Photonic Crystal Fiber-Based True-Time-Delay Beamformer for Multiple RF Beam Transmission and Reception of an X-Band Phased-Array Antenna

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***Abstract*—We report multiple beam transmission and reception of an X-band phased antenna array utilizing highly dispersive photonic crystal fiber (PCF), which has a dispersion value of −600 ps/nm/km at 1550 nm, as true-time-delay (TTD) elements. In the transmission mode, two RF signals with frequencies 8.4 and 12 GHz are simultaneously steered at angles 7.4 and 21.2 degrees, respectively. In the receiving mode experiment, two RF signals with frequencies 8.4 and 12 GHz impinging upon an X-band antenna array from angles −7.4 and −21.2 degrees, respectively, are detected and the angles of arrival are determined accurately. Many RF beams can be simultaneously transmitted or received. The demonstration is only limited by the hardware availability and the bandwidth of the wavelength differentiation capability of the system.**

***Index Terms*—Dispersion, optical beamforming, phased-array antenna, photonic crystal fiber (PCF), true-time delay (TTD).**

I. INTRODUCTION

PHASED-ARRAY ANTENNA (PAA) systems have many advantages over mechanically steered antenna arrays in terms of speed, sensitivity, and size [1]. However, most of phased array antenna radar architectures suffer from problems of being bulky, sensitive to electromagnetic interference (EMI), beam squint effect, and limited bandwidth due to the installation of large amount of electrical cables and microwave phase-shifting devices. Today's phased-array radar technologies call for frequency independent beam steering, compact and light weight systems, large instantaneous bandwidth, and EMI free performance [2]. These features can be realized by using optical true-time delay (TTD) techniques. Furthermore, systems with TTD have the intrinsic capability of multibeam operation due to the fact that the optical signals with different optical wavelengths can propagate through a fiber without interfering with each other, for which the widely used dense wavelength division multiplexing (DWDM) system is an illustrative example. Many optical schemes have been proposed to take advantages of a photonic feed for true-time delay (TTD), including acoustooptic (AO) integrated circuit technique [3], Fourier optics technique [4], bulky optics technique [5], dispersive fiber technique [6], fiber grating technique [7], and substrate guided wave technique [8]. Of these techniques, the dispersive fiber technique can reduce the size and weight of the overall system by a significant factor. Conventional systems use single-mode fibers (SMF) as delay lines to implement the dispersive fiber technique. Since the dispersion coefficient D, of SMF is small (∼18 ps/nm/km @1550 nm), longer lengths of fiber are generally required to generate large time delay values. One alternative to solve this problem is to use highly dispersive photonic crystal fibers (PCF), which can be designed to have very large dispersion values compared to a conventional SMF [9]. By using such highly dispersive photonic crystal fibers as delay lines, we can reduce the length of the fiber dramatically compared to conventional SMF based systems. In this paper, we demonstrate a multiple-beam true time delay beamformer using highly dispersive PCF as delay lines for both transmitting and receiving functions. In Section II, the properties of the highly dispersive PCF are explained. The structural design and working of the beamformer in the transmitting mode is explained in Section III. Section IV describes the structural design and working of the beamformer in the receiving mode. In each of the Sections III and IV, a description and working of a general system is first described, followed by the experimental demonstration and results of our experiment.

II. WORKING PRINCIPLE OF HIGHLY DISPERSIVE PCF

The PCF structure used in the demonstration is based on a dual concentric core configuration [10], [11]. The inner and outer cores are made up of doped silica rods which have a higher refractive index compared to background silica. The refractive index of the inner core is slightly greater than that of the outer core. This concentric-core PCF with a cross section shown in Fig. 1, can support two supermodes just like in a directional coupler [11], which are designed to be nearly phase matched at a wavelength of $\lambda = \lambda_0$. The high dispersion in such a PCF arises from the fact that when $\lambda < \lambda_0$, most of the mode energy is strongly confined in the inner core, and when $\lambda > \lambda_0$, most of the mode energy stays in the outer core. Near the phase-matched wavelength, there is a strong coupling between the two modes and a part of mode energy is in the inner core and a part of it is in the outer core. This redistribution of mode energy causes the refractive index to change rapidly with wavelength leading to a very high dispersion value near the phase matched wavelength

