Continuous True-Time-Delay Beamforming Employing a Multiwavelength Tunable Fiber Laser Source

Jianping Yao, *Senior Member, IEEE*, Jianliang Yang, and Yunqi Liu

***Abstract*—A true-time-delay system for wideband continuous phased array beamforming employing a novel multiwavelength tunable fiber laser source with equally increased or decreased wavelength spacing is proposed. The wavelength tuning is realized by stretching or compressing the fiber Bragg gratings cascaded in the laser cavity. To ensure a wavelength tuning with equally increased or decreased wavelength spacing, the gratings are mounted onto a plastic plate with angles between adjacent gratings selected such that the forces applied to the gratings has an equal force increment. Time delays with equally increased or decreased time delay difference for the equally spaced wavelengths are obtained when the modulated lightwaves are reflected at different locations of a linearly chirped grating. A four-channel chirped grating based true-time-delay system using the proposed light source has been constructed and experimented. Equally increased or decreased time delays are obtained when the wavelengths are tuned.**

***Index Terms*—Fiber Bragg gratings, fiber optics, optical fiber delay lines, phased array antenna, true-time-delay beamforming.**

I. Introduction

PHOTONIC true-time-delay (TTD) beamforming [1]–[6] has been considered a promising technique for future wideband phased array antenna systems and has been intensively studied recently. An efficient way to achieve TTD beamforming is to use fiber grating delay lines. There are, in general, two types of fiber grating delay lines: the one uses discrete fiber Bragg gratings (FBGs) [1] and the one uses a chirped grating [4]. Discrete FBG TTD system can work at microwave frequencies lower than 3-GHz [4] with discrete beam steering. To achieve continuous beam steering at higher microwave frequencies, a chirped grating based system should be used [5], [6]. The difficulty employing chirped grating based system is that one needs to provide a multiwavelength source in which the wavelengths should be tuned simultaneously with equally increased or decreased wavelength spacing. For a TTD system with N channels, for example, N tunable laser sources with the wavelengths controlled by a programmable wavelength controller should be used. This makes the whole TTD system bulky and expensive. To solve this problem, in this letter, we propose to use a new multiwavelength tunable laser source that can simultaneously generate multiwavelength lasing with equally increased or decreased wavelength spacing. The wavelength tuning is realized by stretching or compressing the FBGs cascaded in the laser cavity. To ensure a wavelength tuning with equally increased or decreased wavelength spacing, the gratings are mounted onto a plastic plate with angles between adjacent gratings selected such that the forces applied to the gratings have an equal force increment. Time delays with equally increased or decreased time delay difference for the equally spaced wavelengths are obtained when the modulated lightwaves are reflected at different locations of the linearly chirped grating. A four-channel chirped-grating-based TTD system has been constructed and experimented. Equally increased or decreased time delays have been obtained when the wavelengths are tuned.

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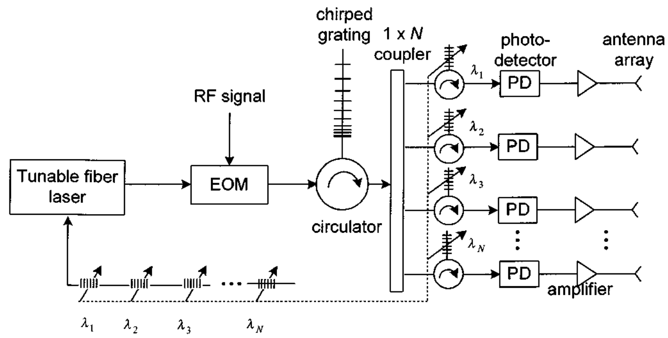

Fig. 1. Chirped grating based true-time-delay beamforming system.

II. System Configuration

An N-channel TTD beamforming system using the proposed tunable laser source is shown in Fig. 1. The use of a chirped grating rather than an array of discrete FBGs in the TTD system is to generate continuous and smaller time delays. If the multiwavelength tunable source with equal-wavelength spacing is applied to the chirped grating, continuous time delays with equal time-delay difference are generated.

The multiwavelength source is generated by a fiber ring laser which is constructed with a length of erbium-doped fiber pumped by a laser diode at 980 nm [7]. The output of the multiwavelength laser is send to an electrooptic modulator through a polarization controller, to which an RF signal is applied. The modulated light signals are sent through an optical circulator to the linearly chirped grating. Time delays with equally increased or decreased time delay difference for the equally spaced tunable wavelengths are obtained when the

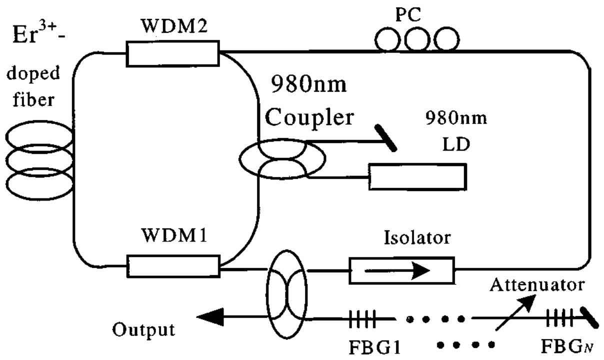

Fig. 2. Multiwavelength fiber laser incorporating cascaded FBGs.

modulated lightwaves are reflected at different locations of the linearly chirped grating. The time-delayed signals are then split into N channels by a $1 \times N$ lightwave splitter and are applied to the photodetectors through the N tunable filters to separate the N wavelengths. The tunable filters should be tuned instep with the FBGs in the fiber ring laser. The detected electrical signals are amplified by preamplifiers and power amplifiers and then sent to the antenna array.

