Highly Dispersive Photonic Crystal Fibers for True-Time-Delay Modules of an X-band Phased Array Antenna

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ABSTRACT

A two-dimensional optically controlled phased array antenna (PAA) system is proposed. The system employs highly dispersive photonic crystal fibers (HDPCFs) to provide the true-time-delays (TTD). Independent azimuth and elevation control is obtained through a mid-stage optical wavelength conversion process. The dispersion of the fabricated is as high as -600 ps/nm·km around 1550 nm which is 33 times of conventional telecom SMF. By employing the PCFs to increase the dispersion, the TTD module size can be proportionally reduced. A 64-element (8×8) PCF-based PAA system is under construction. Simulation results operating at X-band are shown in this paper.

Keywords: Photonic crystal fiber (PCF), phased array antenna (PAA), true time delay (TTD), wavelength tuning

1. INTRODUCTION

Phased array antenna (PAA) is one of the key technologies in modern radar and communication systems. They offer advantages of low visibility, high directivity, quick steering without hardware movement, reduced weight and less power consumption. Each antenna element of a PAA must have the correct phase condition to accomplish the desired beam scanning. However, the conventional electrical phase trimmer technique is an intrinsically narrow-band technique that introduces beam squint. A popular solution is true time delay (TTD) techniques, which are free of beam squint effect in the PAA system. Additionally, optical TTD techniques have the advantages of wide bandwidth, compact size, reduced weights, and low electromagnetic interference compared with electrical TTD techniques [1]-[4]. Many optical TTD techniques have been proposed for obtaining TTD capability [4]. However, most of the techniques require a large number of precisely time-delay matched optical elements such as lasers and optical delay segments. The result is complex system designs that may suffer from large power losses, specialized component needs, instability, or inability to easily scale to real-world two-dimensional (2-D) arrays. Esman et al proposed a fiber-optic TTD using conventional high dispersion fiber, commercial dispersion compensating fiber (D = -100 ps/nm·km), to meet these requirements [2]. However, the dispersion is fairly small, long fibers are needed in the TTD module to get the total amount of dispersion which is needed. If the fiber dispersion absolute value can be designed to be higher, the total fiber length will be decreased significantly. Photonic crystal fibers (PCFs) provide large tuning ability in increasing the dispersion absolute value to meet this requirement [5-7].

It is well known that conventional single-mode fibers (SMFs) based on weakly guiding structures of doped silica can be tailored to increase dispersion by increasing the refractive index difference between core and cladding [5]. Due to the small index variation from doping over the transverse cross section, dispersion of conventional highly dispersive fibers, e.g. dispersion compensating fibers (DCFs), cannot be changed significantly. This shortcoming may be overcome by the design of PCFs, which can be tailored to exhibit both high positive and negative dispersion [5-7]. The novel cladding structure of PCFs consisting of an array of micrometer-sized air holes allows for flexible tailoring of the dispersion curve [5-9]. Considerable work has already been done to obtain a basic understanding of the dispersion properties of both modified total internal reflection (MTIR) guiding and photonic bandgap (PBG) guiding PCFs for both high dispersion and ultra-flatten zero dispersion [5-9].

In this letter, we propose a novel optical TTD module using highly dispersive PCF (HDPCF) and a 2D continuously wavelength tunable phased array antenna (PAA) system based on these novel TTD modules that only require two wavelength tunable lasers for the control of the entire array of antenna elements or subarray. The approach is based on dispersion-enhanced photonic crystal fibers (PCFs) reported herein and other commercially available components and has potentially high reliability and stability as it requires no mechanically moving parts and no optical

Photonic Crystal Materials and Devices II, edited by Ali Adibi, Axel Scherer, Shawn-Yu Lin,
Proc. of SPIE Vol. 5360 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.527992

alignments during operation. This is the first time that it has been proposed to marry PCF with PAA to implement the advantage of PCF into a TTD module to control a PAA system. To our knowledge, this will also be the first system demonstration using PCF. A 2-D antenna array with independent azimuth and elevation control by using mid-stage optical wavelength conversion is proposed.

