Fiber Bragg-Grating True Time-Delay Systems: Discrete-Grating Array 3-b Delay Lines and Chirped-Grating 6-b Delay Lines

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***Abstract*—We describe wavelength-addressed 3- and 6-b fiber-optic true time-delay (TTD) lines implemented using ultraviolet-inscribed Bragg gratings. The 3-b delay line is fabricated from an array of discrete- and uniform-period Bragg gratings, and a minimum time delay of 9.09 ps is selectable, making it suitable for phased-array antenna (PAA) beamforming control at RF frequencies of up to about 3 GHz with 10° phase resolution. The 6-b delay line is fabricated using a chirped-period Bragg grating, and is suitable for beamforming control at RF frequencies of up to ∼ 48 GHz, with 10° phase resolution.**

***Index Terms*— Fiber Bragg grating, microwave photonics, phased-array antennas.**

I. Introduction

THE USE OF fiber optics for implementing true time-delay (TTD) control of microwave phased-array antenna (PAA) systems has been investigated for many years [1], [2], and several system demonstrations have been reported [3]–[5]. TTD is used in place of simple phase-shifting techniques in wide-bandwidth applications in order to prevent the occurrence of beam squint at the extremes of the frequency scan. While this can be realized by replacing phase-shifting microwave waveguides with switched lengths of electrical waveguide or cable, such components sustain high loss at high RF frequencies and are susceptible to electrical crosstalk and temperature-induced time-delay changes. In contrast, optical TTD control networks are lightweight, compact, immune to electromagnetic interference and crosstalk, and can offer significantly lower transmission loss and higher signal bandwidth capacity. Use of optical-fiber transmission-line beamforming networks for both communications and radar antennas can, therefore, overcome many of the problems associated with electrical TTD control networks, and have the potential to become a low-cost alternative to them.

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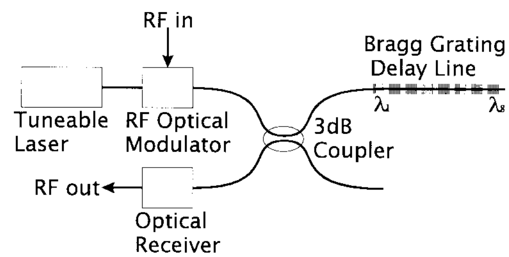

Fig. 1. 3-b discrete fiber Bragg-grating delay line.

To implement an optical RF beamforming network, the RF signal is impressed on an optical carrier as an intensity modulation, and the optical carrier distributed to the antenna elements via optical fibers. While fiber-optic-based TTD systems have been demonstrated using switched lengths of fiber, such systems require bulk optical elements compromising the compact nature of the optical fiber. Alternatively, a dispersive element fiber may be used and the acquired time delay varied by tuning the optical-carrier wavelength. This dispersive element may be high-dispersion optical fiber [5]; however, a simpler and more compact approach to wavelength switching accesses the inherent advantage of wavelength-selected time delays through the use of a series of in-fiber Bragg gratings [6], [7] fabricated along a single length of optical fiber. Each Bragg grating has a different central wavelength and individual gratings are addressed by wavelength tuning the optical carrier, thereby selecting the length of fiber traversed by the optical signal and so choosing the time delay. This is illustrated in Fig. 1. Previous work on fiber Bragg-grating TTD delay lines [8], [9] has been solely concerned with arrays of discrete Bragg gratings, which have been used to create time delays of less than 20 ps in duration [9], suitable for beam-forming control at RF frequencies of up to about 1.5 GHz. In this paper, we present results for a 3-b optical-fiber Bragg-grating TTD delay line capable of producing delays of less than 10 ps, suitable for beamforming at frequencies of up to approximately 3 GHz and the extension of the technique to the first 6-b optical-fiber Bragg-grating TTD delay line, utilizing chirped in-fiber Bragg gratings. The 6-b delay line is capable of producing delays of quasi-continuously variable duration between ∼ 0.6 and 59 ps, making it suitable for beamforming control at RF frequencies of up to ∼ 48 GHz, with 10° phase resolution.

With a fiber Bragg-grating TTD line, the gratings are used in reflection so a 3-dB coupler, introducing > 6-dB loss, is required to route the signal to the photodetector for conversion to an electrical signal. This loss is comparable to that experienced by a typical 4-b nonwavelength-switched TTD device. Use of an optical circulator would further reduce the loss to < 3 dB.

The maximum number of time-delay elements which can be fabricated in each delay line is determined by the tuning range of the optical source $\Delta\Lambda$ and the optical bandwidth of each grating. The optical bandwidth $\Delta\lambda$ of a Bragg grating [10] determines the minimum possible wavelength spacing between adjacent gratings in the delay line and, hence, the maximum number of discrete time-delay elements, $N_{\max}$, which can be addressed by a single optical source as follows:

$$N_{\max} \approx \frac{\Delta\Lambda}{\Delta\lambda}. \quad (1)$$

The minimum achievable time delay, $T_{\min}$, is given by

$$T_{\min} = \frac{2nd_g}{c} \quad (2)$$

where d_g is the center-to-center spacing between gratings, n is the refractive index of the optical fiber, and c is the free-space speed of light.