As can be seen from Fig. 1, the critical device in this TTD system is the tunable laser source, which should generate multiwavelength lasing with equally increased or decreased wavelength spacing. In this letter, we propose a novel tunable multiwavelength fiber ring laser that can generate the required tunable multiwavelength output. The wavelengths of the fiber laser are determined by the center wavelengths of the incorporated FBGs. The wavelength tuning is realized by stretching or compressing the gratings mounted onto an organic plate. To make the wavelength spacing increased or decreased equally, the gratings are mounted onto the organic plate with angles between adjacent gratings selected such that the forces applied to the gratings generate equally increased or decreased wavelength spacing. Fig. 2 shows the optical configuration of the multiwavelength fiber ring laser using discrete FBGs, in which N uniform FBGs with different peak wavelengths are cascaded in the cavity to achieve multiple wavelength reflections. Since the Bragg wavelength is related to the period of the FBG, the wavelength tuning can be obtained when a force is applied to the FBGs to change the period of the FBGs. The relationship between the Bragg wavelength λ_B and the period Λ of an FBG is given by $\lambda_B = 2n_{\text{eff}}\Lambda$ and $\Delta\lambda_B = 2n_{\text{eff}}\Delta\Lambda$, where n_{eff} is the effective refractive index of optical fiber, $\Delta\lambda_B$ is the wavelength shift.

The tuning method is schematically illustrated in Fig. 3. The organic plate on which the gratings are glued has large elastic constant. When forces are applied to the gratings via compressing one side of the organic glass, the gratings will experience a tensile or compressive strain depending on the direction of the forces applied, which results in a period change of the FBGs. Since the gratings are mounted on the plastic plate with angles selected such that the forces applied to the gratings are 0, ΔF, $2\Delta F$, $3\Delta F, \ldots$, the resulted wavelength shifts in the fiber gratings will be 0, $\Delta\lambda$, $2\Delta\lambda$, $3\Delta\lambda, \ldots$, as shown in Fig. 4. One may note that the tuning method in this experiment is slow and is dependent on the organic plate. To improve the tuning performance, some fast tuning technique, such as piezoelectric actuator method [8], [9], can be employed to achieve equally spacing tuning. It is reported [9] that the tuning speed of the piezoelectric actuator method can be in the range of tens of nanometers per milliseconds.

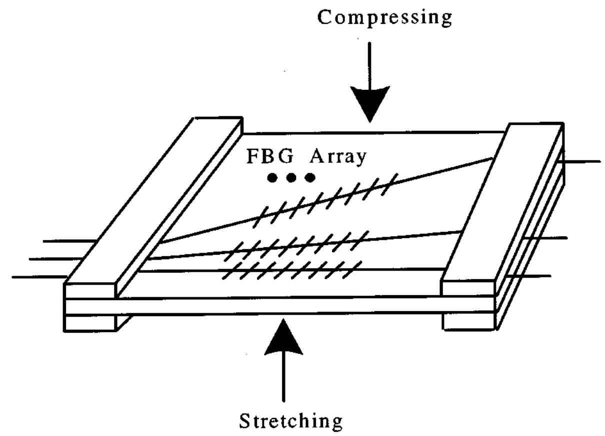

Fig. 3. Wavelength tuning by applying strain.

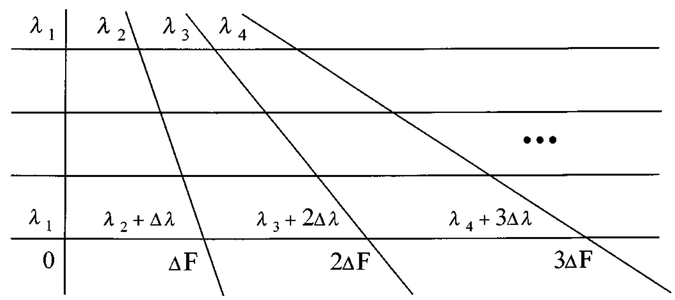

Fig. 4. Wavelengths tuning when forces are applied to the FBGs with an equal force increment.