2. 2-D WAVELENGTH TUNABLE PAA SYSTEM

As shown in Fig. 1, a TTD module is proposed using photonic crystal fiber (PCF) delay lines. Each line has the same nominal group delay but with slightly different net dispersion. This is easily made by connecting varying lengths of HDPCFs and dispersion shifted fibers (DSFs) ($D \approx 0$ ps/nm·km around 1550nm). Thus, the relative delay of the signals among the links may be changed by tuning the optical wavelength. At the central tuning wavelength λ_0, say 1550 nm, all the time delays are matched by trimming the DSF. Thus, at λ_0 the main antenna beam will be directed broadside. At wavelength less (or greater) than λ_0,

$$\Delta t = \int_{\lambda_0}^{\lambda} (D_{HDPCF} - D_{DSF}) \Delta l_{HDPCF} \, d\lambda \tag{1}$$

each of the fiber delay lines adds (or subtracts) a time delay proportional to its dispersion coefficient D and the HDPCF length, resulting in element phasing such that the main antenna beam is steered in dual directions, i.e., azimuth and elevation. Because the relative phasing is formed by true time delay through the dispersion-enhanced PCF array, beam squint is eliminated and all microwave frequencies are directed at the same angle. [2]

The proposed schematic of the 2-D N×N wavelength tunable PAA system setup is shown in Fig. 1. An elevation-control tunable laser is modulated by a polymer-based Mach-Zehnder intensity modulator in which the microwave signal comes from a network analyzer [10]. The optical signals then pass through a 1×N optical power splitter. After the splitter the optical signals are injected into the TTD module described above. After mid-stage wavelength conversion by a semiconductor optical amplifier (SOA), the optical signals are converted to the wavelength of the azimuth-control tunable laser. Wavelength conversion eliminates the optical/electrical/optical conversion loss. [11] Similar to the first stage, after wavelength conversion each optical channel is input to another TTD module after another 1×N optical power splitter. After the appropriated time delay within the delay modules, the N×N optical signals are converted into the corresponding electrical signals by N×N photodectors. The electrical signals are then connected to an N×N phased array antenna head. By tuning the elevation and azimuth wavelengths we can obtain the 2-D continuously-tunable true-time delay. [10]

As seen from the system description, the proposed approach is based on fibers and other commercially available components and has potentially high reliability and stability as it requires no moving parts during operation. The complexity and cost of the whole system could be greatly reduced. By using HDPCFs instead of conventional highly dispersive fibers, the dispersion is dramatically increased so that the total fiber length will be decreased significantly. This makes the optical TTD modules ultra-compact.

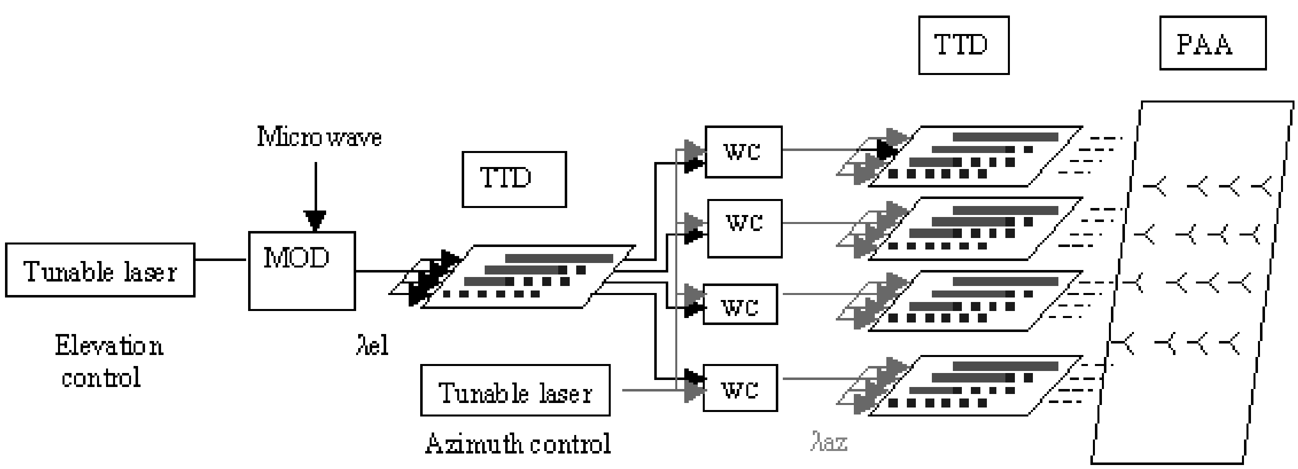

Fig. 1. 2-D highly dispersive photonic crystal fiber enhanced wavelength continuous tunable PAA system structure. (Dashed line: HDPCF; solid line: DSF; MOD: modulator; WC: wavelength conversion)

