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Two-Dimensional Fiber Beamforming System Based on Mode Diversity

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ABSTRACT In this paper, a novel two-dimensional (2D) beamforming system based on mode diversity and true-time delay (TTD) of optical fiber is proposed. The system is composed of two cascaded TTD units, which are single-mode fiber TTD line array and mode TTD line array of few-mode fiber. For the first time, the mode diversity technology is applied to the 2D beamforming system which can realize beam scanning at a single wavelength and greatly reduces the cost and complexity. A beamforming system with 3×3 array antenna is built, and the properties of which are experimentally evaluated under a single wavelength of 1550.52 nm. The azimuth and elevation angles can reach the scanning range of $\pm 60°$. The gain performance are characterized, which decreases about 6 dB when the angle changes from $(0.11°, -0.11°)$ to $(59.82°, 60.21°)$ or $(-59.25°, -60.02°)$. The influence of frequency and mode coupling on the system performance are evaluated. The beam direction of the system is independent of microwave signal frequency while the test scope is 8.5 GHz to 11.5 GHz. Mode coupling has no effect on the beam direction of the system.

INDEX TERMS Beamforming, few-mode fiber, optical true time-delay, mode division multiplexing.

I. INTRODUCTION

Beamforming technology, which plays a critical role in the phased array antenna, has been widely used in radar systems and wireless communication network [1]–[4]. The two-dimensional beamforming system based on optical true-time delay technology [5]–[9] shows excellent performances in terms of operating frequency and bandwidth. The system with advantages of low loss and anti-electromagnetic interference can realize wide coverage and long distance scanning in space which is essential for acquisition radars, mobile communication base stations. In this context, the two-dimensional beamforming system based on optical true-time delay technology has been widespread concern.

At present, there have been many reports on the two-dimensional fiber true-time delay beamforming system. Byung-Min Jung proposed a 2×2 optical phased array based on a fiber delay line matrix using two distributed feedback lasers. The time delay of x and y directions of planar array were respectively controlled by the fiber length and the wavelength. Then azimuth beam steered within $\pm 30°$ and the elevation beam steered within $\pm 90°$ [10]. Maggie Yihong Chen proposed a 3×3 optical phased array, a two-stage delay unit was generated by combining the high dispersion fiber with the waveguide delay line. The delay change of x direction was achieved by adjusting the wavelength, and that of y direction was realized by adjusting the length of the waveguide delay line. Finally, the scan range of azimuth beam was from 0° to 60°, and that of the pitch beam was from 0° to 24.3° [11] Ortega proposed an 8×8 optical phased array based on a tunable laser and a tunable fiber delay line array. The change of single-mode fiber length and wavelength interval lead to the delay change of both directions. By combining the delays in both directions, it achieved different beam pointing angles such as (27.9°, 13.7°) and (30.4°, 14°) [12]. Also with fiber true-time delay line and WDM technology, Y. Zhou used 4 multi-wavelength lasers to realize a 4-beam two-dimensional beamforming system which achieved the scan range of azimuth and elevation angles to be $\pm 30°$ [13]. Obviously, WDM technology combined with optical fiber delay lines is the mainstream proposal to achieve a two-dimensional true-time delay beamforming

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system. Tunable lasers or multiple fixed wavelength lasers combined with dispersion delay elements are usually required to achieved delay, which makes the system costly. Moreover, it is difficult to realize large delay and wide coverage in both dimensions limited by the narrow wavelength tunability.

In this paper, we propose a two-dimensional fiber true-time delay beamforming system based on mode diversity. A 3 × 3 beamforming system based on few-mode fiber is built. The system consists of two-stage delay units, which is composed of a single-mode fiber delay line array and a mode delay line array of few-mode fiber. By adjusting the true-time delay line of single-mode fiber, the delay of x direction can be controlled. By adjusting the mode delay line array of few-mode fiber, the delay of y direction can be controlled. The two-dimensional beam steering can be realized under the condition of a single wavelength. Compared with beamforming systems using WDM technology, the system we proposed greatly reduces the cost and complexity. Mode diversity is brought as multiplying channel. Different modes in few-mode fiber based on modal dispersion with different propagation constants require different time to pass through a unit length of a few-mode fiber. Combined with optical fiber delay line, it can achieve large delay between different modal channel by regulating the transmission path of different modes and realize wide coverage at a single wavelength, which can overcome the problem of limited scanning range of beamforming systems based on wavelength tuning. The two-dimensional beamforming system with low cost, high integration density and wide coverage in space is realized. Experimental results show that the two-dimensional beamforming system based on mode diversity can achieve the scanning range of ±60° in azimuth and elevation angle at a single wavelength of 1550.52nm. The increase of scan angle can bring the attenuation of the gain of system. When the angel of both dimensions increase by 60°, the gain decreases approximately 6 dB. Combined with the gain performance, we investigate the effect of frequency and mode coupling on system performance. The beam direction of the system is independent of microwave signal frequency while the test scope is 8.5 GHz to 11.5 GHz on account of the super path loss in millimeter band. Mode coupling has no effect on the beam direction of the system.