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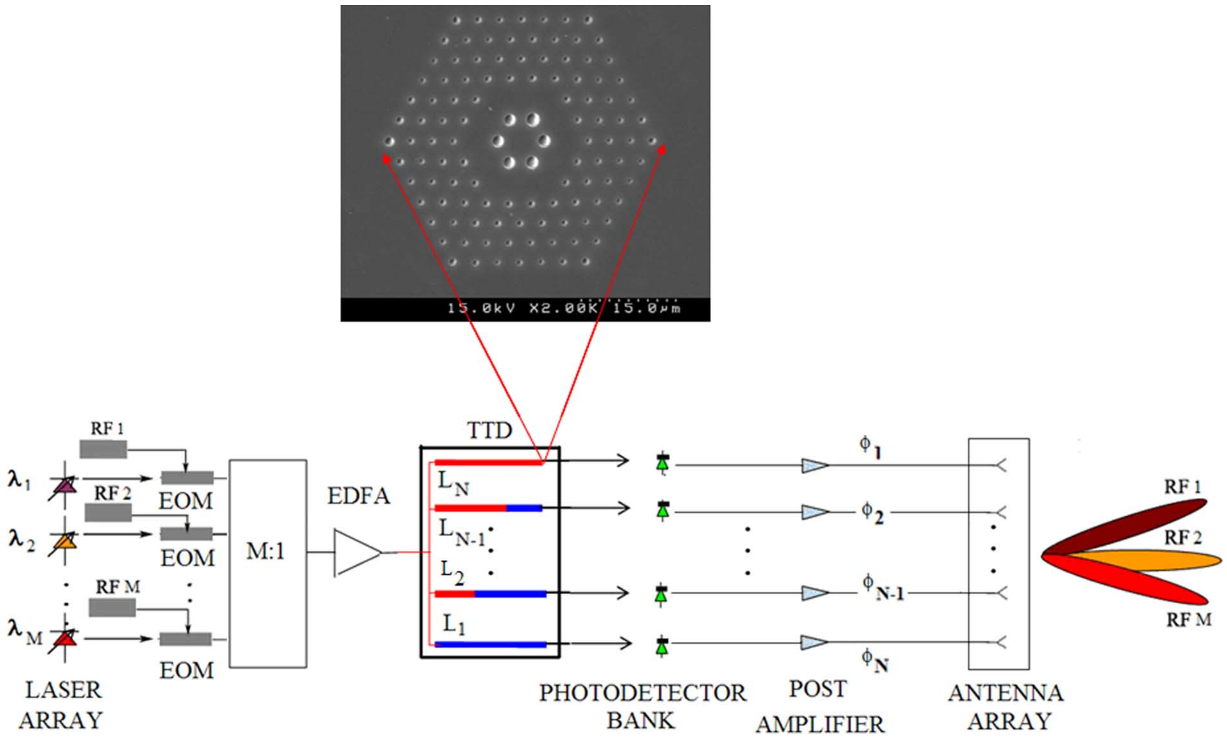


Fig. 1. Structure for simultaneous transmission of multiple beams, EOM: EDFA, TTD. The cross-sectional schematic view of the PCF is also shown.

[12]. We have previously reported the use of this PCF for single RF beam steering [13], [14]. The PCF has a chromatic dispersion coefficient of −600 ps/nm/km, measured at a wavelength of 1550 nm. The dispersion value of the PCF is 33 times larger compared to that of a conventional SMF which is ~18 ps/nm/km at 1550 nm. This means that we can shrink the length of the fiber used in this system by a factor of 33 compared to the system using SMF alone, making the system compact and light weight.

III. The Structure and Working Demonstration of Multiple-Beam Transmission

Using the PCF-based TTD module, multiple-beam transmission can be realized by using the scheme as shown in Fig. 1. A general system is shown wherein a multiple number (M) of RF signals are transmitted simultaneously using an antenna array having N elements. A single set of TTD lines generates the required time delay values for each element in the antenna array.

External cavity tunable lasers are used to generate a multiple number of optical carrier waves with wavelengths λ_1 to λ_{M}. RF signals with different frequencies are modulated onto these optical carrier waves using electrooptic modulators (EOM). After passing through the EOMs, the optical carrier waves are combined together through an M-to-1 combiner and amplified using an erbium-doped fiber amplifier (EDFA). A 1-to-N optical power splitter divides the amplified optical signal to N TTD lines. Each TTD line has an equal length and consists of different lengths of PCF and SMF segments. The lengths are chosen in such a way that at a wavelength of λ_0, the nominal delay through each TTD line is the same and the beam is radiated broadside at the antenna array.

