Wideband true-time-delay beam former that employs a tunable chirped fiber grating prism

Yunqi Liu, Jianping Yao, and Jianliang Yang

A fiber grating prism that consists of four tunable chirped-grating delay lines for wideband true-time-delay beam forming is proposed and demonstrated. The chirped gratings are produced by use of the grating bending technique in which a uniform grating is surface mounted on a simply supported beam. We obtained chirped gratings with different chirp rates by bending the uniform gratings with different beam deflections. Four linear chirped fiber gratings with identical spectral width but linearly increased grating length are fabricated. The spectra and time-delay responses of the tunable chirped gratings are measured. A chirped-grating prism for wideband true-time-delay beam forming by use of four chirped gratings is constructed and tested experimentally. We obtained different time delays by tuning the wavelength of the optical carrier. The proposed true-time-delay beam former with a four-element phased-array steerer is suitable for continuous beam forming at microwave frequencies up to 20 GHz.

OCIS codes: 060.0060, 060.2330, 060.2340, 060.2430, 230.1480.

1. Introduction

Photonic true-time-delay (TTD) beam forming has been considered a good alternative for wideband phased-array antenna (PAA) systems thanks to its many advantages, such as immunity to electromagnetic interference, low loss, small size, lightweight, and the possibility of controlling several arrays by use of wavelength division multiplexing.[1–9] A promising way to achieve TTD beam forming is to use a fiber grating prism (FGP), which can be built by use of arrays of discrete fiber Bragg gratings (FBGs) or chirped gratings. For discrete FBG-based FGPs,[1–4] the prism is constructed by use of a number of discrete FBGs with different center wavelengths written at different physical locations of the fiber delay lines. The spacing between any adjacent gratings determines the time delay, which in turn determines the beam-pointing direction of the array antenna. The discrete FGB-based approach assures broadband TTD operation but allows only discrete beam-pointing angles. It can produce a minimum time delay of approximately 10 ps and is suitable for beam forming at microwave frequencies of less than 3 GHz.[4] For a chirped-grating-based FGP that uses linear chirped fiber gratings,[3–8] the TTD unit allows continuous beam steering and produces smaller time delays. In most approaches in which a single chirped grating is used,[6,7] multiple tunable laser sources are required. Different time delays are produced by tuning the wavelength spacing of optical carriers that are reflected at different locations of the chirped grating. The use of just one fiber-chirped grating for the whole TTD system avoids the time-delay inaccuracies induced by the position mismatches of many gratings. For an N-channel TTD unit, N tunable laser sources (TLSs) with equally increased or decreased wavelength spacing controlled by a programmable multiwavelength controller should be incorporated into the system, which causes the whole system to be bulky and expensive. In the discrete FGP, to increase the operating frequency, one can replace the first delay line by a chirped-grating delay line,[9] leading to a discrete-chirped FGP. We recently reported that the discretely chirped FGP allows for discrete beam forming at higher microwave frequencies whereas the complex TTD system remains the same.[9]

To increase the operating frequency, we propose and demonstrate a four-channel chirped-grating-

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Received 9 August 2002; revised manuscript received 10 January 2003.
0003-6935/03/132273-05$15.00/0

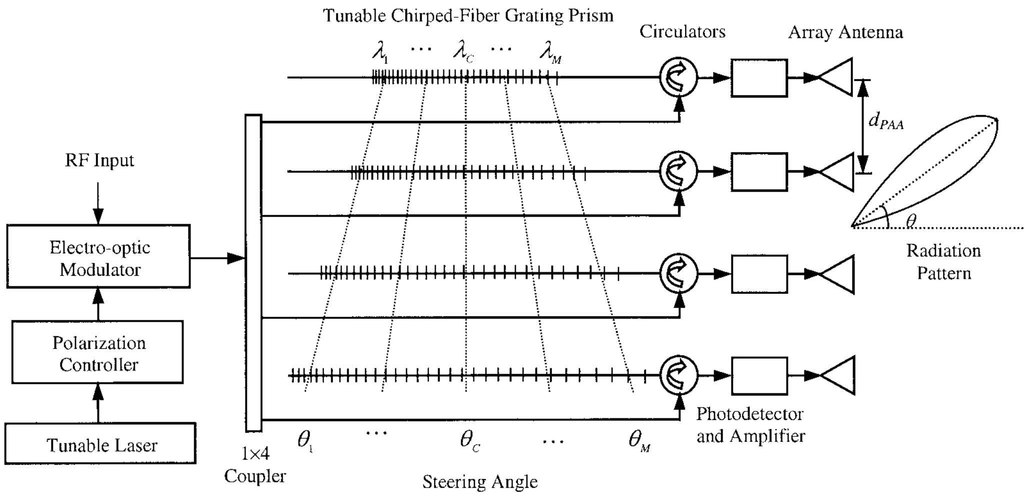

Fig. 1. Experimental setup of the tunable chirped fiber grating prism beam former for a four-element wideband PAA system.