II. SYSTEM MODEL

A 2D fiber beamforming system based on mode diversity is built. The system adopts a two-stage time delay unit structure scheme in which a single-mode fiber TTD line array cascaded with a mode TTD line array of few-mode fiber are used to realize 2D beamforming with a single wavelength laser. The specific structure is shown in Fig. 1.

The system is composed of two TTD units. The first unit is realized the time delay for x direction and the second unit is realized the time delay for y direction. A single-wavelength laser (Canalaser LxFNS1-DM) produces continuous (CW) light with a wavelength of 1550.52 nm. The microwave signal is modulated on the optical carrier by

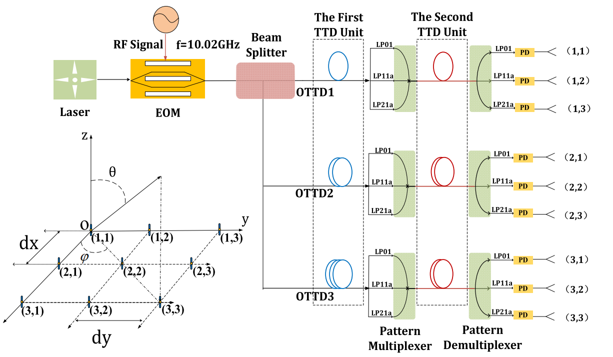

FIGURE 1. Structure diagram of 2D fiber beamforming system based on mode diversity.

an electro-optic modulator (40G LN Optical Modulator). The modulated optical signals are respectively injected into the three optical true-time delay (OTTD) branches ($OTTD_1$, $OTTD_2$, $OTTD_3$). After passing through the single-mode fibers (the first TTD unit) with lengths L_{x1}, L_{x2} and L_{x3} in the three OTTD branches, the signals of the adjacent OTTD branche can achieve a time delay. We set the length difference as $\Delta L_x = L_{x3} - L_{x2} = L_{x2} - L_{x1}$ and get the delay difference $\Delta\tau_x$ in x direction. Then the signal transmits into the Photon Lantern 1 (PL) of each OTTD branch in the second TTD unit that emerged as spatial mode multiplexer which converts the signal to LP_{01}, LP_{11a} and LP_{21a} modes. Based on the mode dispersion effect, different signal modes propagate at a different speed in the few-mode fiber. After the signal transmits over a few-mode fiber with length of L_y, a delay between each mode can be achieved, and the delay difference $\Delta\tau_{\mathrm{y}}$ in y direction is obtained. Then the signals with two-stage delay enter PL2 for mode demultiplexing. Trough photoelectric conversion by photoelectric detector (40G PIN-TIA Photodetector Module), the 9-channel coherent microwave signals with the delay difference $\Delta\tau_{\mathrm{x}}$, $\Delta\tau_{\mathrm{y}}$) between the adjacent antenna elements are acquired and the microwave signals are sent by the 3 × 3 antenna array to form the spatial beam pointing angle (θ, ϕ).

To realize the 2D beam steering in space, a combination of different $\Delta\tau_{\mathrm{x}}$, $\Delta\tau_{\mathrm{y}}$) is necessary. When length difference of the single-mode fiber in the first TTD unit is changed to ΔL_{x1} (or ΔL_{x2} or ΔL_{x3} etc.), the delay difference between adjacent OTTD branches becomes $\Delta\tau_{x1}$ (or $\Delta\tau_{x2}$ or $\Delta\tau_{x3}$ etc.). When the length of the few-mode fiber in the second TTD unit is changed to L_{y1} (or L_{y2} or L_{y3} etc.), the delay difference between adjacent modes becomes $\Delta\tau_{y1}$ (or $\Delta\tau_{y2}$ or $\Delta\tau_{y3}$ etc.). Combining the different delay differences, 2D beams with different directions can be obtained, and the beam pointing angles can be expressed as (θ_1, φ_1), (θ_2, φ_2), (θ_3, φ_3), etc.

III. EXPERIMENTAL RESULTS AND ANALYSIS

We test the performance of the 2D fiber beamforming system based on mode diversity, the experimental setup is built shown in Fig. 2.