II. Experimental Results

A fiber Bragg-grating delay line containing eight discrete Bragg gratings was fabricated in boron–germania codoped single-mode fiber which had been presensitized by immersion in hydrogen [11]. Each grating had a length of 2 mm, a full-width at half-maximum (FWHM) bandwidth of $\sim$ 0.5 nm, and a peak reflectivity of $\sim$ 60%. The delay line was fabricated to have a 1-mm center-to-center spacing between the gratings, whose central wavelengths were 1494.10, 1498.75, 1501.05, 1503.75, 1515.05, 1518.05, 1521.85, and 1524.65 nm, respectively. From (2), a 1-mm spacing between adjacent gratings in a delay line corresponds to a minimum time delay of 9.67 ps.

The time-delay measurements were performed either in the 130 MHz–20 GHz range using a GaAs optical modulator and a network analyzer or at 1 GHz using a lithium–niobate modulator and a vector voltmeter. An external-cavity grating-tuned semiconductor laser with a resolution of 1 pm was used as the optical source.

The measured absolute time delay at the peak reflection wavelength of each grating is plotted as a function of wavelength (position along the delay line) in Fig. 2. The time-delay measurement resolution was less than 1.0 ps. The gratings lie on a dispersion of ($-$2.65 $\pm$) 0.15 ps/nm, and the average delay step size is 12.36 ps. The small deviations of the experimentally measured values away from the straight-line fits can be attributed to uncertainties in the precision of the positioning of the Bragg gratings during fabrication and to resonance effects caused by the physical overlapping of the gratings. This fiber Bragg-grating delay line is suitable for beamforming control, with 10° phase resolution at RF frequencies of up to $\sim$ 3 GHz.

The 9.09-ps delay steps represent the practical lower limit on the delay step size which can be produced through the use of delay lines comprising discrete linear Bragg gratings.

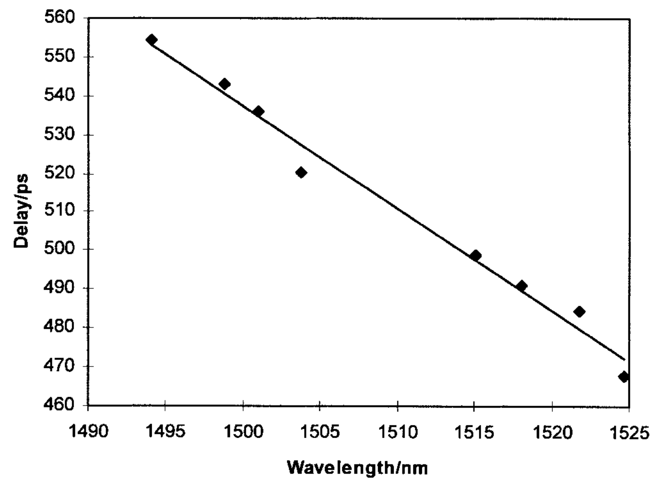

Fig. 2. Time delay as a function of wavelength for a gratings array with 2-mm-long gratings and 1-mm separation.

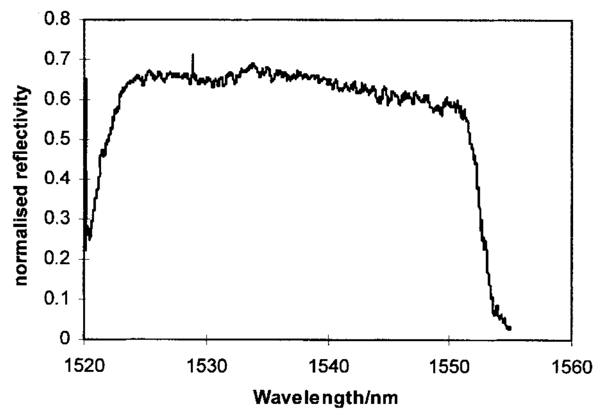

Fig. 3. Reflectivity of the 30-nm chirped Bragg grating for TTD control of PAA's.

In order to produce time-delay steps of significantly smaller duration, and thus increase the RF frequency at which 10° phase-resolution beamforming control can be achieved, a single chirped Bragg grating can be used in place of the array of linear gratings. This enables production of effective continuously variable time delays, rather than discrete delay steps as mentioned above. Tuning the optical source wavelength across the bandwidth of the chirped grating results in the point of reflection within the grating *sliding* along its length. The minimum time delay which can be created using a chirped-grating delay line is thus determined by the optical-carrier-tuning step size and the optical bandwidth of the grating.

Four chirped Bragg gratings with bandwidths of 7, 12, 20, and 30 nm, respectively, were fabricated in hydrogenated boron–germania codoped single-mode optical fiber, each with a length of 4 mm and a reflectivity of $\sim$ 60%. The grating amplitude profile was approximately Gaussian so as to improve the linearity of the group delay characteristic. The minimum achievable time delay for each grating was measured using both the 130-MHz–20-GHz and 1-GHz measurement systems, and the individual spectral profiles recorded. Fig. 3 shows the normalized spectral profile of the 30-nm chirped grating.

