Research on optical true-time delay of multiple optical carriers in phased array antenna

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In order to improve the bandwidth and ability to resist electromagnetic interference of phased array antenna, we use the real-time delay technology of optical fiber. By using phase control principle of optically controlled phased array, we deduce the relation formula of time delay and phase control. Based on multiple optical carriers and optical switch delay technology, we analyze design method of optical fiber time delay system and give the results of the experimental test. From the results, we find that the system can improve ability of phased array antenna about phase control and resisting electromagnetic interference in broadband condition.

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Through optical true-time delay, phased array antenna can increase antenna bandwidth[1–3]. At the same time, optical delay line is resistant to electromagnetic interference, low loss, and ease of integration, etc. The essence of applying light real-time delay technology to optical phased array is to modulate microwave/radio frequency (RF) signal on the optical carrier, delay time in optical domain implementation, and to control the phase of optically controlled phased array by real-time delay[4,5]. Based on the multiple optical carriers and the optical switch delay technique, we study optical fiber real-time delay systems and their use in optically controlled phased array antenna.

Phased array structures are introduced in many literature studies, in order to discuss convenient, one-dimensional phased array, for example, as shown in Fig. 1. The array element spacing is d, the number of array elements is N, the microwave frequency is f_r, the wave number $k = 2\pi f_c/c$, and c is the electromagnetic wave velocity. If the amplitude of the electromagnetic wave emitted by each array element is the same, electromagnetic wave emitted by adjacent arrays with the same phase difference $\Delta\varphi = \varphi_n - \varphi_{n-1}$ ($\Delta\varphi$ also known as the adjacent space phase difference) can be obtained by electromagnetic field distribution in the θ direction as

$$E(\theta,t) = \frac{\sin(N\phi)}{\sin\phi}\exp(\mathrm{i}2\pi f_r t). \tag{1}$$

When the molecule and the denominator also tend to be 0 in Eq. (1), E is the amplitude of the θ direction[4], namely to meet

$$\Delta\varphi = 2\pi d\sin\theta/\lambda. \tag{2}$$

According to $\lambda = c/f_r$ in Eq. (2), the phase difference of adjacent space can be set as

$$\Delta\varphi = 2\pi f_r d\sin\theta/c. \tag{3}$$

When the antenna signal frequency changes from f_0 to $(f_0 + \Delta f)$, adjacent matrix phase difference is $2\pi f_r d\sin\theta/c$, and the spatial phase difference is $2\pi(f_0 + \Delta f)d\sin\theta'/c$, where Δf is the instantaneous bandwidth, and $\theta' = \theta - \Delta\theta$ ($\Delta\theta$ is known as the oblique angle)[6–8].

According to the equilibrium condition of two-phase difference: $(f_0 + \Delta f)\sin\theta' = f_0\sin\theta$,

$$2\pi(f_0 + \Delta f)d\sin\theta'/c = 2\pi f_0 d\sin\theta/c. \tag{4}$$

If the adjacent array can provide internal phase difference of $\Delta\varphi = 2\pi f_r\Delta\tau$, where $\Delta\tau$ is time delay of adjacent array, and is substituted in Eq. (3), we can obtain

$$\Delta\tau = d\sin\theta. \tag{5}$$

Equation (5) shows that, when structure of phased array antenna is fixed, the microwave beam direction θ related to delay difference $\Delta\tau$ of adjacent array elements has nothing to do with the emitted microwave frequency. If we control the adjacent matrix cell delay difference $\Delta\tau$, that is to say, we control the beam direction angle θ. This is the phase control principle of the optical fiber delay to optically controlled phased array.