For wavelengths greater than or less than λ_0, different time delays are induced in each TTD line, with a constant time delay difference between adjacent channels at each wavelength, and the beam is steered at an angle θ given by [2]

$$\tau = \frac{d.\sin\theta}{c} \tag{1}$$

where τ is the time-delay difference between adjacent delay lines, d is the antenna element spacing, and c is the speed of light in free space.

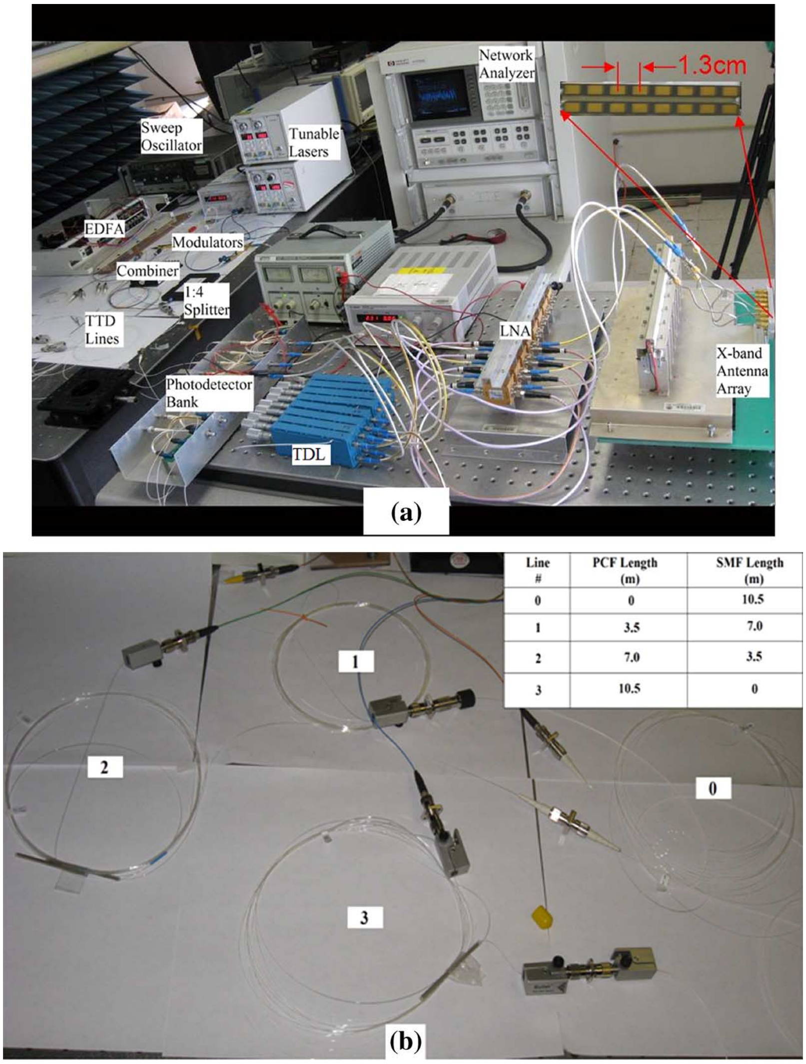
Suppose there are N true time delay lines having PCF segments of lengths $L_1, L_2, L_3 \ldots$ and L_N, respectively, as shown in Fig. 1. The additional time delay generated in a delay line having PCF segment of length L_i is given by

$$T_{\mathrm{delay,i}} = L_i \int_{\lambda_0}^{\lambda} D_{\mathrm{PCF}}(\lambda) d\lambda + (L - L_i) \int_{\lambda_0}^{\lambda} D_{\mathrm{SMF}}(\lambda) d\lambda \quad i = 1, 2, 3 \ldots \mathrm{N}. \tag{2}$$

The first term is contributed by the PCF section and the second term by the conventional single mode fiber. If we consider the difference of delay time τ, between the ith and the $(\mathrm{i}+1)$th delay line, we have

$$\tau = (L_i - L_{i+1}). \int_{\lambda_0}^{\lambda} \left[D_{\mathrm{PCF}}(\lambda) - D_{\mathrm{SMF}}(\lambda)\right].d\lambda \quad i = 1, 2, 3 \ldots \mathrm{N} - 1. \tag{3}$$