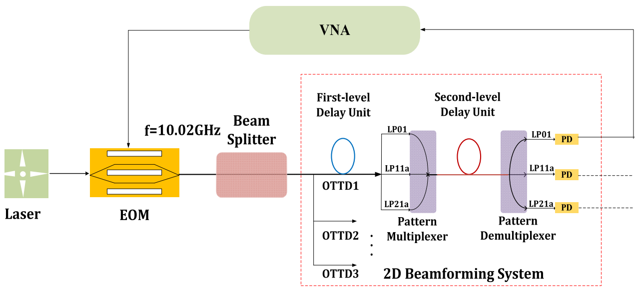

FIGURE 2. The experimental setup of 2D fiber beamforming system.

The performance of the 2D fiber beamforming system is performed by using a continuous wave laser with working wavelength $\lambda = 1550.52\ nm$. The center frequency of microwave signal is $f = 10.02\ GHz$, and the intervals between adjacent antenna units are $d_x = d_y = \lambda_{10.02\ GHz}/2 = 0.015\ m$, the number of antennas is N = 9.

The delay difference between LP_{01} and LP_{11a} modes is 6 ps/m and which is 11.7 ps/m between LP_{01} and LP_{21a} modes. A certain length of single-mode fiber at each channel pigtail of PL2 is added to form the isochromatic distribution of the delay between modes. The optical fiber delay lines are precisely cut and the length of which are measured accurately with a minimum resolution of 0.1 mm –0.2 mm. Statistics table of supplementary single-mode fiber length for each channel with different beam pointing angles is shown in Table 1.

TABLE 1. Statistics table of supplementary single-mode fiber length with different beam pointing angles.

Channel / Angle	LP_{01}(mm)	LP_{11a}(mm)	LP_{21a}(mm)
$(60.00^\circ, 60.00^\circ)$	--	--	0.37
$(54.44^\circ, 23.41^\circ)$	--	--	0.16
$(24.17^\circ, 52.43^\circ)$	--	--	0.17
$(0^\circ, 0^\circ)$	2.16	1.05	--
$(-24.17^\circ, -52.43^\circ)$	13.14	6.49	--
$(-60.00^\circ, -60.00)$	30.35	14.99	--

By tuning the length difference ΔL_x of the single-mode fiber to be 4.44 mm, 7.65 mm, 2.56 mm, 0 mm, −2.56 mm, −4.44 mm, and the length ΔL_y of the few-mode fiber to be 6.24 m, 2.69 m, 2.70 m, 0.9 m, 2.7 m, 6.24 m, the delay difference and beam pointing angle are measured and shown in Table 2. The radiation pattern of each 2D beam pointing angle is simulated by Matlab software using sinc function as shown in Fig. 3. As can be seen from the Fig. 3 that the actual beam pointing angle measured by the system has a certain deviation from the design angle. The time delay error range of each channel of the system is −0.5 ps to 0.7ps, and the average error is 0.38ps, which are affected by the optical fiber cutting accuracy and measurement error. Compared with the designed angle, the maximum deviation and average deviation of the tested beam pointing angle are 0.75° and 0.19°, respectively.

TABLE 2. Experimental and calculated pointing angle coordinate measured delay difference of 2D fiber beamforming system based on mode diversity.

Delay(ps)		Designed Angle		Measured Angle	
$\Delta\tau_x$	$\Delta\tau_y$	θ	φ	θ	φ
21.61	37.41	60.00	60.00	59.82	60.21
37.25	16.13	54.44	23.41	54.50	23.42
12.46	16.20	24.17	52.43	24.28	52.05
0	0	0	0	0.11	-0.11
-12.46	-16.20	-24.17	-52.43	-24.17	-52.10
-21.61	-37.41	-60.00	-60.00	-59.25	-60.02

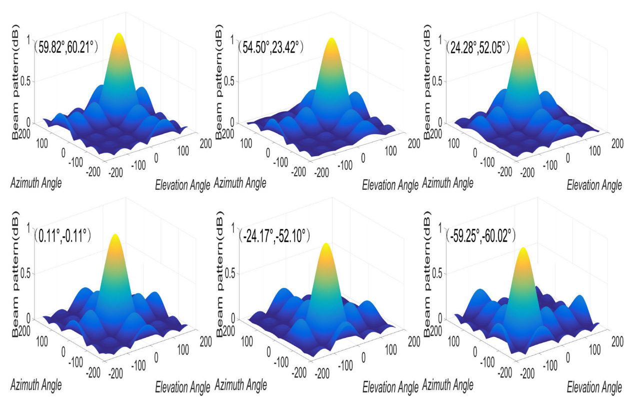

FIGURE 3. The radiation pattern of 2D beamforming system based on few-mode fiber.

