A 7-bit photonic true-time-delay system based on an 8×8 MOEMS optical switch

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We demonstrate a 7-bit photonic true-time-delay (TTD) system which uses an 8×8 micro-optical-electro-mechanical system (MOEMS) optical switch for phased array antennas (PAAs) beamforming applications. The switch controls the optical signal to pass by the fiber delay lines (FDLs) of different lengths. Different time delays between adjacent channels are obtained due to the chromatic dispersion of FDLs. Therefore, the system cannot be disturbed by the environment. The measured time delay responses are nearly linear with the wavelength spacing between optical carriers as well as the lengths of FDLs, which agrees well with the theoretical analysis.

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During the last few years, photonic true-time-delay (TTD) units have been widely researched for wide-band squint-free beamforming for phased array antennas (PAAs). The advantages provided by TTD beamforming technique include low loss, small size, light weight, large instantaneous bandwidth, high resolution, and no electro-magnetic interference (EMI). Since micro-optical-electro-mechanical system (MOEMS) switch possesses many desired properties such as low insertion loss, fast switching time, and easy electronic control, it can be used as an economical and efficient alternative to implement a TTD feeder in combination with fiber delay lines (FDLs)[1−11]. One approach is usually employed to construct a MOEMS beamsteerer. In this scheme, all the antenna elements share the same optical carrier. The optical signals corresponding to different elements are controlled by MOEMS switches to pass by independently different FDLs[1−4]. The time delays between adjacent channels are obtained by different lengths of FDLs. Because the light paths are separated, the time delay differences of elements are easily disturbed by the environment, which affects the accuracy of beampointing.

In this letter, we propose and demonstrate a new TTD system in which every antenna element corresponds to a different optical carrier. All the optical carriers share the same FDLs which are composed of 7 sections of dispersion compensating fibers (DCFs). The lengths of FDLs are controlled by an 8×8 MOEMS switch. This is a 7-bit TTD system. Different orders of time delays between adjacent optical carriers are obtained due to the chromatic dispersion of FDLs. Because all of the optical carriers share with the same light paths, the time delay differences between adjacent channels are independent of external factors and the beampointing of antennas is accurate. In the experiment, a two-element TTD unit is constructed and the time delay responses of the TTD system are measured. The results show that the time delay differences vary linearly with the wavelength spacing between adjacent optical carriers and the lengths of FDLs, which agrees well with theoretical analysis. When the wavelength spacing between adjacent optical carriers is 3.2 nm, the minimum time delay step is much smaller than 1 ps and the maximum time delay is nearly 300 ps.

Figure 1 shows the configuration of the proposed 7-bit optical TTD feeder system using an 8×8 MOEMS switch for linear PAAs. In the system, N laser sources with identical wavelength spacing are applied. The

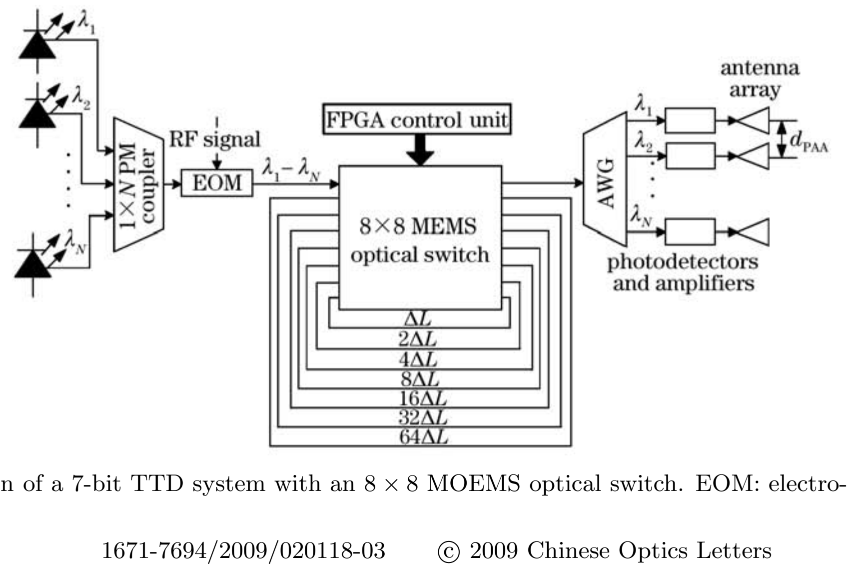

Fig. 1. Configuration of a 7-bit TTD system with an 8×8 MOEMS optical switch. EOM: electro-optical modulator.

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outputs of the laser sources are multiplexed by a 1 × N polarization maintaining (PM) coupler. Then the coupled light is externally modulated by a radio frequency (RF) signal. The modulated optical signal is fed to the TTD unit which is composed of an 8×8 MOEMS switch and 7 sections of DCF delay lines. The 8×8 MOEMS switch is controlled by a field programmable gate array (FPGA) control unit. During this process, the combination of the 8×8 MOEMS switch and 7 sections of DCF delay lines provides different time delays to the corresponding antenna elements. Then the delayed optical signal is demultiplexed by an arrayed waveguide grating (AWG) and detected by the following high-speed photodetectors before antenna-radiator elements.

For the TTD system shown in Fig. 1, the beampointing angle corresponding to the main lobe of the antenna array θ_0, can be expressed as

$$\sin\theta_0 = \frac{c\Delta t_{\mathrm{d}}}{d_{\mathrm{PAA}}}, \tag{1}$$

where d_{PAA} is the element spacing of the antenna array, c is the light speed in free space, and Δt_{d} is the time delay difference between adjacent channels. The equation indicates that the beampointing direction is determined by the time delay difference and is independent of the microwave frequency. Therefore, the TTD system is suitable for wideband applications.