The basic idea of fiber real-time delay network of multiple optical carriers is each antenna array corresponds

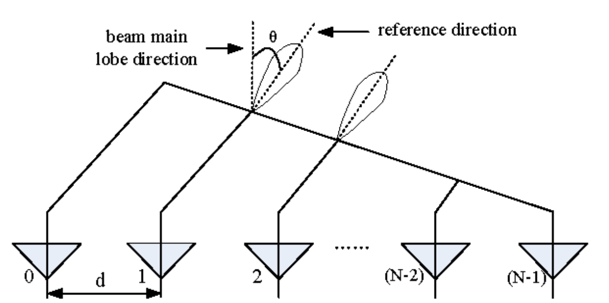

Fig. 1. Transmit diagram of the one-dimensional phased array antenna.

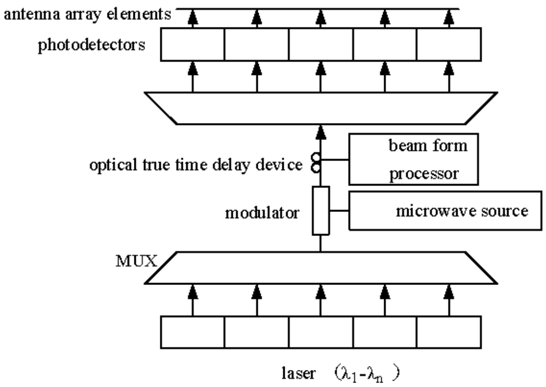

Fig. 2. Photonic true-time delay structure of multiple optical carriers.

to an optical carrier, sharing the optical fiber delay line has different delays in different sub-arrays using fiber dispersion (Fig. 2).

It should be pointed out that each laser center wavelength and the corresponding filter center wavelength is consistent, the tuning range and filter bandwidth are also consistent. Wavelength tuning range of each laser does not allow overlapping part, otherwise, there are two different time delays in same array element.

Optical fiber delay line receives modulated optical signal from laser and corresponding delay. The basic idea is to use optical switch control signals through the paths of different lengths, to obtain different delays. The quantity N of 2×2 optical switch determines the choice number ($2N$–1) of delay state, $\Delta\tau$ is the unit delay which determines the delay step size of retarder, so the delay selection range of retarder is 0–($2N$–1)×$\Delta\tau$.

Figure 3 shows concrete structure of optical true-time delay line. Selection of eight optical switch array (l×2), four groups optical switch array (2×2) consisting of a fiber delay line (4bit), can obtain 16 discrete delay quantities. Each fiber length is based on the following layer, the upper fiber is longer ΔL, the length of the time delays satisfy $\Delta\tau$, $2\Delta\tau$, $4\Delta\tau$, and $8\Delta\tau$ by selecting ΔL.

The mode controller controls the N lasers whose optical signal wavelengths are λ_1, λ_2 ... λ_N, respectively. N channel optical signals of different wavelengths through a 1×N polarization maintaining coupler is coupled with the polarization state into the same optical fiber, the coupled multi-carrier optical signal is modulated by RF signal through electro-optical modulator (EOM).

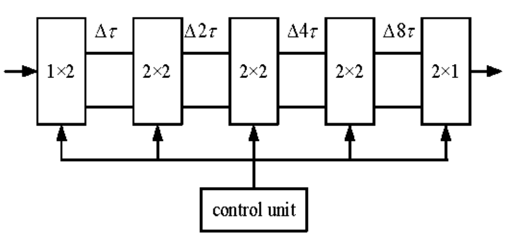

Fig. 3. Structure of optical true-time delay line.

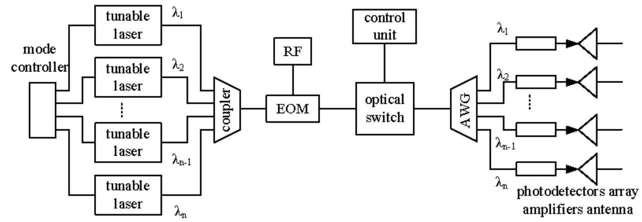

Fig. 4. Optical fiber time delay system based on multiple optical carriers.

