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

Harish Subbaraman, Maggie Yihong Chen, Member, IEEE, and Ray T. Chen, Fellow, IEEE

Abstract—We report multiple beam transmission and reception of an X-band phased antenna array utilizing highly dispersive photonic crystal fiber, which has a dispersion value of -600 ps/nm/km at 1550 nm, as true-time-delay elements. In the transmission mode, two RF signals with frequencies 8.4 GHz and 12 GHz are simultaneously steered at angles 7.4 degrees and 21.2 degrees respectively. In the receiving mode experiment, two RF signals with frequencies 8.4 GHz and 12 GHz impinging upon an X-band antenna array from angles -7.4 degrees 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, true-time delay.

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 techniques (TTD).

Furthermore, systems with TTD have the intrinsic capability of multi-beam 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 acousto-optic (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 @1550nm), 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 photonic crystal fibers as delay lines for both transmitting and receiving functions. In section 2, the properties of the highly dispersive photonic crystal fibers are explained. The structural design and working of the beamformer in the transmitting mode is explained in section 3. Section 4 describes the structural design and working of the beamformer in the receiving mode. In each of the sections 3 and 4, 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 Photonic Crystal Fiber

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 direction 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 [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 1550nm. The dispersion value of the PCF is 33 times larger compared to that of a conventional SMF which is $\approx$18 ps/nm/km at 1550nm. 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 $\lambda_1$ to $\lambda_M$. RF signals with different frequencies are modulated onto these optical carrier waves using electro-optic 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 $\lambda_0$, 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 $\lambda_0$, 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 ‘$\theta$’ given by [2]:

$$\tau = \frac{d \cdot \sin \theta}{c} \quad (1)$$

Where $\tau$ 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 $L_1$, $L_2$, $L_3$...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:

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

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 $\tau$ between the $i^{th}$ and the $(i+1)^{th}$ delay line, we have:

$$\tau = (L_i - L_{i+1}) \int_{\lambda_0}^{\lambda} |D_{PCF} (\lambda) - D_{SMF} (\lambda)| d\lambda \quad i = 1, 2, 3...N-1 \quad (3)$$

Since the dispersion coefficient of the PCF is much larger compared to that of the SMF, for a fixed wavelength $\lambda$, the 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 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 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 eqn (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 8dBm. The optical signals are independently modulated with two RF signals with frequencies 8.4GHz and 12GHz generated by HP 8620C sweep oscillator and HP 8510C network analyzer respectively, using two high speed LiNbO₃ modulators. A maximum of 7dB 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 13dBm. The amplified signal is split into 4 channels using a 1:4 optical power splitter and distributed to the four TTD lines. The power splitting creates fanout loss of 6dB for each delay line path. The total length L, of each delay line is 10.5 meters, and the lengths of PCF segments used in the 4 delay lines are 0m, 3.5m, 7m, and 10.5m respectively. The maximum insertion loss added due to the delay lines is 11dB. The lengths are chosen such that at a wavelength of 1545nm, the nominal delay through each TTD line is the same. This implies that at 1545nm, the RF signal is radiated broadside at the X-band (8-12GHz) 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 35dB. After amplification, the electrical signals are fed to a 4-element X-band antenna array, which has an element spacing of 1.3cm. 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 true-time-delay lines and their composition are shown in Fig. 2(b).

The far field radiation pattern of the phased antenna array (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 8.4GHz and 12GHz. We also measured the Spurious Free Dynamic Range (SFDR) of the setup by simultaneously transmitting two closely spaced RF frequencies at 8GHz and 8.1GHz respectively through the network. The SFDR is found to be 104dB.Hz⁻¹/². The steering angle of the beam is 7.4 degrees for a wavelength of 1547.72nm, and is 21.2 degree for 1552.52nm. 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 Eq (3) and substituting the result in Eq (1). The result is shown in Fig. 4.
Fig. 3. Simulated and measured far field patterns of two RF signals with frequencies 8.4GHz and 12GHz steered simultaneously at angles of 7.4 and 21.2 degrees respectively.

This 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.

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 PM, the signals corresponding to wavelength \( \lambda_M \) 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 \( \theta \), 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 true-time delay 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 GHz and 12 GHz signal sources at -7.4 degrees 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 1530nm to 1560nm, and the outputs from the photodetectors are measured for two different RF frequencies and the measured data is shown in Fig. 7 for two frequencies of 8.4GHz and 12GHz.

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

These wavelengths correspond to the complementary angles of 7.4 degrees 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 multi-beam 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.

![Fig. 7. Signal power measured at the photodetector vs. receiving angle. The signal power peaks appear at 1547.72nm and 1552.52nm respectively for 8.4GHz and 12GHz respectively.](image)

**V. CONCLUSION**

We present an optical beamformer in the transmitting and receiving mode, employing highly dispersive photonic crystal fibers as true time delay elements. Dual beam operation in the transmitting and receiving modes are demonstrated for RF frequencies of 8.4GHz and 12GHz. 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 photonic crystal fibers in the true time delay lines makes the overall system compact and less complex. Such a compact, light-weight system, with the capability of multiple beam transmission and reception, is highly attractive for military and commercial applications.

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The antenna system used in the demonstrations is provided...
REFERENCES


Harish Subbaraman received the B. E. degree in Electronics and Communication Engineering from Chaitanya Bharathi Institute of Technology, Hyderabad, India, in 2004, and the M. S. E degree in Electrical Engineering from the University of Texas at Austin, in 2006. He is currently working toward a Ph. D degree at the Microelectronics Research Center, The University of Texas at Austin. His current research focuses on optical true-time-delay feed network for phased-array-antenna systems.

