Wavelength Interrogator Based on Closed-Loop Piezo-Electrically Scanned Space-to-Wavelength Mapping of an Arrayed Waveguide Grating

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***Abstract*—We demonstrate a novel technique for the interrogation of grating-based fiber optic sensors. The proposed technique is based on space-to-wavelength mapping using an arrayed waveguide grating (AWG). The beam position along the AWG input coupler is controlled by a closed-loop piezoelectric motor. By employing a real-time position feedback encoder, the absolute position of the input light beam can be accurately obtained, which would yield a precise interrogation of the wavelength due to a fixed relationship between the beam position and the transmission wavelength of the AWG channel. The proposed system for the interrogation of fiber Bragg grating (FBG) sensors and a tilted-FBG sensor is experimented. An interrogation resolution of 3 pm and an interrogation range of 18 nm are demonstrated as well as the multichannel measurement capability. Initial results show that the proposed interrogation system has the potential of being packaged into a compact, light weight, and cost-effective interrogator with good performance.**

***Index Terms*—Arrayed waveguide grating (AWG), fiber Bragg grating (FBG), tilted fiber Bragg grating (TFBG), wavelength.**

I. Introduction

An arrayed waveguide grating (AWG) is a key device in wavelength division multiplexed (WDM) optical communication systems, in which the AWG is used to implement wavelength multiplexing or de-multiplexing, to increase the transmission capacity of the communication system [1]. An AWG can also be used in an interrogation system. The key advantages of using an AWG in an interrogation system are the small size, light weight, good stability and multichannel measurement capability [2]. Numerous interrogation techniques implemented using an AWG have been proposed [3]–[8]. Sano *et al.* [3] proposed to interrogate a fiber Bragg grating (FBG) sensor by measuring the power ratio of the light powers from two adjacent AWG channels. Since only two AWG channels are used, the measurement range is limited. To increase the measurement range, Niewczas *et al.*. [4] proposed to measure the powers of more than two AWG channels. The measurement range can also be increased based on a technique using interferometric wavelength shift detection [5]. To overcome the low interrogation resolution associated with these techniques in [3]–[5], Cheben *et al.* [6] proposed to use a high-resolution silicon-on-insulator AWG. The interrogation resolution can also be increased by using a thermally tunable AWG [7].

To increase the interrogation flexibility and the interrogation wavelength range, a technique for wavelength interrogation based on space-to-wavelength mapping was first proposed and demonstrated by us [8], in which an open-loop piezoelectric (piezo) motor was employed to scan the input light beam along the AWG input coupler. Since the beam position was not known, an additional wavelength reference device, such as a sampled chirped FBG in [8], was used. The use of an additional wavelength reference made the system complicated and the interrogation wavelength range limited. To overcome these technical challenges, we propose and demonstrate an AWG-based interrogation technique based on space-to-wavelength mapping using a closed-loop piezo motor.

The proposed interrogation technique is evaluated under both small- and large-scale wavelength ranges. First, a single fiber Bragg grating (FBG) sensor is successfully interrogated under a small-scale wavelength range. Since the proposed technique provides an absolute position of the input light beam, experimental results indicate that an accurate measurement with a high resolution of 3 pm is achieved. Then, a multichannel measurement of our proposed interrogation technique is tested by simultaneously interrogating four-distributed FBG sensors with the use of four designated AWG channels. Finally, the interrogation under large-scale wavelength range is tested by reconstructing the transmission spectrum of a tilted-FBG (TFBG) sensor, a 18-nm wavelength range is achieved by setting the travel range of the piezo motor to 540 μm. A TFBG sensor is one kind of short-period grating with the grating planes slanted or blazed with respect to the fiber axis [9]. Due to the tilt of the grating, multiple resonances within a large-scale wavelength

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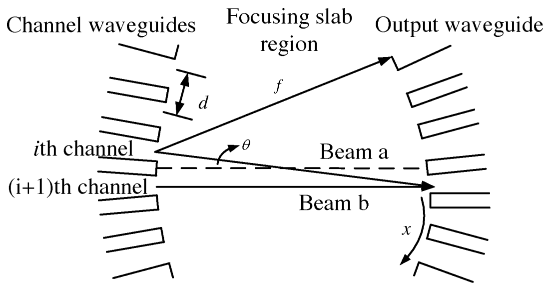

Fig. 1. Enlarged view of the second focusing slab region.