based FGP. The proposed FGP, which consists of four linear chirped-grating-based delay lines, can function at higher microwave frequencies with continuous beam steering. The chirped gratings used in the system were produced by use of the grating bending technique. The chirp rate of each chirped grating was tuned by bending a uniformed FBG surface mounted on a simply supported beam. Four chirped gratings with identical spectral width and linearly increased grating length were produced and were used to construct the chirped-grating prism. We show that the proposed TTD unit with a four-element phased-array steerer is suitable for beam forming at frequencies up to 20 GHz.

2. Principles and Theoretical Analysis

Figure 1 shows the experimental setup of the tunable chirped FGP beam former for a four-element wideband PAA system. The tunable laser source was externally modulated with an electro-optic modulator (EOM). A polarization controller was incorporated between the tunable laser source and the EOM to control the polarization state. The modulated light feeds a group of N single-mode fibers through an equal-path 1:N power divider ($N = 4$). Each fiber delay line includes a linear chirped fiber grating. The different peak-reflection wavelengths of the chirped gratings were controlled to within the tunable range of the tunable laser source. Four optical circulators were used to direct the modulated light to the FGP. The reflected light was time delayed in accordance with the particular grating address. Each wavelength was associated with a different round-trip time delay. For the proposed system, the time delays associated with wavelength λ_C are identical in all four delay lines of the prism, where λ_C is the reflection wavelength that corresponds to the midpoints of the chirped gratings. The N photodetectors recover the individually time-delayed microwave signals that feed the N antenna–radiator elements. The time delay of the microwave signal depends on the locations from which the light is reflected at the gratings, and we can control it by tuning the wavelength of the optical carrier. So we can control the scanning angle of the radiation pattern by tuning the wavelength of the TLS. To ensure an acceptable signal-to-noise ratio at the output of the photodetectors, an erbium-doped fiber amplifier was incorporated into the system in front of the 1×4 coupler to compensate for insertion loss.

The steering angle resolution of the TTD unit can be expressed as[2]

$$\theta_{\min} = \arcsin(4nf_m d_{\min}/c), \tag{1}$$

where $n = 1.5$ is the effective refractive index of the fiber core, $d_{\min}$ is the minimum grating spacing, f_m is the maximum microwave frequency, and c is the free-space speed of light. The beam-pointing angle of the system that corresponds to the mainlobe of array antenna θ_0 can be expressed as

$$\sin \theta_0 = \frac{c\Delta t_d}{d_{\mathrm{PAA}}}, \tag{2}$$

where d_{PAA} is the element spacing of the antenna array, and Δt_d is the time-delay difference between adjacent channels. For the proposed system, the radiation angle of the PAA can be expressed as

$$\sin \theta_0 = \frac{c\Delta\lambda}{d_{\mathrm{PAA}}} k_1 = \frac{2n\Delta d}{d_{\mathrm{PAA}}}, \tag{3}$$

where k_1 is the chirp rate of the first chirped fiber grating, $\Delta\lambda$ is the wavelength tuning step of the tunable laser source, and Δd is the grating location difference between adjacent delay lines with respect to the wavelengths from λ_C to $\lambda_C + \Delta\lambda$. Figure 2 shows the configuration of the relative grating location difference that determines the radiation angle of the PAA system. The midpoints of the four chirped gratings have the same wavelength λ_C and the identical time delay. Then the grating location difference at this point is equal to 0, which corresponds to 0° radiation angle. We determined the beam-

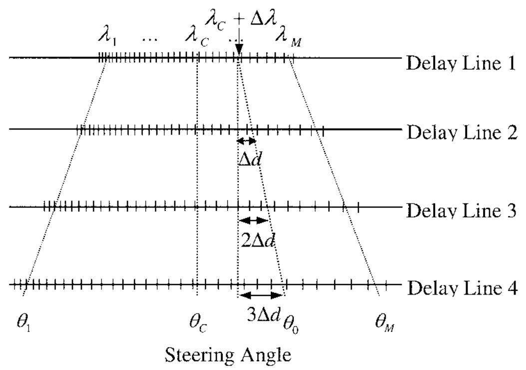

Fig. 2. Configuration of the relative grating location difference that determines the radiation angle of the PAA system.

pointing direction by the grating location difference that can be controlled by changing the wavelength tuning step and that is independent of the microwave frequency. Therefore, the FGP is a TTD beam former and is suitable for wideband applications. From Eq. (3), the radiation angle can be expressed as

$$\sin \theta_0 = k\Delta\lambda = k(\lambda_L - \lambda_C), \tag{4}$$

where λ_L is the output wavelength of the TLS, $k = ck_1/d_{\mathrm{PAA}}$ is a constant determined by the chirp rate of the first chirped grating and the PAA element spacing.