3. HDPCF THEORY

The transverse section of a modified total internal reflection (MTIR) guiding PCF consists of a regular hexagonal array of microscopic holes in silica glass, polymer or other materials that extend along the entire fiber length. There is a defect (missing a hole) located at the center of the regular hexagonal structure. This structure is defined by the distance between the centers of two consecutive holes, or the pitch, Λ, and the hole diameter d, as shown in Fig. 2. The guiding mechanism is provided by the photonic crystal cladding that localizes light in the silica core, preventing transverse radiation [8]. Standard optical fiber analogies do not help due to the large index contrast and complex structure of PCF, so Maxwell's equations must be solved numerically. The dispersion of PCF can be calculated using the full vectorial plane-wave expansion (PWE) method [8-9]. This method is fast and accurate compared with other methods. The approach involves the solution of the eigenvalue problem corresponding to the vector equation for the magnetic field **H**(**r**) [9]:

$$\nabla\times[\frac{1}{\varepsilon(\mathbf{r})}\nabla\times\mathrm{H}(\mathbf{r})]=\frac{\omega^2}{c^2}\mathrm{H}(\mathbf{r}) \qquad (3)$$

where ε(**r**) is the periodic dielectric constant, ω is angular frequency, and c is velocity of light in a vacuum.

Then, using the Bloch theorem and expanding the periodic component of the solution to the equation in a Fourier series, the result can be written as [9]

$$H(r)=\sum_{G}\sum_{\gamma=1,2}h_{k+G,\gamma}\exp[\mathbf{i}(\mathbf{k}+\mathbf{G})\mathbf{r}] \qquad (4)$$

where **k** is the wave vector, **G** is the reciprocal lattice vector, and γ indicates two field directions perpendicular to the vector **k**+**G**. For a given wave vector **k**, variational methods can be employed to find the solution to this problem. This problem only needs to be solved in the irreducible first Brillouin zone, which reduces the calculation significantly. However, there is another important thing we need to notice. Since there is a defect (missing air hole) in the PCF center and the air hole diameter can be different to tune the dispersion, we need to use a supercell having a size of DxD instead of a natural unit cell to implement the periodic boundary conditions, as shown in Fig. 2 [8]. Here D is the number of the elements in one side of the supercell.

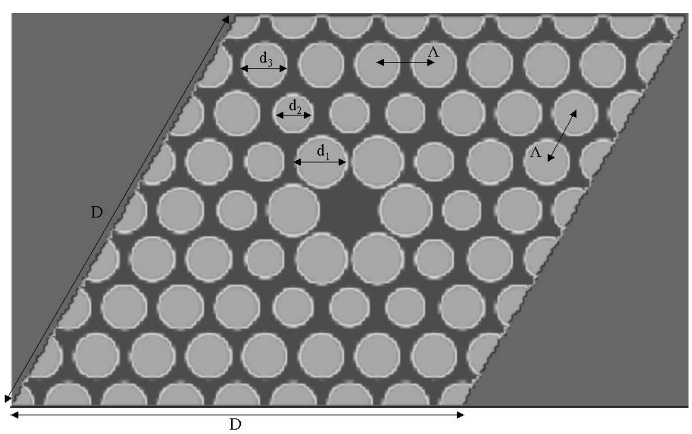

Fig. 2. Transverse section of a model HDPCF. The box with dimensions DxD corresponds to the supercell used to implement boundary conditions.

The group velocity dispersion or simply the dispersion D(λ) of the guided mode of the PCF can be directly calculated from the modal effective index $n_{eff}(\lambda)$ of the fundamental mode over a range of wavelengths [8]

$$\mathrm{D}(\lambda)=-\frac{\lambda}{c}\frac{d^2n_{eff}(\lambda)}{d\lambda^2} \qquad (5)$$

where the effective refractive index of the mode is given by $n_{eff} = \beta[\lambda,n_m(\lambda)]/k_0$, β is the propagation constant, and k_0 is the free-space wave number. In order to design the required dispersion, the total dispersion D(λ) is calculated as a sum of the geometrical waveguide dispersion $D_w(\lambda)$ and the material disperion $D_m(\lambda)$ in the first-order approximation [5]

$$D(\lambda) \approx D_w(\lambda) + \Gamma(\lambda) \cdot D_m(\lambda) \qquad (6)$$

where $\Gamma(\lambda)$ is the waveguide confinement factor in silica. $D_w(\lambda)$ can be obtained without considering the material dispersion and $D_m(\lambda)$ can be obtained directly from the Sellmeier formula [12]. $D_m(\lambda)$ is mostly determined by the wavelength dependence of the fiber material (e.g., the pure silica) and, therefore, cannot be altered very much in the design for the engineering of $D(\lambda)$. On the other hand, $D_w(\lambda)$ of PCF is strongly related to the structure and, therefore, can be changed significantly to achieve the desired characteristics of $D(\lambda)$ [5].

