Optical true time delay unit for multi-beamforming

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Abstract: An optical true time delay (TTD) unit capable of adding independent time delays to multiple RF signals is proposed, which can be used for multi-beamforming in both transmit and receive modes. In the proposed unit, N RF signals with different center frequencies are modulated on an optical frequency comb (OFC). After transmission through a dispersive element, the RF-modulated OFC is split into N paths. In each path, a comb line is selected by a tunable optical filter. Thanks to the chromatic dispersion of the dispersive element, independently-controllable TTDs can be obtained in all paths. Then, a microwave photonic filter (MPF) is incorporated in each path, allowing a designated RF signal to undergo the TTD in that path. A proof-of-concept experiment is carried out. A two-path unit with a low-pass MPF in one path and a high-pass MPF in the other path is built. Controllable TTDs up to ~1.4 ns with a step of ~69 ps are demonstrated based on a 25-GHz-spacing OFC. In addition, a wideband multi-beam phased-array antenna system that can work in both transmit and receive modes is designed using the proposed TTD unit.

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1. Introduction

To solve the beam-squint problem in wideband phased-array antenna systems, extensive efforts have been devoted to the beamforming technique by true time delay (TTD). Thanks to the advantages such as low loss, large bandwidth and immunity to electromagnetic interference, optical technologies are considered as the most promising way to realize the TTD. Until now, numerous optical TTD schemes have been reported, which include the acousto-optic spatial Fourier decomposition with linear phase-shifting [1], the stimulated Brillouin scattering (SBS) based slow light [2], ring resonator based photonic integrated circuit [3, 4], tunable optical delay line with optical switches [5], and dispersion with tunable laser source [6]. However, few of the reported methods could provide independent TTDs for multiple RF beamforming. As the fast development of modern radar and warfare systems [7, 8], there is increasing demand for multi-task phased-array antennas where independent steering of multiple RF signals with different frequencies is required. Therefore, it is highly desirable to realize an optical TTD beamformer with independent and controllable TTDs for multiple RF signals. To achieve this goal, some pioneer works have been reported [9–12]. In [9], an optical TTD multi-beamforming network is proposed utilizing highly dispersive photonic crystal fibers. The key problem associated with this approach is that different architectures have to be applied for transmit and receive modes, which is complex, inefficient and inflexible. To increase the flexibility of the system, one promising solution is to construct a phased-array antenna system using a number of independent delay units. Similar to the T/R modules in an active electronically-scanned array where each antenna is connected to an independent T/R module, an ideal TTD unit for each antenna element is expected to support both transmit and receive modes. A photonic delay unit using a large port-count demultiplexer and fast tunable lasers is implemented for beamforming in the transmit mode [10], which can be altered to support the receive mode [11]. However, the schemes cannot process multiple RF signals independently due to the lack of RF filters. Recently, an optical TTD unit using a mode-locked laser (MLL) and a dispersive element is reported to simultaneously steer multiple RF signals [12], but the unit cannot work in the receive mode since it implements RF signal generation simultaneously. In addition, the incorporation of frequency-fixed and narrowband RF filters in the unit restricts the operation bandwidth of the system.

In this paper, we propose an optical TTD unit with independent delays for multiple RF signals, which can be used in both transmit and receive modes. In the proposed unit, an optical frequency comb (OFC) carried with N different RF signals are transmitted through a dispersive element, which are split into N paths. In each path, a comb line is selected by a tunable optical filter to form a certain TTD, and a RF signal is selected by a microwave photonic filter (MPF), determining which RF signal undergoes the TTD in the path. As a result, all the RF signals can obtain independent TTDs. If the proposed unit is applied in a phased-array antenna system operated in either transmit or receive mode, multiple independent beams steering can be realized. A proof-of-concept experiment is carried out. A

two-path unit is built using a polarization modulator (PolM). The power splitter and tunable optical filters are implemented by a multiport programmable optical filter, and two MPFs for high-pass and low-pass filtering are incorporated in the two paths of the unit, respectively, which are realized by the PolM and polarization-maintaining fibers (PMFs) [13]. An independently-controlled time delay with an adjustable range of ~1.4 ns and a tuning step of ~69 ps is achieved. Based on the proposed optical TTD unit, a wideband multi-beam phased-array antenna system that can work in both transmit and receive modes is also designed.
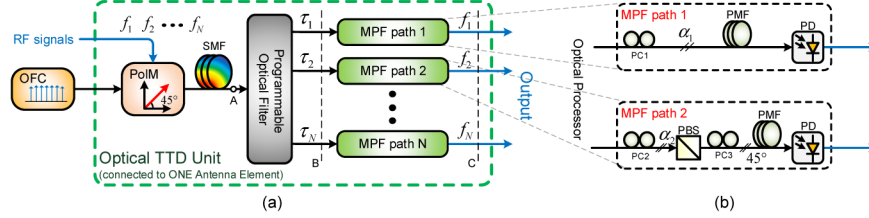

Fig. 1. (a) The schematic diagram of the proposed optical TTD unit, and (b) the configuration of the two paths in the experimental setup.