The far-field pattern of the N-element phase array with element spacing of d_{PAA} is given by[9]

$$AF(\theta) = |f(\psi)| = \left|\frac{\sin(N\psi/2)}{N\sin(\psi/2)}\right|, \tag{5}$$

$$\psi(\theta) = -\beta d_{\mathrm{PAA}} \sin\theta + \alpha, \tag{6}$$

where $\alpha = \beta n 2\Delta d$, $\beta = 2\pi/\lambda_m$, λ_m is the wavelength of the microwave signal, and θ is the radiation angle.

3. Experimental Results and Discussions

Figure 3 shows the experimental setup for the time-delay measurements. The light of the TLS is sent to the EOM through the polarization controller. A 10-GHz microwave signal from the signal generator is applied to the modulator. The modulated light is reflected by the chirped fiber grating at the different locations of the delay line. The index-matching gel is used to reduce the Fresnel reflection at the fiber end. The reflected light is split into two beams.

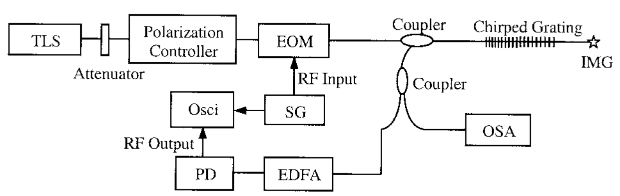

Fig. 3. Experimental setup for the time-delay measurements: TLS, tunable laser source; Osci, oscilloscope; SG, signal generator; OSA, optical spectrum analyzer; PD, photodetector; IMG, index-matching gel.

One is sent to the optical spectrum analyzer (OSA). The other is amplified by the erbium-doped fiber amplifier and then converted to an electrical signal by a high-speed photodetector. The detected signal is sent to the oscilloscope (Agilent DCA 86100A). The microwave signal generated by the signal generator is also sent to the oscilloscope to compare the time delay with the detected time-delayed signal. The tunable laser source selects a desired time delay by selection of the corresponding reflection point at the chirped fiber grating by tuning its output wavelength.

One can tune the chirp rates of the four fiber gratings by bending the uniform FBGs surface mounted on one side of a simply supported beam.[10] The simply supported beam has a length of 100 mm and a thickness of 4.5 mm, whose midpoint is deflected by use of a high-precision micrometer. With this technique, four chirped fiber gratings with identical spectral widths but linearly increased grating length are produced and tested. The grating lengths are 1.5, 3, 4.5, and 6 mm. The spectral width of the tunable chirped gratings is approximately 11 nm. The center wavelength of the chirped gratings is approximately $\lambda_C = 1553.0$ nm. We used the OSA with a high-resolution tunable laser source to measure the spectrum of the fiber gratings. The output power of the TLS was kept constant at the wavelength range from 1520 to 1620 nm. The ripples of the broadband light source were then excluded from the measurements of the grating spectrum. The spectrum of the fiber grating can be measured more accurately than the method by simple use of an OSA with a broadband source because of the high wavelength resolution of the TLS. The time-delay responses of the four chirped fiber gratings were measured experimentally at 10 GHz. The time delay associated with wavelength λ_C was selected as the reference for time-delay measurements.

Figure 4 shows the reflection spectra and time-delay responses of the four chirped fiber gratings. Note that the time-delay response is not linear around the longest and shortest wavelengths. So we used only the central sections of the gratings that correspond to a range of 1548.5–1557.5 nm of their spectra for the experiment. The bending of the gratings leads to grating ripples in the reflection spectra, which induces the signal fluctuation at the antenna array. The largest ripples arise at the two sides of the reflection spectra that correspond to the shortest and longest wavelengths. These large ripples do not affect the signal amplitude of the TTD unit because only the central sections of the gratings are used for the experiments. For the TTD unit, the small-signal fluctuations found at the central grating sections can be compensated in the electronic domain.[2] Because the beam-pointing angle is determined only by the time delays of the N-channel time-delayed signals, the ripples of the grating reflection do not affect the antenna beam-pointing angle. The only effect of the grating reflection fluctuation that is due to bending on the TTD unit is its effect on the channel coeffi-