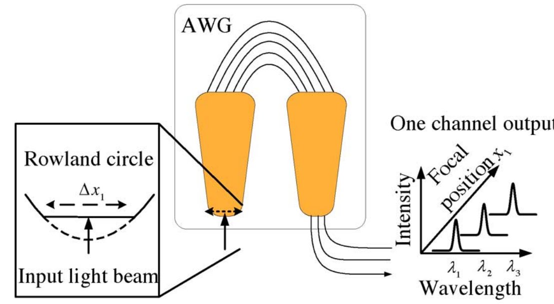

Fig. 2. Schematic methodology of the proposed approach.

range are generated which are sensitive to the refractive index of surrounding medium and make it ideal for biomedical applications [10]. However, these multiple resonances require a wavelength interrogation technique to have a high bandwidth with light weight and miniaturized size. Our proposed interrogation technique is poised to provide the solution to these challenges. The proposed interrogation unit can be packaged into a light weight, small size, cost-effective interrogator with a high resolution and a broad wavelength interrogation range.

II. Theory

An AWG is a passive optical device based on planar lightwave circuits and consists of input/output waveguides, two focusing slab regions, and a phase array of multiple channel waveguides located between the two slab regions (input and output couplers) with a constant path difference, ΔL, between adjacent waveguides. Different wavelengths experience different phase retardations within each channel waveguide. The wavelengths are spatially separated at the second focusing slab region. The phase retardations of two light beams passing through the ith and $(i+1)$th channel waveguide within the region of the second focusing slab are well documented in [1], [11] with an illustration shown in Fig. 1.

The channel waveguide separation is d, and the radius of curvature is f. After two light beams, Beam a and b, are introduced into the first focusing slab region at the position of x_1 (not shown in the figure) and travel through the ith and $(i+1)$th channel waveguide respectively, the two beams will constructively interfere at the focal point x. In order to satisfy the condition of constructive interference, the difference between the total phase retardations of the two beams passing through the ith and $(i+1)$th channels should be an integer multiple of 2π. Then, the interference condition can be described as [1]

$$\beta_s(\lambda_c)\frac{d_1 x_1}{f_1} - \beta_s(\lambda_c)\frac{dx}{f} + \beta_a(\lambda_c)\Delta L = 2m\pi \qquad (1)$$

where d_1 and f_1 are the channel waveguide separation and the radius of curvature in the first focusing slab region, β_s and β_a denote the propagation constants in the slab region and channel waveguide, λ_c is the center wavelength of the AWG, and m is an integer.

By differentiating (1), we obtain the relationship between the output focal point x and the wavelength λ for a fixed input position x_1, shown as

$$\frac{\Delta x}{\Delta\lambda} = -\frac{N_a f_1 \Delta L}{n_s d \lambda_c} \qquad (2)$$

where n_s is the refractive index of the slab region and N_a is the group refractive index of the channel waveguides. Since an AWG is a reciprocal device, the dependence of the wavelength λ on the input position x_1 for a fixed output focal point x, that is the space-to-wavelength mapping, could be expressed by

$$\lambda_A(x_1) = \lambda_A(x_0) + \kappa_A \Delta x_1 \qquad (3)$$

where $\lambda_A(x_0)$ and $\lambda_A(x_1)$ are the transmission wavelengths of the designated AWG channel with the input light beam at positions x_0 and x_1, respectively; Δx_1 is the spatial position difference between x_0 and x_1; and κ_A is the space-to-wavelength mapping coefficient that is determined by the material and structure of the AWG as defined by the right part of (2).

From (3), the wavelength of a fixed output channel of an AWG will be tuned if the input light position is scanning along the first focusing slab region (input coupler). Since the geometrical profile of the slab region is a Rowland Circle, significant loss will be generated if directly coupling light from a fiber to the slab region. In our proposed approach, we cut the Rowland Circle into a slab waveguide in a small region to reduce the losses. Further experimental results reveal that the error induced by the slight structure changes in the operation of an AWG is small and negligible. A schematic of the methodology is shown in Fig. 2.

By employing a closed-loop controlled piezo motor, the real-time position of the input light beam can be accurately obtained. Thus, the wavelength can be interrogated by substituting the beam position into (3) without the need for an additional wavelength [8].

III. Experimental Setup and Results

The relationship between a beam spatial position and the transmission wavelength of a designated AWG channel is tested, with the result shown in Fig. 3.