The gain characteristic versus different pointing angles is evaluated. We assume that the antenna elements in the array are the same, frequency-independent, and isotropic. The radiations pattern of the azimuth and elevation angle of the system are obtained, as depicted in Fig. 4, and the gain are analyzed according to the radiation patterns.

It can be seen from the Fig. 4 that the 3 dB beam width of the main lobe is gradually broadened with increasing the beam scan angle when the system beam is scanning. For the reason that the gain of the system is inversely proportional to the beam width of the main lobe of the antenna, the system gain can be reduced when the main lobe beam width increases. The system gain is measured according to the beam width method. The system gain is 24.00 dBi when the scan angle is (0.11°, −0.11°). As the scan angle ranges from (0.11°, −0.11°) to (59.82°, 60.21°) or (−59.25°, −60.02°), the main lobe beam width broaden doubled and the system gain is reduced by 6.03dB and 5.97 dB to 17.97 dBi and 18.03 dBi. Therefore, the larger the scan angle of a two-dimensional beam system based on mode diversity, the lower the system gain is.

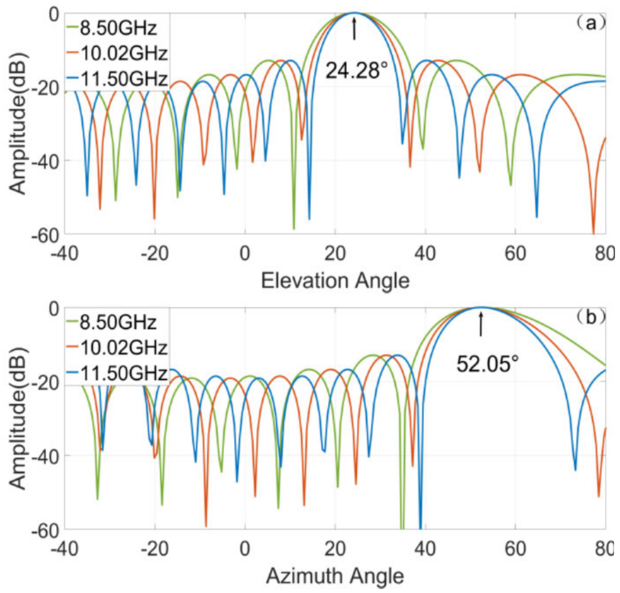

FIGURE 4. **The radiation pattern of the beam pointing angle (24.28°, 52.05°) at different frequencies. (a) Elevation angle. (b) Azimuth angle.**

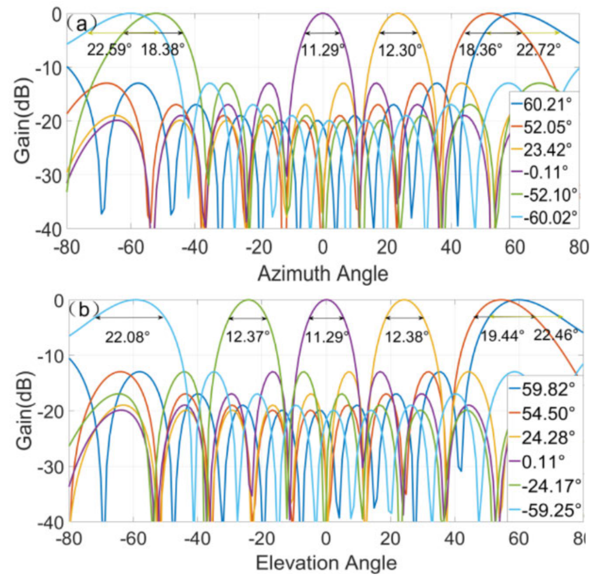

FIGURE 5. **The radiation pattern with different beam pointing angles. (a) Radiation pattern of azimuth angles. (b) Radiation pattern of elevation angles.**

In order to further evaluate the performance of the 2D fiber beamforming system based on mode diversity, we separately studied the influence of frequency and mode coupling on the system performance.

The optical true time delay technology can solve the problem of beam squint [14]. For the novel 2D beamforming system based on mode diversity and TTD of optical fiber, we validate comprehensively the beam pointing angle combined with the gain performance. Taking into account of reduction of gain impacted by beam broadening and the supramaximal path loss in millimeter band, we test the effective beam direction of the system in the frequency range of 8.5-11.5GHz.