Since the dispersion coefficient of the PCF is much larger compared to that of the SMF, for a fixed wavelength λ, the



Line #	PCF Length (m)	SMF Length (m)
0	0	10.5
1	3.5	7.0
2	7.0	3.5
3	10.5	0

Fig. 2. (a) Experimental setup for simultaneous dual RF beam steering, EDFA, TTD, LNA, TDL. (b) Four TTD elements used in the experiment are shown. Each delay line has a length of 10.5 m and consists of a different length of PCF and SMF with a difference of 3.5 m of PCF between adjacent lines. A table containing the composition of the delay lines is also shown.

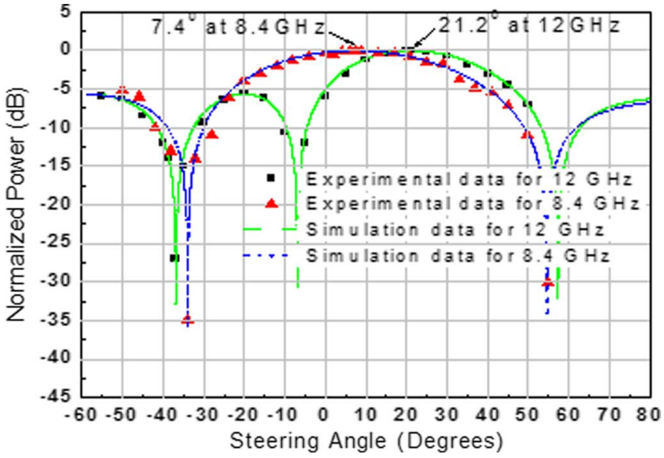


Fig. 3. Simulated and measured far field patterns of two RF signals with frequencies 8.4 and 12 GHz steered simultaneously at angles of 7.4 and 21.2 degrees, respectively.

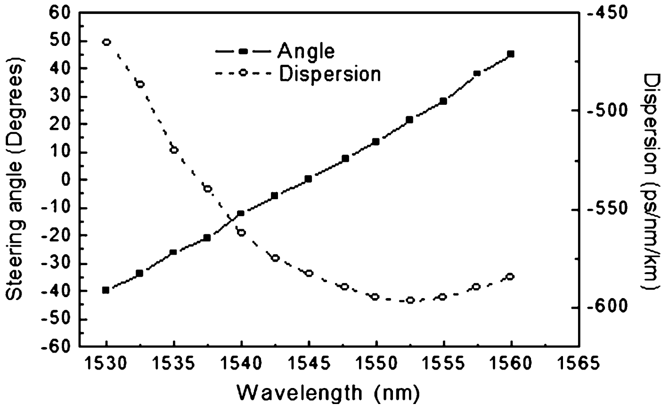


Fig. 4. The solid curve shows the calculated steering angle of RF beam as a function of wavelength. The dashed curve shows the measured dispersion coefficient of the PCF. The spacing between adjacent antenna elements is 1.3 cm as indicated in Fig. 2(a).

difference of time delays between different channels are only determined by the lengths of the PCF segments. Therefore, by making the lengths of the PCF an arithmetic sequence, we can achieve equal time delay differences between adjacent TTD

