\lambda_i} + (j-1) \cdot \Delta\tau_{HDF,\lambda_i} \tag{3}$$

With $k = 1, N$; $j = 1, M$, and τ^0_{FBG,λ_i} is the time delay caused by the FBG with Bragg wavelength λ_i in the first FBG fiber. In order to make the $N \times M$ time delays have a constant step increment, the values of $\Delta\tau_{FBG,\lambda_i}$ and $\Delta\tau_{HDF,\lambda_i}$ should satisfy

$$\Delta\tau_{FBG,\lambda_i} = M \cdot \Delta\tau_{HDF,\lambda_i} \tag{4}$$

Then time delay difference between any adjacent antennas is

$$\Delta\tau_i = \Delta\tau_{HDF,\lambda_i} \tag{5}$$

The photodetectors (PDs) recover the $N \times M$ individually time delayed microwave signals, which are amplified and sent to the antenna radiator elements. The separation of adjacent antennas is Λ. When Λ is equal to half a wavelength of the operation microwave frequency, the microwave signals radiated from the array antenna will collectively form a radiation in a specific direction θ_i.

$$\sin\theta_i = 2f_m \Delta\tau_i \tag{6}$$

where f_m is the frequency of microwave signal. It can be seen that higher microwave frequency requires smaller $\Delta\tau_i$, and $\Delta\tau_i$ is determined by Δd_i and M,

$$\Delta\tau_i = \frac{2n_{eff}\Delta d_i}{Mc} \tag{7}$$

Here, the manufacturing precision of Δd_i is the critical factor because it determines the accuracy of $\Delta\tau_i$, and eventually influence the precision of the steering angel. The inaccuracy of the steering angle cause by the Δd_i can be evaluated by

$$\delta(\theta_i) = \frac{1}{M} \frac{4f_m n_{eff}}{c \cdot \cos\theta_i} \delta(\Delta d_i) \tag{8}$$

With $\delta(\Delta d_i)$ the imprecision of Δd_i. Suppose the tolerance error of θ_i is less than 1°, then the scanning range corresponding to $\delta(\Delta d_i)$ is

$$\theta_{max} = \cos^{-1}\left[\frac{1}{M} \frac{4f_m n}{c \cdot \pi/180^\circ} \delta(\Delta d_i)\right] \tag{9}$$

It can be seen that both the steering precision and the scanning range are notably improved by the factor of $1/M$. The calculated θ_{max} as functions of $\delta(\Delta d_i)$ for different values of M are shown in Fig. 2 with $f_m = 40$ GHz. We can see that larger M can achieve greater scanning range. Take $\delta(\Delta d_i) = 0.05$ mm as an example, when $M = 1$, equivalence to a traditional FBG prism, the scanning range is zero or the errors in all directions are larger than 1°. If $M = 5$, the scanning range can reach 63°.

Fig. 3 shows the simulated far field intensity patterns for $f_m = 40$ GHz and $\delta(\Delta d_i) = 0.05$ mm. The total number of the antenna elements is 20. It can be seen that when $M = 1$, the steering directions obviously deviate from the required directions especially for large angles. When $M = 4$, all the steering directions are much more precise.

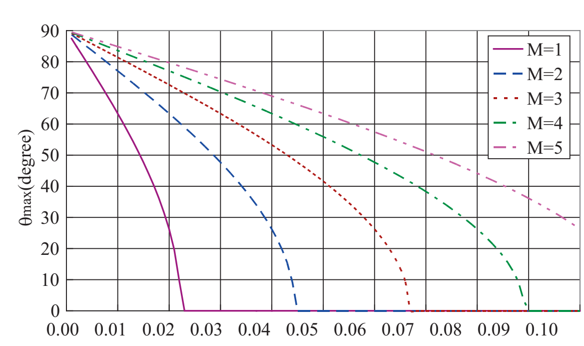

Fig. 2. The calculated scanning range θ_{max} as functions of $\delta(\Delta d_i)$ for different values of M. $f_m = 40$ GHz.

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