Fig.5 shows the radiation pattern of the beam pointing angle (24.28°, 52.05°) when the microwave signal frequency is 8.5GHz, 10.02GHz and 11.5GHz, respectively. We can see from Fig. 5 that the two-dimensional beam pointing angle is still (24.28°, 52.05°) when the system signal frequency changes from 8.5GHz to 11.5GHz, there is no beam squint. In addition, the height of sidelobe lever are located the same and remain unchanged [15], [16]. In conclusion, the change of system frequency does not affect the beam pointing angle and sidelobe level. The antenna spacing is set as $d_x = d_y = \lambda_{10.02GHz}/2$ At this point, the main lobe beam widths are (14.57°, 21.60°), (12.38°, 18.36°) and (10.77°, 15.97°), respectively. As the frequency increases, the main lobe beam width becomes narrower and the gain of the system increases. The gain of the system with a signal frequency of 10.02 GHz and 11.5 GHz is respectively 1.42 dB and 2.63 dB higher than the gain of a system with a frequency of 8.5 GHz.

Mode diversity is brought in the beamforming system we proposed to implement 2D beam scanning. The mode coupling exists between the various modes of the few-mode fiber. It can make the energy change between the channels in the second TTD unit, which results in inconsistent amplitudes of the channels. Thus the sidelobe level of the system is affected. We studied the impact of coupling size on system performance by changing the length of the few-mode fiber. The coupling coefficients between the modes of the few-mode fiber are measured ($h_{A,B}$ means coupling A to B): $h_{01,11a} = 0.011dB/m, h_{01,21a} = 0.0003dB/m, h_{11a,01} = 0.035dB/m, h_{11a,21a} = 0.020dB/m, h_{21a,01} = 0.004dB/m, h_{21a,11a} = 0.021dB/m$. The influence of mode coupling with different lengths of few-mode fibers on sidelobe level are shown in Fig. 6.

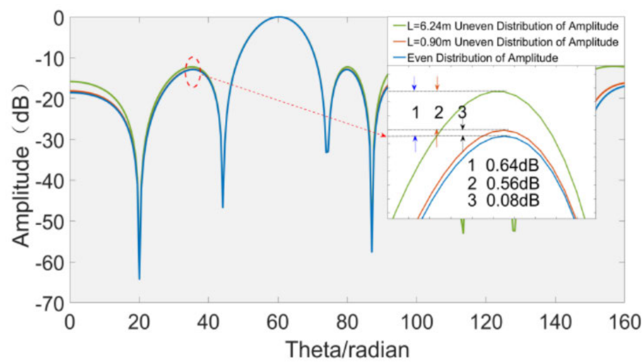

FIGURE 6. **Influence of mode coupling with different lengths of few-mode fibers on sidelobe level.**

The three curves in Fig. 6 are the radiation patterns with a few-mode fiber lengths of 0.9 m,6.24 m and without the mode coupling (power balance), respectively. When the length of the few-mode fiber is 0.9 m, the energy coupling of LP01, LP11a, LP21a modes are 0.11 dB, −0.09 dB, and −0.02 dB, respectively. It can be seen from the Fig. 6 that the system sidelobe level is 0.08 dB higher than that with power equalization. When the length of the few-mode fiber is 6.24 m, the energy coupling of LP01, LP11a, LP21a modes are 0.69 dB, −0.67 dB, and −0.13 dB, respectively. The sidelobe level is 0.64dB higher than that with power equalization. The longer the fiber, the greater the coupling, the more serious the amplitude mismatch between the branches of the system, which results in a gradual increase in the sidelobe level of the system. As the system sidelobe level increases, the gain decreases. The few-mode fiber used in our system is shorter and has good performance. Moreover, the beam main lobes of the three curves in the figure completely coincide, that is, mode coupling has no effect on the beam direction of the system.

IV. CONCLUSION

In this paper, the 2D optical fiber beamforming system realizes wide-range beam scanning in 2D space by adjusting the two-stage TTD unit under the condition of a single wavelength. The radiation pattern of the system with 6 beams pointing downward is tested, which achieves a ±60° scan range of azimuth angle and elevation angle. We get the relation of the gain of the system and the beam width of different pointing angles, which are inversely proportional. The larger the scan angle, the lower the system gain is. Apart from that, we also discuss the influence of signal frequency change on beam pointing and the effect of mode coupling on system performance which show that: the beam direction is independent of the signal frequency and without beam squint. The beam side-lobe level is related to the mode coupling and weakening or eliminating mode coupling has conducive to reducing the beam sidelobe level.

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