2. Principle of the optical TTD unit

Figure 1(a) shows the schematic diagram of the proposed optical TTD unit, which can be used to control the time delays of the feeding and the received signals of one antenna element in a phased-array antenna system. An OFC with multiple comb lines is sent to a PolM which is driven by the RF signals to be processed. After the PolM, the RF signals are modulated on each comb line of the OFC. Then, the optical signal is sent to a spool of single mode fiber (SMF). In the SMF, a certain comb line undergoes a time delay given by $\Delta\tau = D(\lambda - \lambda_0)$, where D is the chromatic dispersion coefficient, λ is the wavelength of the comb line, and λ_0 is a reference wavelength. As a result, various time delays of the multiple RF signals can be obtained at point A in Fig. 1(a). If the center frequencies of the multiple RF signals are $\{f_1, f_2, \cdots, f_N\}$, the combination of RF frequencies and time delays can be expressed as a Cartesian product of the delay set and the frequency set, given by

$$S_{\mathrm{A}} = \{\tau_1, \tau_2, \cdots\} \times \{f_1, f_2, \cdots, f_N\} \tag{1}$$

After that, an N-port programmable optical filter is inserted to select N comb lines, which are then split into N paths. This process determines particular delays for different paths, making the RF signals have the form of

$$S_{\mathrm{B}} = \{\tau_p\} \times \{f_1, f_2, \cdots, f_N\} \tag{2}$$

In each path, a wavelength-independent MPF is incorporated to pick out the desired RF signal. At the output of each MPF, only one RF signal with a certain time delay is achieved, which can be expressed as

$$S_{\mathrm{C}} = \{(\tau_p, f_q)\} \tag{3}$$

Thanks to the flexible wavelength selection by the programmable optical filter, any combination of p and q in Eq. (3) can be achieved. Thus an independent and controllable time delay is introduced to a certain RF signal in each path, and multi-beamforming can be realized thereafter.

   To demonstrate the concept, a two-path unit with two independently-controlled time delays is investigated. The optical filter is programmed to select two comb lines from the OFC, and the two comb lines are split into two paths, as shown in Fig. 1(b). In the upper path, a two-tap high-pass MPF (MPF1) with tap coefficients of {1, −1} is implemented by a

polarization controller (PC: PC1) and a length of PMF together with the PolM in the trunk line [13]. The PolM is a special phase modulator that can support both TE and TM modes with opposite phase modulation indices [14]. By tuning the bias voltage of the PolM to introduce a phase difference of 90° between the two principal axes of the PolM, two complementary optical microwave signals are generated, which are along the two principal axes of the PMF, yielding the implementation of two filter-taps with opposite signs. Considering the dispersion-induced power fading in the SMF, the frequency response of the upper path can be written as [15, 16]

$$\left| H_{\mathrm{MPF1}}(\omega) \right| \propto \left| \sin(\frac{1}{2}z\beta_2\omega^2 - 2\alpha_1) \right| \cdot \left| \sin\frac{\tau_{\mathrm{DGD1}}\omega}{2} \right| \tag{4}$$

where z is the length of the SMF, β_2 is the second-order derivative of the propagation constant with respect to the angular frequency, α_1 is the angle between one of the polarization axes of the signal from the PolM and one of the principal axes of PMF which can be adjusted by PC1, and τ_{DGD1} is the differential group delay of the PMF. From Eq. (4), the shape of the MPF can be finely adjusted through the dispersion-induced power fading function by tuning α_1. In the lower path, another MPF (MPF2) is inserted. The polarization-modulated signal is converted to a linearly-polarized signal by a polarization beam splitter (PBS) and then aligned by PC3 to have an angle of 45° to one of the principal axes of the PMF. Thus, two in-phase optical microwave signals are sent respectively to each principal axis of the PMF, achieving a low-pass RF filter with two tap coefficients of {1, 1}. The frequency response of MPF2 is given by

$$\left| H_{\mathrm{MPF2}}(\omega) \right| \propto \left| \sin(\frac{1}{2}z\beta_2\omega^2 - 2\alpha_2) \right| \cdot \left| \cos\frac{\tau_{\mathrm{DGD2}}\omega}{2} \right| \tag{5}$$

where α_2 is the angle between one of the polarization axes of the signal from the PolM and one of the principal axes of the PBS, which can be adjusted by PC2. According to Eq. (5), the frequency response of MPF2 can also be optimized through adjusting α_2.