In this system, the time delay difference is determined by the chromatic dispersion of FDLs, the wavelength spacing between adjacent optical carriers, and the length of FDLs. It can be described as

$$\tau = D\cdot\Delta\lambda\cdot L, \tag{2}$$

where D is the chromatic dispersion parameter of FDLs, $\Delta\lambda$ is the wavelength spacing between adjacent optical carriers, and L is the length of FDLs. In the proposed system, D is a constant while $\Delta\lambda$ and L are changeable. So the time delay difference is linear with the wavelength spacing between adjacent optical carriers and the length of FDLs. Therefore, the beampointing direction is determined by the wavelength spacing between adjacent optical carriers and the length of FDLs.

For this system, 7 sections of DCFs whose lengths are respectively ΔL, $2\Delta L$, $4\Delta L$, $8\Delta L$, $16\Delta L$, $32\Delta L$, and $64\Delta L$ are connected to the 8×8 MOEMS switch. The 7 sections of DCFs constitute the FDLs. The fiber connections of the switch are controlled through an array of micro-mirrors on a microchip and are selectively activated to connect the desired fiber paths. An algorithm is applied in the FPGA control unit to control the micromirrors within the 8×8 MOEMS switch to be on or off, which results in 128 independent lengths of FDLs and 128 orders of time delays. Therefore, the FDLs are 7-bit TTD lines.

In the experiment, a distributed feedback (DFB) laser and a tunable laser were applied. The wavelength of the DFB laser was 1554.6 nm. The tunable laser was used to change the wavelength spacing between adjacent optical carriers.

Firstly, the lengths of FDLs were fixed while the tunable laser was tuned to change the wavelength spacing between adjacent optical carriers with a step of 0.8 nm. The corresponding time delay differences were measured, as shown in Fig. 2. The lengths of FDLs used were 1.3 km and 88.9 m, respectively. The chromatic dispersion parameter of FDLs was measured to be about −144.0 ps/(nm·km) at 1550 nm. Figure 2 shows that the time delay differences are nearly linear with the wavelength spacing between adjacent optical carriers.

Secondly, we measured the relationship between the time delay differences and the lengths of FDLs. The separated lengths of DCFs connected to the 8×8 MOEMS optical switch were 5, 10, 20, 40, 80, 160, and 320 m. The wavelength spacings between the DFB laser and the tunable laser were 3.2, 5.6, and 8 nm respectively. When the wavelength spacing between the two lasers was 3.2 nm, the minimum time delay step was much smaller than 1 ps, corresponding to the minimum length of FDLs of 5 m. Due to the precision limitation of experimental equipments, the FPGA control unit was used to change the lengths of FDLs with a step of 50 m. The measured time delay responses are shown in Fig. 3, which indicates that the time delay differences are nearly linear with the lengths of FDLs.

For the conventional double-sideband intensity modulation (IM) scheme, RF power varies as $P(f,z)\propto\cos^2(\frac{\pi D\lambda_0^2 f_{\mathrm{sc}}^2}{c}Z)$[12,13], where f_{sc} is the frequency of RF signal, Z is the fiber length, and λ_0 is the optical carrier wavelength. From it, we know that the chromatic dispersion will cause periodic RF power degradation, and when the RF normalized power degrades to −1 dB, the experimental 7-bit TTD unit can be used for PAA beamforming at microwave frequencies up to 11.40 GHz. The frequency of the RF signal used in our system is from 3 MHz to 10 GHz and the chromatic dispersion of the FDLs has little impact on the system. At higher

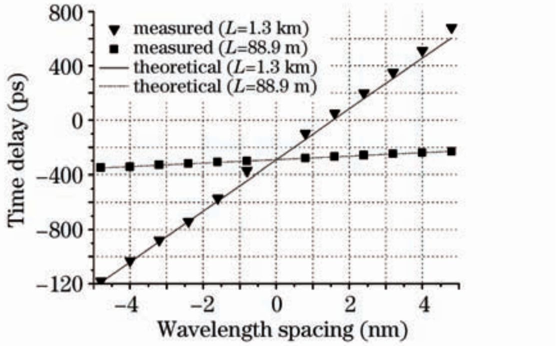

Fig. 2. Time delay differences for different wavelength spacings between adjacent optical carriers.

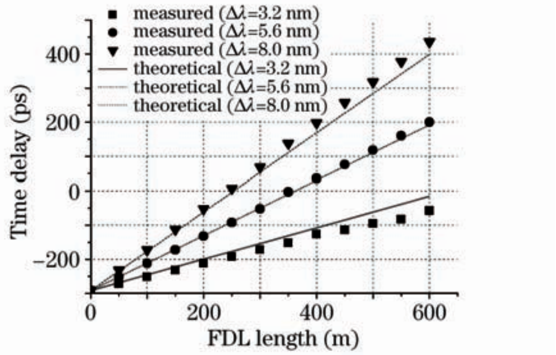

Fig. 3. Time delay responses for different lengths of FDLs.

frequencies, the chromatic dispersion of the FDLs will cause noticeable RF power degradation and the single-sideband modulation technique should be employed.

In conclusion, we demonstrate a new 7-bit TTD system that uses an 8×8 MOEMS optical switch and 7 sections of DCFs for TTD beamforming. Two-beam transmission which generates 128 independent orders of time delays is investigated by using a DFB laser and a tunable laser. Different carriers share the same MOEMS switch and FDLs. The measurement results show that the time delays of different optical carriers are linearly proportional to the wavelength spacing between adjacent optical carriers as well as the lengths of FDLs, which agrees well with the theoretical analysis. The proposed system can be further used for wideband continuous beamforming at frequencies from 3 MHz to X-band.

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