III. Experimental Results

A four-channel chirped-grating-based TTD system using the proposed multiwavelength light source is constructed and experimented. The time delay response is measured with the four wavelengths tuned from 1547.64, 1549.21, 1551.36, and 1554.1 nm to 1547.64, 1551.64, 1556.60, and 1561.24 nm for a microwave frequency at 4 GHz. The experimental setup is shown in Fig. 5, where the multiwavelength tunable fiber laser is used as a light source to provide the four tunable wavelengths with equally increased or decreased spacing. In the system, the 4-GHz RF signal is modulated onto the optical carriers via a high-speed electrooptic modulator. The modulated light is sent to the chirped grating with a chirped rate of 14.4 ps/nm. The chirped grating in the system acts as a dispersion component. For different wavelengths, the locations of reflections are different, which leads to different time delays. When the wavelengths of the tunable laser source are tuned with equally increased or decreased wavelength spacing, equally increased or decreased time delays are obtained. The time-delayed signals are then sent to the photodetectors through the tunable filters, which act as a comb filter with four passbands to separate the four-channel signals. It should be noted that in order to

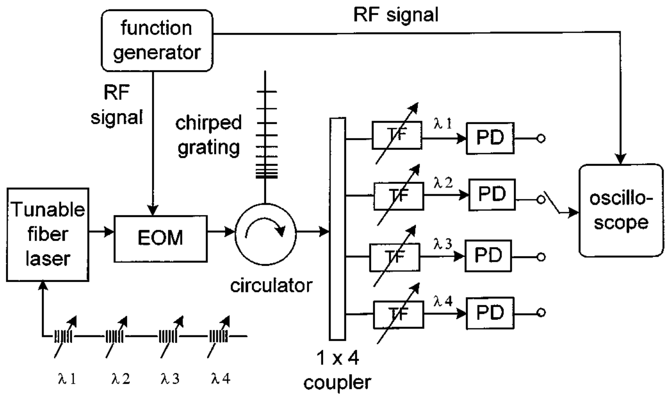

Fig. 5. Experimental setup of the continuous TTD beamforming system.

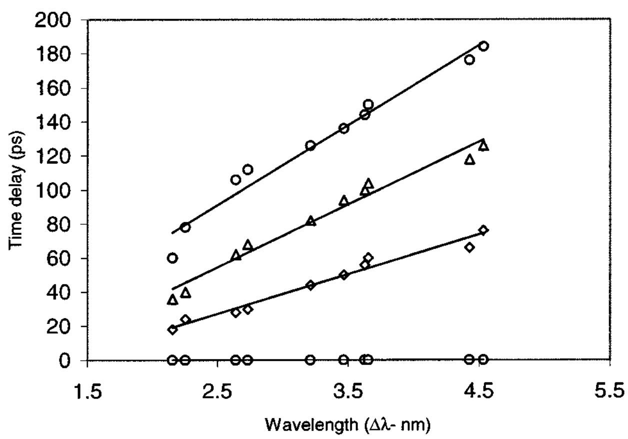

Fig. 6. Time delays versus increased wavelength spacing.

separate the four-channel signals when the wavelengths are tuned, the four tunable filters should be tuned instep with the gratings in the fiber laser. The tunable filters in the experiments are Fabry–Pérot filters, which were coupled to single-mode fibers at both the input and output and were tuned manually. As shown in Fig. 1, the Fabry–Pérot filters can be replaced by FBGs with the same center wavelengths as the FBGs in the laser cavity. Each of the gratings is mounted onto the organic plate in parallel with the corresponding grating in the laser cavity. When tuned, the center wavelengths of the two gratings will have the same wavelength shift and instep tuning is, thus, achieved. The Fabry–Pérot filters used in the experiment are commercial product with a tunable range from 1530 to 1563 nm and 3-dB bandwidth of 1.95 nm. The time delays are measured using an oscilloscope by comparing the phase difference of the RF signal directly from the function generator and the signals with different time delays from the TTD network.

The time delays for the four-channel TTD beamforming system when the wavelengths are tuned from 1547.64, 1549.21, 1551.36, and 1554.1 nm to 1547.64, 1551.64, 1556.60, and 1561.24 nm with equally increased wavelength spacing are measured. For λ_1, it is not tuned, the reflection of this wavelength is always at the same location of the chirped grating and no time delay is produced. For λ_2, λ_3, and λ_4, when tuned, the wavelength spacings are increased equally, which leads to equally increased time delays, as can be observed from Fig. 6. The time delays of the four-channels system are measured when the wavelengths are tuned with the wavelength spacing increased from 2.15 to 4.53 nm at 4 GHz. Some small deviations are observed from the plot. It is believed that these small deviations are caused due to the measurement errors.

IV. Conclusion

In conclusion, a TTD beamforming system that can provide wideband continuous beam steering using a novel tunable multiwavelength fiber laser source with equally increased or decreased wavelength spacing has been proposed. Using the proposed fiber ring laser as a tunable multiwavelength light source, a four-channel TTD system has been constructed and experimented. The results showed that when the wavelengths were tuned with equally increased wavelength spacing; equally increased time delays were obtained.

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