The modulated signal passes a set of optical switches, which are turned on or turned off by a control unit, so that the light signal passes different fiber delay lines to generate different optical delay. The delayed light signal goes through an array waveguide grating (AWG) demultiplexer, demultiplexed to different ports. The single wavelength optical signal from different ports is converted to electrical signals through photoelectric detector, then amplified and launched out (Fig. 4).

In specific verification process, that is, selection of dispersion compensation fiber (DCF) as optical delay line, the dispersion coefficient is 136 ps/nm. Four wavelength tunable lasers (divided into two groups) are used to realize wavelength difference in the adjacent optical carrier by tuning the wavelength of tunable laser.

In the validation of the relationship between the wavelength difference and fiber real-time delay, the length of optical fiber delay line is fixed at 68.3 m and 800 km, step size is 1.0 nm to adjust laser. The relationship between the measured adjacent optical carrier wavelength and fiber real-time delay is shown in Fig. 5.

In the validation of the relationship between the length of optical fiber delay line and the optical fiber real-time delay, four of the laser, in turn, form the wavelength differences of 2.8, 5.6, and 8.4 nm. The control unit controls the length of optical signal through the DCF model optical fiber. When the length of the fiber delay line is 8 m, the optical real-time delay is less than 1 ps, so as to change the length of optical fiber delay line in the step size of 50 m. The relationship between measured length of optical fiber delay line and optical fiber real-time delay is shown in Fig. 6.

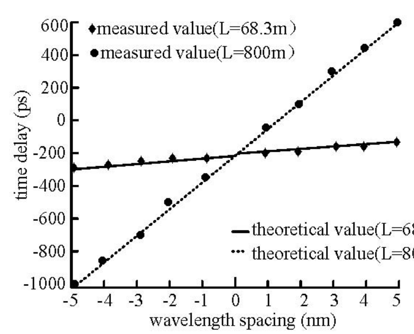

Fig. 5. Real-time delay responses of different wavelengths spacing.

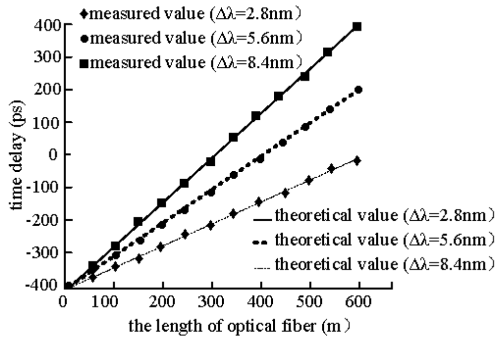

Fig. 6. Real-time delay responses of different lengths of optical fiber.

According to the formula of real-time delay $\Delta\tau = D \cdot \Delta\lambda \cdot L$, real-time delay is linearly related to the length of optical fiber delay line and adjacent optical carrier wavelength difference. Figure 5 shows that when the length of the optical fiber delay line is fixed, real-time delay and the wavelength difference of adjacent carrier have linear relation. We can see from Fig. 6 that when the adjacent optical carrier wavelength difference is constant, the real-time delay and the length of the optical delay are in linear correlation, consistent with the theoretical analysis.

In conclusion, through one-dimensional phased array electromagnetic field distribution, we deduce the fixed structure of phased array antenna in the microwave beam direction θ, which relates only to neighboring elements delay difference $\Delta\tau$, and has nothing to do with the emitted microwave frequency. That is to say, if the neighboring elements delay difference ΔT is controlled, the beam pointing angle θ will be controlled. Then by using multiple optical carriers and optical switch delay technology, we design the fiber real-time delay system and verify the real-time delay which shows linear correlation with the length of the optical fiber delay line and the wavelength difference between the adjacent optical carrier. Therefore, phased array antenna can be controlled in the phase by controlling the optical fiber delay line length and the adjacent optical carrier wavelength difference, and can improve the bandwidth and immunity to electromagnetic interference.

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