Ray Chen is the Cullen Trust Endowed Professor at UT Austin. He received the B. S. degree in physics from the National Tsing Hua University, Hsinchu, Taiwan, R.O.C., in 1980, the M.S. degree in physicsin 1983, and the Ph.D. degree in electrical engineering from the University of California in 1988, respectively. From 1988 to 1992, he was a Research Scientist, a Manager, and the Director of the Department of Electrooptic Engineering, Physical Optics Corporation, Torrance, CA. He joined the University of Texas at Austin (UT Austin) in 1992 as a member of the faculty of the Electrical and Computer Engineering Department, where he started an optical interconnect research program and is currently the Cullen Trust for Higher Education Endowed Professor and the Director of the Nanophotonics and Optical Interconnect Research Laboratory, Microelectronics Research Center. He was the Chief Technical Officer/Founder and Chairman of the Board of Radiant Research from 2000 to 2001, where he raised $18 million A-Round funding to commercialize polymer-based photonic devices. He was also the Founder and Chairman of the Board of Omega Optics, Inc., since its inception in 2001. He has been a Consultant for various federal agencies and private companies and has delivered numerous invited talks to professional societies. He has served as the Editor or as a Coeditor of 20 conference proceedings. His group at UT Austin has reported its research findings in more than 460 published papers, including over 70 invited papers with over 1500 citations according to Google Scholar Search. He is the holder of 17 issued patents. His research interests include nanophotonic passive and active devices for optical interconnect applications, polymer-based guided-wave optical interconnection and packaging, and true-time-delay wideband phased array antenna. Experiences garnered through these programs in polymeric material processing and device integration are pivotal elements for the research work conducted by his group. Dr. Chen is a Fellow of the Optical Society of America (OSA) and the International Society of Optical Engineering (SPIE). He is the recipient of 93 research grants and contracts from such sponsors as the Department of Defense, the National Science Foundation, the Department of Energy, the National Aeronautics and Space Administration, the State of Texas, and private industry. He was the recipient of the 1987 University of California Regent’s Dissertation Fellowship and the 1999 UT Engineering Foundation Faculty Award for his contributions in research, teaching, and services. During undergraduate years with the National Tsing Hua University, he led a university debate team that won the national debate contest national championship in Taiwan in 1979. He was the Chair or a Program Committee
Member for more than 70 domestic and international conferences organized
by the IEEE, SPIE, OSA, and the Photonics Society of Chinese Americans.
Reviewer # 1

Q.1 The authors should add dynamic range and loss information on the set-up.

Ans: The comments have been answered in the manuscript. The loss information and the dynamic range information are also included in the revised manuscript.
Q.1: In figure 4, if the solid line is simulated, why is the line not straight? There appear to be some minor variations, but the method of calculating this line is not described.

Ans: In Figure 4, the simulated solid line is derived using the dispersion curve and equations (3) and (1).

The time delay between adjacent lines is calculated using eq. (3) and the dispersion curve. This result is substituted in Eq. (1) in order to calculate $\theta$. Therefore, the solid line for the calculated steering angle is not a straight line as the time delay depends on the nature of the dispersion curve also.

Q.2: In Figures 3 and 7, (transmit and receive modes) there does not appear to be very great extinction between the two steering angles. Do I understand correctly that in Figure 7, plotting power versus wavelength is equivalent to plotting power versus receive angle? If so, it should be labeled that way. In this case, it appears hard to distinguish the 7.4° signal from the 21.2° signal. The text says that the number of RF beams that can be simultaneously detected is limited by the bandwidth of the WDM. What was the bandwidth of the one used in this experiment? With the gentle curves of Figure 7 it is hard to accept that hundreds of beams could be distinguished as mentioned in the manuscript.
Ans: In Figure 7, the idea is to vary the wavelength and monitor the output power. Since the incoming angle is fixed, we are only trying to verify the incoming angle by means of monitoring the power at different wavelengths. Since each wavelength specifically corresponds to one angle in the transmit mode for our setup, the same wavelength will show a maximum power for the complementary angle in the receive mode.

For the transmitting mode, as was shown in Fig. 3 of the manuscript, we are limited by the number of hardware components we have in order to perform the experiment. If a large number of antenna elements are used, then the radiation pattern main lobe width becomes narrow, and the side lobes diminish. The following figure shows the simulated result for the far field radiation pattern at 7.4 degrees for 8.4GHz using 2, 4, 8, 24, and 100 antenna elements with spacing between elements as 1.3cm. It can be clearly seen that the angle becomes clearly distinguishable as the number of elements is increased, and therefore hundreds of signals can be detected simultaneously. In our demonstration, we used 4 antenna elements to measure the far-field radiation pattern.
Fig 1: Far-Field radiation pattern at 7.4 degrees for 9GHz. As the number of elements is increased, the main lobe becomes narrower, and distinguishable.

For the receiving mode, the signal coming from -7.4 degrees and the signal coming from -21.2 degrees are on two different RF frequencies. Therefore, we first set up the microwave spectrum analyzer (MSA) to receive one frequency and plot the power versus wavelength. Then, the MSA is set up to receive the other frequency and the same procedure is followed. The DWDM used has 200GHz channel spacing. In our demonstration, we chose -7.4 and -21.2 degrees so that the wavelengths correspond to one of the CWDM channels. If a 256-channel Arrayed Waveguide Grating (AWG) with 25GHz channel spacing, spanning from 1525nm to 1580nm is used, then the incoming angle can be determined accurately within 0.06 degree error. Also, if more number of antenna elements are used, then the received power maxima will peak more distinctly at
the wavelength which satisfies the receiving condition compared to other nearby wavelengths.