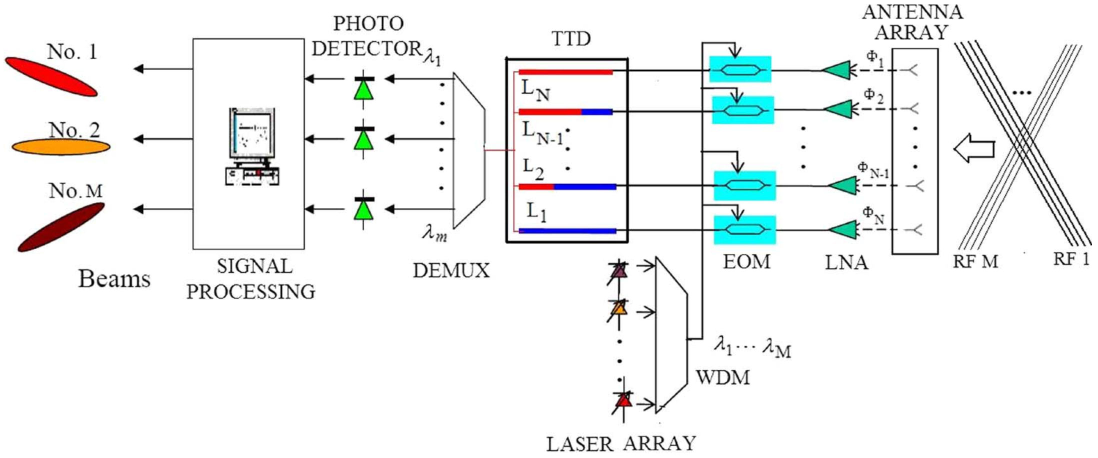


Fig. 5. Structure of the receiving mode with multiple incoming beams, WDM, LNA, EOM, TTD, DEMUX.

lines at any given wavelength, thus, forming a wavelength-tuned TTD line. After the optical signals pass through the TTD lines, they are converted back to electrical signals at the photodetector bank. These electrical signals now provide the phase information for the antenna array. Since for a fixed optical wavelength, the time delay is only related to the lengths of PCF segments, the delay time of the each output electrical signal is controlled continuously by tuning the optical wavelengths. Each optical wavelength creates a time delay set corresponding to a specific steering angle as given by (1). By injecting laser beams with multiple wavelengths simultaneously, one can generate equivalent number of independently steered RF far field patterns at the same time due to the squint-free nature of the TTD lines.

The number of beams that can be steered simultaneously is limited by the availability of hardware. We demonstrate a simultaneous dual-beam steering based on the structure shown in Fig. 1. Two tunable laser sources are used to generate two optical carriers with different wavelengths. The tunable lasers have an output power of 8 dBm. The optical signals are independently modulated with two RF signals with frequencies 8.4 and 12 GHz generated by HP 8620C sweep oscillator and HP 8510C network analyzer respectively, using two high-speed $\mathrm{LiNbO_3}$ modulators. A maximum of 7–dB loss is encountered after passing through the modulator. The optical signals are first combined through an optical combiner and amplified using an EDFA. The EDFA has a maximum output of 13 dBm. The amplified signal is split into four channels using a 1:4 optical power splitter and distributed to the four TTD lines. The power splitting creates fanout loss of 6 dB for each delay line path. The total length L, of each delay line is 10.5 m, and the lengths of PCF segments used in the four delay lines are 0, 3.5, 7, and 10.5 m, respectively. The maximum insertion loss added due to the delay lines is 11 dB. The lengths are chosen such that at a wavelength of 1545 nm, the nominal delay through each TTD line is the same. This implies that at 1545 nm, the RF signal is radiated broadside at the X-band (8–12 GHz) antenna array. The photodetectors convert the optical signals into electrical signals, which are then amplified by the X-band low-noise amplifiers (LNA) that have a gain of 35 dB. After amplification, the electrical signals are fed to a 4-element X-band antenna array, which has an element spacing of 1.3 cm. The actual experimental setup used for the demonstration of dual beam steering is shown in Fig. 2. An expanded view of the antenna array is shown in Fig. 2(a). The TTD lines and their composition are shown in Fig. 2(b).

The far-field radiation pattern of the PAA is measured by fixing the PAA on an accurate positioner and measuring the received power at a fixed standard horn antenna connected to a microwave spectrum analyzer (MSA). The simulated and measured far field patterns are shown in Fig. 3 for the two beam operation at RF frequencies of 8.4 and 12 GHz. We also measured the spurious free dynamic range (SFDR) of the setup by simultaneously transmitting two closely spaced RF frequencies at 8 and 8.1 GHz, respectively, through the network. The SFDR is found to be 104 $\mathrm{dB.Hz}^{2/3}$.

The steering angle of the beam is 7.4 degrees for a wavelength of 1547.72 nm, and is 21.2 degrees for 1552.52 nm. From Fig. 3, it can be seen that the measured patterns agree well with the simulated results, showing the capability of multiple beam transmitting capability of our system. We also calculated the steering angle (θ) of the RF beams at different wavelengths by using (3) and substituting the result in (1). The result is shown in Fig. 4.

These data can further be used to verify the results of the dual beam receiving experiment which is explained in the following sections.