3. Experimental results

An experiment based on the setup in Fig. 1 is carried out. The OFC with a spacing of 25 GHz (~0.2 nm) is generated by an optical comb generator (OptoComb WTEC-01-25). The PolM in the TTD unit has a bandwidth of 40 GHz and a half-wave voltage of 3.5 V at 1 GHz (Versawave Inc.). The length of the SMF is ~20 km. The programmable optical filter (Finisar WaveShaper4000s) has a center frequency setting resolution of 1 GHz. The PMF in each MPF is ~42-meter long, which provides a differential group delay of ~60 ps. An 18-GHz photodetector (PD) with a responsivity of 0.65A/W is used to perform optical-to-electrical conversion. Erbium doped fiber amplifiers (EDFAs) are placed after the OFC module and the optical filter, respectively, to boost the optical signals. A 20-GHz electrical vector network analyzer (Agilent N5230C) is employed to measure the frequency response.
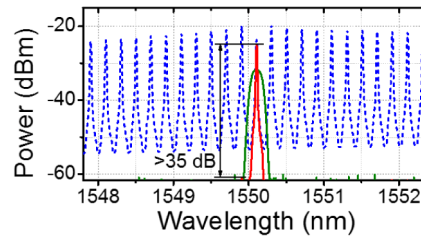

Fig. 2. Optical spectrum of the OFC (dashed line), the transmission response of the programmable optical filter (solid green line), and one of the filtered comb line (solid red line).

Figure 2 shows the optical spectrum (dashed line) of the generated OFC with a comb line spacing of 25 GHz. The programmable optical filter is set to have a bandwidth of 0.2 nm,

with the filter response, for example at 1550.1 nm, and the filtered comb shown as the solid lines in Fig. 2. As can be seen, the transmission response of the filter has two steep edges, which guarantees an aliasing-free operation for RF signals up to 12 GHz around each comb line. After the optical filter, the comb line at 1550.1 nm is successfully selected, and the adjacent-comb lines are suppressed by more than 35 dB. Owing to the attenuation-programmable capability of the optical filter, the slight power variation between different comb lines of the OFC can be easily compensated.

The RF magnitude responses of the unit are shown in Fig. 3. Thanks to the flexibility of polarization modulation, the notches and peaks of the dispersion-induced power fading response can be moved to any desired RF frequencies [15], achieving an optimized filtering effects. When compared with the calculated response of the Mach–Zehnder modulator (MZM)-based MPF shown as the dashed line in Fig. 3(a), a much better high-pass filter is achieved by the proposed scheme. Similarly, a low-pass filter with better response is realized in MPF2, shown in Fig. 3(c). Because the time delay is controlled by selecting different comb lines in the OFC, the characteristics of the MPFs using different comb lines are measured. As shown in Figs. 3(b) and 3(d), no obvious power variation is observed in the passband of each MPF, which verifies the wavelength independency of the MPFs. In the proof-of-concept experiment, only two RF signals are tested in the system, so two MPFs with high and low pass responses are sufficient to differentiate the two signals. If more than two RF signals are presented, advanced MPFs with better passband flatness, stopband extinction and Q factor should be applied. Since there is an optical frequency comb in the system, by selecting more comb lines via enlarging the bandwidth of the optical filter, more taps could be formed [17].
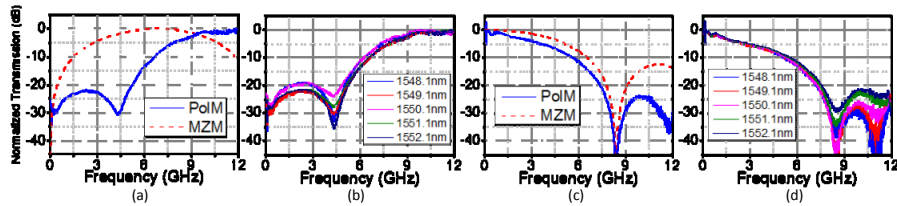

Fig. 3. Magnitude responses of the TTD unit in (a,b) MPF1 path and (c,d) MPF2 path.
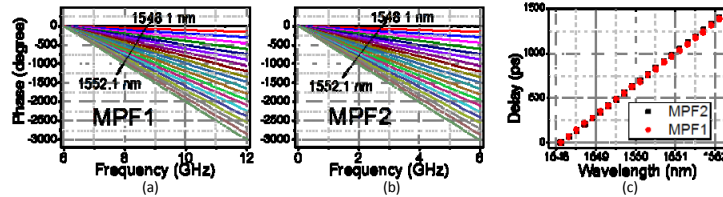

Fig. 4. Phase responses of the TTD unit in (a) MPF1 (high-pass filter) path and (b) MPF2 (low-pass filter) path as well as (c) the calculated time delays of the system.