The method described above can be used for both silica core modified total internal reflection (MTIR) guiding PCFs and hollow-core photonic bandgap (PBG) guiding PCFs. For MTIR guiding PCF, it has both waveguide and material dispersion. But for our high dispersion design, the waveguide dispersion is usually at least one order larger than the material dispersion, and we will mainly focused on waveguide dispersion. For hollow-core PBG guiding PCFs, it has no material dispersion, but only waveguide dispersion. The dispersion parameter becomes very large and negative as the guided mode approaches the lower band edge, and very large and positive as it approaches the upper band edge [6]. In this letter, we only study MTIR guiding PCFs.

4. HDPCF EXPERIMENT AND PAA SIMULATION

Various PCFs have been designed and/or purchased from MIT Photonic-Bandgap software package [13], Rsoft™, Crystal Fibre™, and BlazePhotonics™. Fig.3 shows one of the Scanning electron micrograph (SEM) image of the HDPCF fiber fabricated which is suitable for our application. It is fabricated by using the stack-and-draw technique, where silica glass capillaries are stacked in a lattice array, fused together, and then drawn successfully down to PCF. The stack-and-draw process proved highly versatile, allowing complex lattices to be assembled from individual stackable units of the correct size and shape. Solid, empty, or doped glass regions could easily be incorporated. Functional defects could be precisely introduced during the stacking process, allowing fabrication of a wide range of PCFs [6-7]. The chromatic dispersion experimental results of these HDPCFs are shown in Fig 4. The dispersion is –600 ps/nm·km at 1550 nm. The dispersion is increased 33 times compared to telecom SMF-28 fiber (D ≈ 18 ps/nm·km), and 6 times compared to conventional highly dispersive fiber, dispersion compensating fiber (DCFs) (D ≈ –100 ps/nm·km).

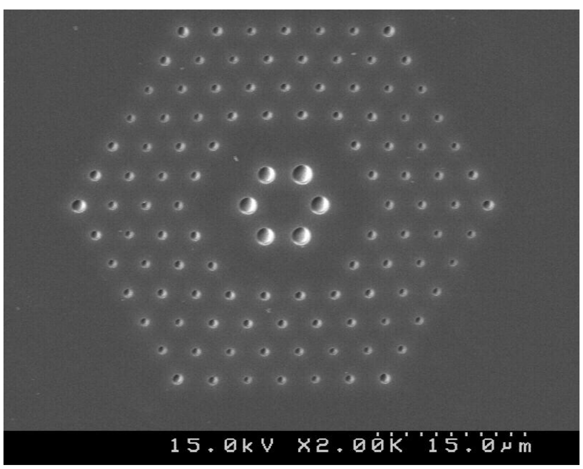

Fig3. Scanning electron micrograph (SEM) image of the fabricated HDPCF.

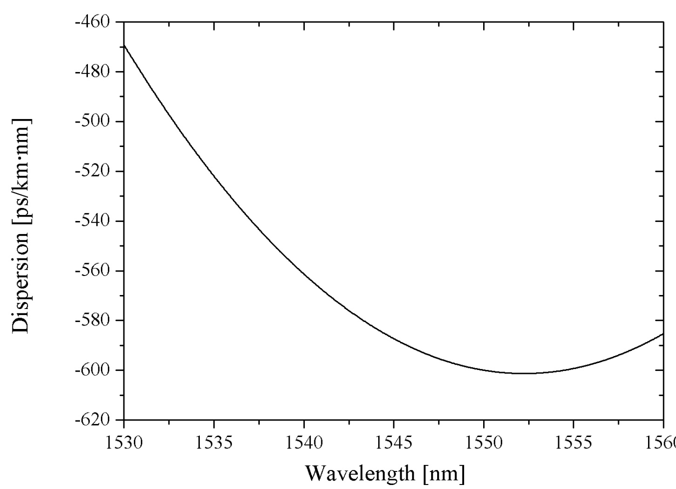

Fig. 4 Chromatic dispersion measurement of the fabricated HDPCF. The measured result is -600 ps/nm·km at 1550 nm.