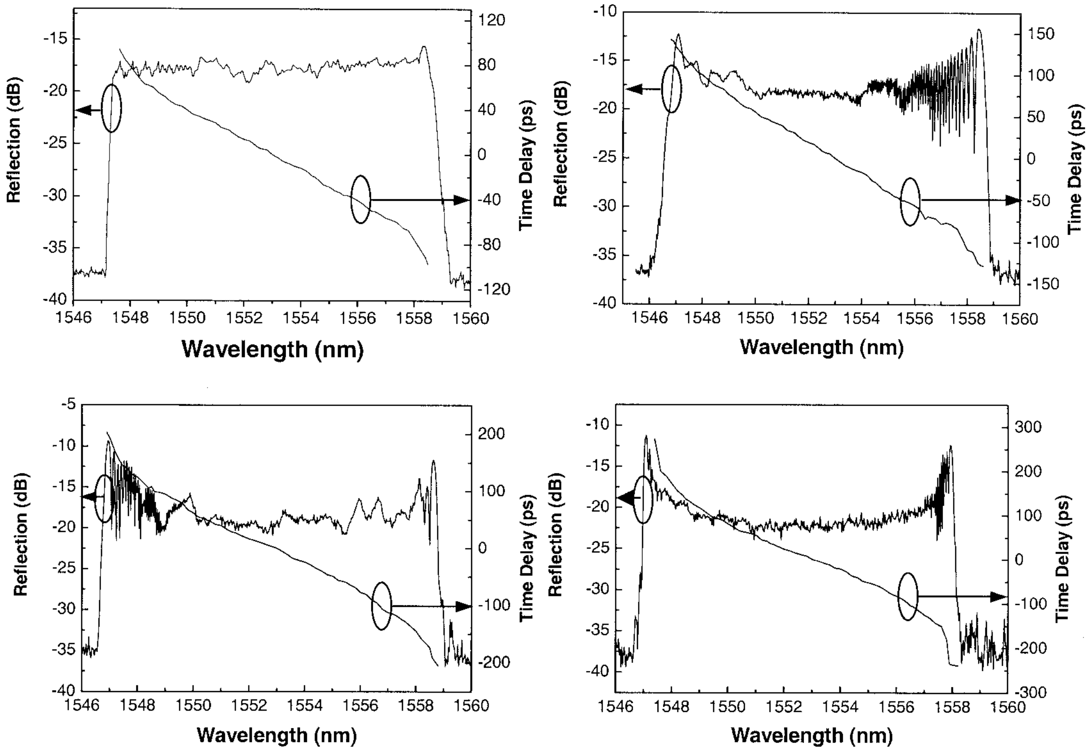

Fig. 4. Reflection spectra and time-delay responses of the four chirped fiber gratings.

cients of the four-channel beam-forming system, which further affects the mainlobe width and the mainlobe-to-sidelobe ratio. By using the electronic equalization technique,[2,8] we compensated for the reflection fluctuation that is due to grating bending in the experiments. The measured time delays of the four tunable chirped-grating delay lines at 10-GHz microwave frequency are plotted as a function of the optical wavelength in Fig. 5. The measured dispersion rates of the four delay lines are 13.7, 18.8, 24.1, and 29.4 ps/nm. The R-squared values of the data fitting are higher than 0.99, which means good linearity of the time-delay characteristics. The small deviation of the time-delay measurements away from linearity could be attributed to the position uncertainties of the gratings and the time-delay measurement errors. For the tunable chirped gratings, the two gratings with a shorter grating length have a better linear time-delay response than the other two with a longer grating length. The strain induced by beam tuning in the fiber has poor linearity for the longer gratings, which leads to a poorer linearity of the time-delay response. In practical systems, a longer supported beam can be adopted to eliminate or to reduce the nonlinearity of the time-delay response.

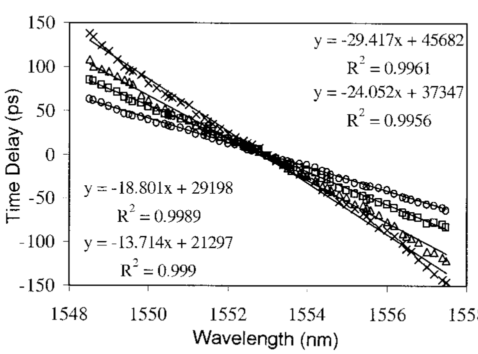

Fig. 5. Experimental time-delay measurements of tunable fiber grating delay lines at the microwave frequency of 10 GHz: ○, grating 1; □, grating 2; △, grating 3; ×, grating 4.