Then, the TTD properties of the proposed unit are investigated by measuring the RF phase responses for the cases when different comb lines are selected by the programmable optical filter, as shown in Fig. 4. In the measurement, the comb line at 1548.1 nm is selected as a reference. 21 comb lines from the OFC are selected in sequence from 1548.1 to 1552.1 nm with a step of 0.2 nm. The measured phase responses are shown in Figs. 4(a) and 4(b), where the linear relationship between the phase and the RF frequency in the passband of each path confirms that the TTD is realized. Based on the phase responses, the obtained time delay is calculated, with the results shown in Fig. 4(c). As can be seen, the two MPF paths have an identical linear relationship between the delay and the wavelength offset, which agrees well with the theoretical prediction. In the experiment, the delay step of the optical TTD unit is ~69 ps and the max time delay is ~1.4 ns.

4. Multi-beam phased-array antenna system

Based on the proposed TTD unit, a multi-beam phased-array antenna system can be constructed. As shown in Fig. 5, the system consists of a shared OFC generator, a shared multi-frequency RF source, a number of antenna elements connected to separated TTD units, several shared RF receivers and a controlling subsystem. In the transmit mode (dashed blue lines), the OFC is modulated at the PolM by signals from the RF source in each optical TTD unit, where RF signals with different center frequencies are delayed independently, combined, and finally sent to the corresponding wideband antenna element for radiation. In the receive mode (solid blue lines), multiple RF signals are captured by each antenna element, modulated onto the OFC, processed by the units, and then sent to the corresponding receivers. In each RF receiver, signals from different antenna elements but with the same center frequency would be combined and superposed to form the beams. Since the proposed TTD unit can introduce independent TTDs to different RF signals, multiple wideband beams can be formed and independently controlled by the system in both transmit and receive modes. It should be noted that if the MPFs in the proposed TTD unit can have overlapped frequency responses or multiple passbands, the system is also able to transmit or receive a RF signal in multiple directions or multiple RF signals in the same direction. In addition, on-chip programmable optical filters and MPFs were recently reported [18, 19], which could significantly simplify the complexity and reduce the size of the proposed TTD unit as well as the multi-beam phased-array antenna system.
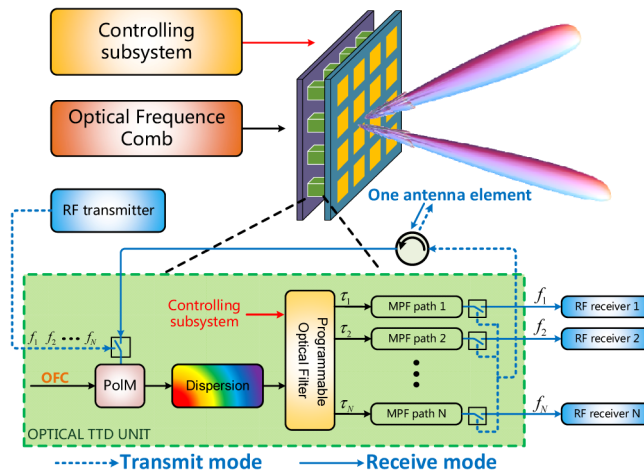

Fig. 5. Schematic diagram of the multi-beam phased-array antenna system based on the proposed optical TTD unit.

5. Conclusion

An optical TTD unit based on fiber dispersion and MPFs has been proposed and demonstrated. In each path of the unit, TTD controlling is realized by a tunable optical filter while RF frequency selection is realized by a MPF. Thanks to the independency of optical filters and MPFs in different paths, the proposed unit can introduce different TTDs to different RF signals, which is useful for steering multiple RF beams with different center frequencies simultaneously and independently. A two-path unit was built. Controllable delays up to ~1.4 ns with a step of ~69 ps are achieved for both the low-pass MPF path and the high-pass MPF path. A multi-beamforming phased-array antenna system utilizing the proposed TTD unit is also designed, which can be used for multi-task radar, satellite communication and other applications.

Acknowledgments