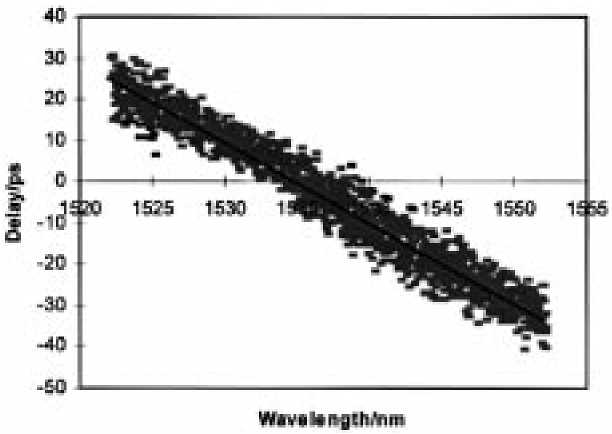

Fig. 4. Time delay as a function of wavelength for 30-nm chirped-grating 1-GHz measurement system.

TABLE I
MEASURED DISPERSION VALUES FOR CHIRPED OR VARYING BANDWIDTHS

Grating Bandwidth (nm)	Dispersion (130MHz-20GHz system) ($ps.nm^{-1}$)		Dispersion (1GHz system) ($ps.nm^{-1}$)	
7	-14.442	± 0.563	-11.841	± 0.196
12	-5.681	± 0.096	-5.231	± 0.048
20	2.479	± 0.040	2.169	± 0.044
30	-1.713	± 0.019	-1.962	± 0.011

Fig. 4, a typical measurement, shows time delay as a function of wavelength for the 30-nm grating measured using the 1-GHz measurement system. Straight-line fits were performed on the experimental data recorded with both the 130-MHz–2-GHz measurement system and the 1-GHz measurement system is shown for each grating and summarized in Table I. We believe that the experimentally significant differences between the two sets of results, which were taken in different conditions, arise due to variation in environmental effects such as temperature and fiber strain.

The above chirped gratings can, therefore, in principle be used to create time delays from as small as 40 fs to as large as 59 ps; the former being that which is available using the smallest wavelength tuning-step size in the 1-GHz measurement system, 0.02-, and the 30-nm grating, and the latter being that produced by tuning the wavelength across an entire grating bandwidth and, hence, utilizing the full 4-mm grating length. In practice, the smallest time-delay step which can be realized is determined by the system characteristics and the optical linewidth broadening effect of modulating the optical carrier. In order to maintain a 10° phase resolution beam-pointing accuracy, the phase error incurred by modulating the optical carrier must be less than 10°. For the 30-nm bandwidth grating, this means that the maximum RF modulation signal frequency which can be applied to the optical carrier is $\sim$ 48 GHz.

In principle, use of 0.23-nm wavelength tuning steps for the 30-nm chirped grating would produce seven bits (128 steps) of $\sim$ 0.3-ps time delay across the grating bandwidth. Similarly, wavelength tuning steps of 0.14, 0.06, and 0.03 nm will produce seven bits of 0.3-ps delay in the 20-, 12-, and 7-nm gratings, respectively. When the RF modulation-based phase error is included, the minimum time-delay step size which can be achieved must be reduced to $\sim$ 0.6 ps in order to comply with the 10° phase resolution requirement, thus the gratings can be used to produce six bits of time delay.

III. CONCLUSION

The use of arrays of discrete linear Bragg gratings as TTD elements has been extended to its practical limit and a TTD element suitable for beamforming control at RF frequencies of up to $\sim$ 3 GHz has been reported. A significant increase in the RF frequency at which fiber Bragg-grating TTD control of PAA's can be controlled has been demonstrated, with the 30-nm bandwidth chirped Bragg grating shown to be suitable for use as a time-delay element for beamforming control at frequencies of up to $\sim$ 48 GHz. The number of delay-step increments available with fiber Bragg-grating optical TTD elements has been greatly increased, with six bits of time delay achievable using the 30-nm bandwidth chirped Bragg-grating TTD element.

In order to increase the RF-signal modulation frequency range which can be used, the chirp rate of the gratings must be decreased, thus reducing the spatial displacement of the reflection points of the optical-carrier modulation sidebands from that of the central optical-carrier wavelength, and thus reducing the time, phase, and error incurred by the signal. We envisage the use of physically longer chirped Bragg gratings to achieve this.

A significant issue for the practical use of these devices is reproducibility and precision. This problem can be overcome by imprinting the gratings using near-field exposure through phase masks. The required delay characteristic can be built into the phase mask using e-beam lithography, and then transferred reproducibly to the fiber Bragg gratings.

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C. Edge, photograph and biography not available at the time of publication.

J. Fells, photograph and biography not available at the time of publication.