Based on the four linear chirped fiber gratings, we constructed a four-element TTD unit. For the TTD unit shown in Fig. 1, the available maximum microwave frequency was determined by the minimum distance allowed in the grating between adjacent wavelengths.[9] As described in Ref. 11, the rf power degradation limits the available maximum microwave frequency for the conventional intensity modulation–direct detection scheme. The maximum microwave frequency that corresponds to the first −3-dB signal bandwidth of the rf power degradation can be expressed as[11]

$$f_{\deg} = (c/4\lambda_C{}^2\delta)^{1/2}, \tag{7}$$

where δ is the chirp rate of the chirped fiber grating. For our system, $\lambda_C = 1553.0$ nm, $\delta = 29.4$ ps/nm, and the maximum microwave frequency is calculated to be approximately 32.5 GHz. When the microwave frequency is close to this frequency, the dominant rf power degradation arises because of the chromatic dispersion of the chirped grating. Then the single-sideband modulation technique should be adopted in place of the current modulation scheme.[7] For TTD

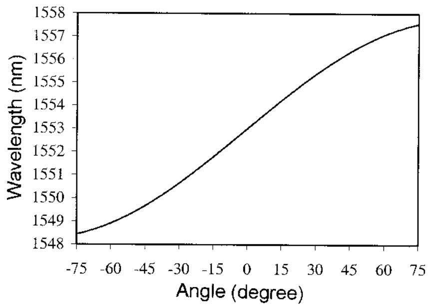

Fig. 6. Relationship between the tunable wavelength of the optical source and the PAA radiation angle.

applications, −3-dB power degradation could be too large. To maintain a good signal level, we consider the first −1-dB signal bandwidth of the rf power degradation to be acceptable, which corresponds to 20 GHz for the proposed system.[11] So the TTD unit with the tunable chirped-grating prism can be used for wideband PAA beam forming at microwave frequencies up to 20 GHz without any dominant rf power degradation. It can also be deduced from Eq. (3) that the steering angle resolution of the TTD unit can be increased if we decrease the wavelength tuning step of the TLS. When continuous wavelength tuning is provided, continuous PAA beam steering is thus realized.

To avoid the existence of more than one mainlobe in the radiation patterns, the array element spacing of the PAA system is set to be half of the wavelength of the microwave frequency.[12] For a 10-GHz microwave signal, the element spacing should be $d_{\mathrm{PAA}} = 15$ mm. Equation (4) can be expressed as

$$\sin \theta_0 = 0.212 \times (\lambda_L - 1553.0). \tag{8}$$

We can control the radiation angle by changing the output wavelength of the TLS. Figure 6 shows the relationship between the tunable wavelength of the optical source and the PAA radiation angle. It can be seen that radiation angle scanning has a higher wavelength sensitivity at the broadside radiation (0° angle) than that near the end-fire array (−90° or 90° angle). The radiation pattern scans at angles from −72.5° to 72.5° when the wavelength of the tunable laser is tuned from 1548.5 to 1557.5 nm.

We note that the beam-pointing accuracy is determined by the time delays of the time-delayed signals, which is determined by the time-delay linearity of the chirped gratings. Figure 5 shows that the time-delay characteristics of the four chirped gratings has high linearity. In the proposed TTD system, the high-precision TLS is used so that highly accurate PAA beam pointing can be obtained. The radiation patterns can be calculated by use of Eqs. (5) and (6) for the four-element PAA system. Note that the mainlobe of the radiation pattern is quite broad since only four array elements are used in the system shown in Fig. 1.[9,12] The proposed four-channel TTD beam-forming unit can be extended to many channels by use of different feed geometry[12] to generate a pencil-shaped beam. As the element number increases, a much-narrower mainlobe would be obtained and the mainlobe-to-sidelobe ratio would be significantly increased.

4. Conclusion

A FGP that consists of four tunable chirped-grating delay lines has been proposed and demonstrated. To the best of our knowledge, this is the first experimental demonstration of an optical TTD beam-forming network by use of tunable chirped gratings that can function at microwave frequencies up to 20 GHz. It should be noted that the chirp tuning setup and the TTD unit were built on a highly stable optical table. For a practical system, proper packaging of the chirped gratings and other optical components were employed to ensure a high degree of system stability.

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