IV. THE STRUCTURE AND WORKING DEMONSTRATION OF MULTIPLE-BEAM RECEIVING

The scheme of the receiving mode for simultaneously receiving multiple number (M) of RF beams is shown in Fig. 5. This configuration can be achieved by slightly modifying the setup of the transmitting mode. In this structure, multiple received RF signals from external sources impinge upon the X-band PAA.

At each antenna element, any arbitrary RF signal arrives with a slightly different time delay due to angle between the incoming RF signal and antenna array, and due to the fact that the antenna elements are spatially separated. Therefore, there is a phase difference between the adjacent element signals for each RF signal,

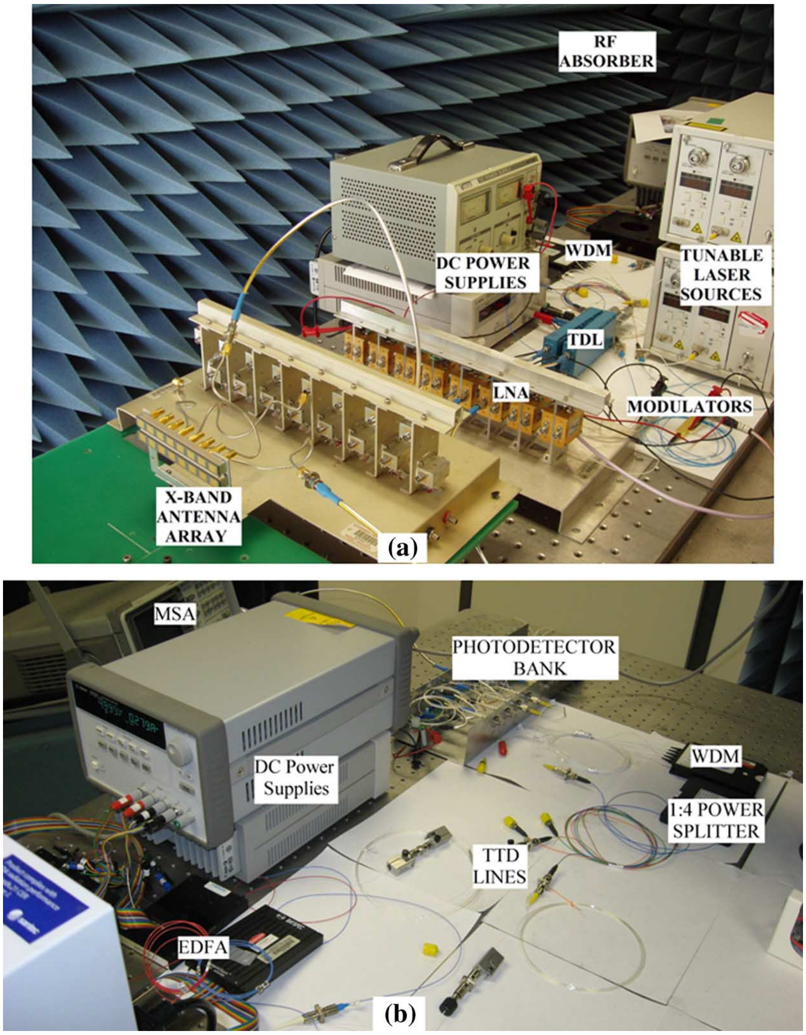


Fig. 6. (a) RF reception and electrooptical conversion setup, LNA, WDM, TDL. (b) TTD lines and signal processing setup, MSA, WDM, TTD, EDFA. The output from the modulators in (a) are connected to the inputs of EDFAs in (b). (The RF sources and the transmitting horn antennas of the setup are not shown in the figure.)

which represents the signature of the angle of incoming RF signals. These signals pass through the LNAs, and each modulates the optical signals coming from the output of a wavelength division multiplexer (WDM) having a multiple number of independent optical wavelengths. The output signal from each modulator passes through a TTD line, and gets delayed time-reversely in reference to the transmission mode, according to the dispersion value and length of the PCF in that line.