A 2-D 8×8 continuously tunable X-band phased array antenna (PAA) is proposed using the fabricated HDPCFs we mentioned above. As shown in Fig. 1, supposing wavelength tuning range $\Delta\lambda$ of the tunable laser is 50 nm (1520 nm – 1570 nm) and 1545 nm is set as the central tuning wavelength, the HDPCFs length difference among adjacent lines ΔL = 2m is corresponding to delay interval Δt = 60 ps (-30 ps – 30 ps), which can cover 90^o PAA tuning range (-45^o – 45^o). This is indicated in Fig. 5, which can be applied to both azimuth and elevation directions since they can tuned independently. When we continuously tune the wavelength, the antenna steering angle can be tuned continuously and simultaneously. Thus to build a 2-D 8×8 X-band PAA with 90^o tuning range, the PAA system only needs 9 identical modules, which are composed of 8 fourteen-meter-long lines in each module. Far field patterns of the proposed 2-D 8×8 X-band PAA are simulated to verify the instant broad RF band. Far-field patterns at 30° of the azimuth scanning angle and –20° of the elevation scanning angle corresponding to 8, 10 and 12GHz are shown in Fig 6. From the figure, it can be seen that there is no beam squint as the RF frequency changes because of the nature of true time delay (TTD).

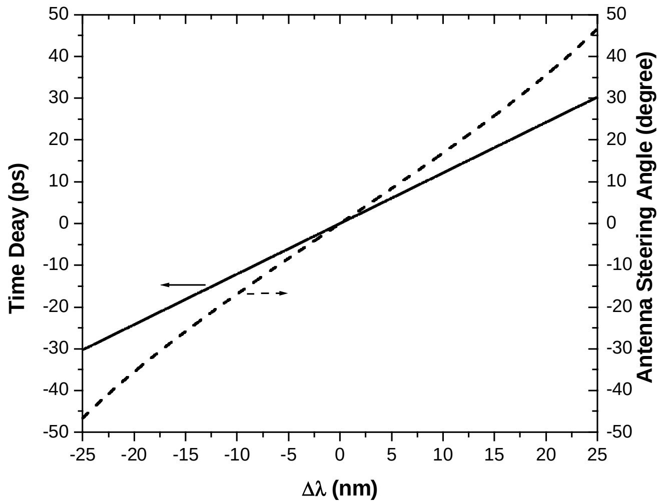

Fig. 5. The time delay among adjacent fiber lines and steering angle of the PAA versus wavelength deviation.

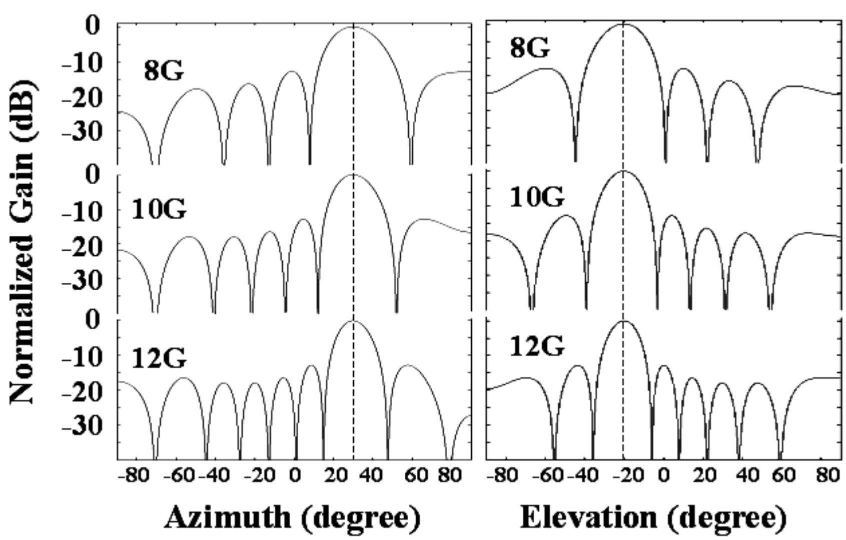

Fig. 6. Comparison of far-field patterns simulation of the PAA at scanning angles with azimuth angle 30° ($\Delta\lambda_{AZ}$ = 17.2 nm, Δt = 20.8 ps) and elevation angle –20° ($\Delta\lambda_{EL}$ = -11.8 nm, Δt = -14.3 ps) at three different frequencies: 8, 10, and 12 GHz.

5. CONCLUSION AND FUTURE RESEARCH PLAN

A two-dimensional optically controlled phased array antenna system employing novel highly dispersive photonic crystal fibers (HDPCFs) enhanced wavelength-continuously tunable true time delay (TTD) devices is proposed. A 2-D antenna array with independent control of azimuth and elevation by using mid-stage optical wavelength conversion is proposed. By increasing the dispersion absolute value of PCF the PAA system size can be greatly reduced. The TTD module using novel PCF and the PAA system demo proposed in this letter is now underway and will be published in the near future.

ACKNOWLEDGMENT

The authors would like to thank Dr. Juerglu Pohlmann of MDA and Dr. Charles Lee of AFOSR for their support and encouragement.

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