The output signals from the TTD lines are then fed to a wavelength division demultiplexer, where different optical wavelengths are separated. At any photodetector, say $\mathrm{P_M}$, the signals corresponding to wavelength λ_{M} coming from all delay lines add up. In order for all the signals to add up constructively for the corresponding direction, the delay lines should alter the phase of signals in such a way that all signals arrive in phase at the corresponding photodetector. Since every wavelength generates one set of time delay values in the delay lines, for a given angle of arrival θ, only one wavelength would be able to compensate phase differences between adjacent elements and deliver maximum power at the photodetector output as also indicated in Fig. 4. The wavelength at which maximum power is detected at the photodetector output corresponds to one angle of arrival. The angle of arrival can, thus, be determined for any RF signal of interest due to the squint-free nature of the TTD lines.

We conduct the experiment in order to receive two RF beams simultaneously. The experimental setup used in the demonstration is shown in Fig. 6. In order to show consistency with the transmitting mode experiment results, we placed the 8.4 and 12 GHz signal sources at −7.4 and −21.2 degrees, respectively.

We use two adjacent antenna elements, two modulators and two adjacent delay lines in the setup. The external RF signals impinge upon the antenna array and the signals received are amplified using LNAs. The amplified signals modulate the output signal of a WDM, comprising of two optical wavelengths coming from the two laser sources. The modulated optical signals are amplified using EDFA and fed to two adjacent delay lines. The wavelengths are demultiplexed at the output of the delay lines and fed to a photodetector bank. The photodetectors converts the optical signals into electrical signals. A microwave spectrum analyzer (MSA) is used to monitor the detected RF output power from the photodetectors. The wavelengths on the tunable lasers are tuned from about 1530 to 1560 nm, and the outputs from the photodetectors are measured for two different

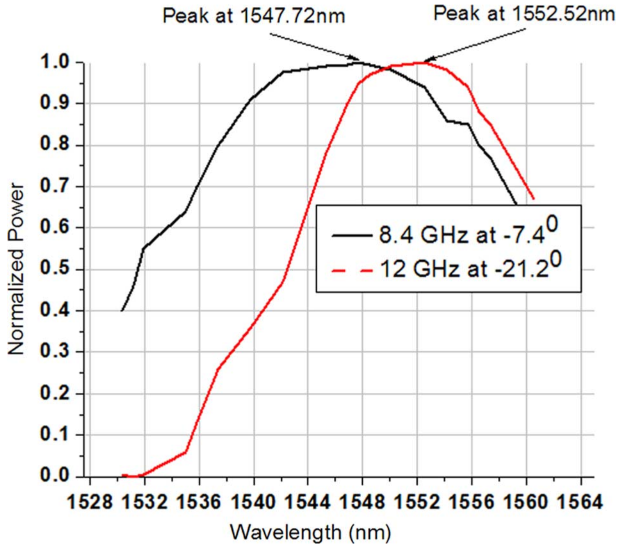


Fig. 7. Signal power measured at the photodetector versus receiving angle. The signal power peaks appear at 1547.72 and 1552.52 nm, respectively, for 8.4 and 12 GHz, respectively.

RF frequencies and the measured data is shown in Fig. 7 for two frequencies of 8.4 and 12 GHz.

It can be seen from the figure that at wavelengths of 1547.72 and 1552.52 nm, there is a peak in the detected output power at for 8.4 and 12 GHz, respectively.

These wavelengths correspond to the complementary angles of 7.4 and 21.2 degrees, respectively, in the transmitting mode experiment, which are also shown as two data points on Fig. 4. This not only shows the multiple beam receiving capability of our system, but it also shows that the results obtained are consistent with the transmitting mode experiment. We are limited by the available hardware to conduct multibeam reception.

In principle, the total number of RF beams that can be simultaneously detected is limited by the bandwidth $(\Delta\lambda)$ of the WDM. As a result, hundreds of RF beams are detectable simultaneously.

V. CONCLUSION

We present an optical beamformer in the transmitting and receiving mode, employing highly dispersive PCF as TTD elements. Dual-beam operation in the transmitting and receiving modes are demonstrated for RF frequencies of 8.4 and 12 GHz. The results of the receiving mode are in accordance with the results obtained in the transmitting mode, thus, showing the high bandwidth capability of the system. Utilization of short lengths of highly dispersive PCF in the TTD lines makes the overall system compact and less complex. Such a compact, lightweight system, with the capability of multiple beam transmission and reception, is highly attractive for military and commercial applications.

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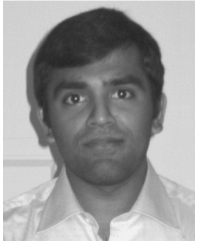

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