First, the proposed interrogation technique is evaluated for measuring small-scale wavelength shift. When the position of the input light beam is varied from 0 to 15 μm, we obtain the transmission spectrum. The AWG transmission spectrum is measured using a photodetector (PD) and a tunable laser source with a tuning step of 1 pm. As shown in the inset of Fig. 3, a linear fitting function is obtained which gives the space-to-wavelength mapping coefficient κ_A

$$\lambda_A(x_1) = 1543.000 + 0.0327\Delta x_1 \qquad (4)$$

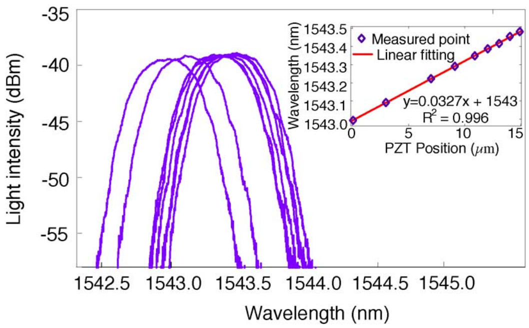

Fig. 3. Spectrum and wavelength shift of a designated AWG channel as a function of the beam position.

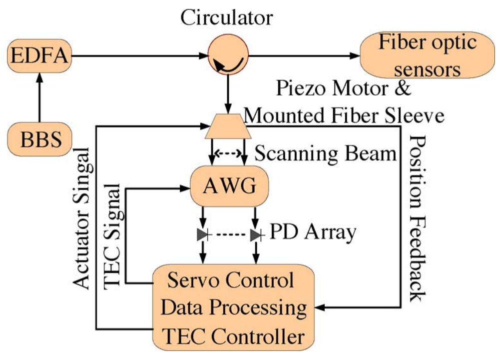

Fig. 4. Experimental setup of the proposed interrogation technique based on space-to-wavelength mapping using a closed-loop piezo motor.

The unchanged transmission spectrum with respect to the input light beam position and its linear relationship validate the assumption that the operation of an AWG is not affected by the structure changes when cutting the Rowland Circle into a slab waveguide in a small region.

A tuning spectral range of 0.49 nm is obtained within a 15-μm travel range of the input light beam and the coefficient is measured to be 0.0327 nm/μm.

The experimental setup is shown in Fig. 4. A light beam from a broadband source (BBS) is amplified by an erbium-doped fiber amplifier (EDFA), and then sent to the fiber optic sensors through a circulator. The output fiber tail of the circulator is mounted on top of a closed-loop piezo motor, fixed and protected by a fiber sleeve, which is pre-aligned with the input coupler of an AWG using a positioning stage. The piezo motor moves horizontally driving the fiber tail to scan along the input coupler. A capacitive position encoder is embedded in the piezo motor to provide the absolute position of the scanning fiber tail. With the position feedback, an actuator signal is properly set to drive the piezo motor to reach the specified position. This is regarded as the closed-loop (servo) control. Due to the temperature dependence of the AWG transmission wavelength (reported as 11 pm/°C [12]), a thermal electrical cooler (TEC) is attached to the base of the AWG to compensate for the thermal variations due to the temperature drift. The output light power of the AWG is detected by a PD array. A Labview program is developed to collect and process the measurement data, and implement servo control of the piezo motor.

The interrogation of an FBG sensor under four different temperatures (16°C, 19.5°C, 22°C, and 25.5°C controlled by an oven) is demonstrated. At each temperature, the position of the input light beam changes from 0 to 15 μm with a tuning step of 0.1 μm, resulting in a spectral interrogation resolution of $\sim$ 3 pm. Fig. 5 illustrates the output power as a function of the absolute position. The peak value representing the absolute PZT position in accordance to the transmission wavelength of the FBG is directly estimated by a standard programming module from the Labview program with the capability to search the peak value. By employing (4), we are able to calculate the Bragg wavelength of the FBG sensor for the four temperatures. For each temperature, the measurement result is shown in Fig. 6. The variation between the Bragg wavelengths interrogated by the proposed technique and the values measured by an Agilent tunable laser source (81640B) is observed to be within $\pm$4 pm.

Only one AWG channel is used in the above experiment. As discussed, one significant feature of applying an AWG for the wavelength interrogation is that it has multichannel measurement capability. In a second experiment, the interrogation of four distributed FBGs using four designated AWG channels is performed, in which the output powers of the four AWG channels are monitored. Fig. 7(a) shows the spectrum of each AWG channel when the input light beam is located at four different positions (0 μm, 5 μm, 10 μm and 15 μm) along the AWG input coupler. It is seen that the transmission wavelength of an AWG channel is shifted while the spectrum shape remains unchanged and the wavelength shift in each AWG channel keeps the same. The different power levels of the four AWG channels are believed to be attributed to the nonuniform gain profile of the EDFA. The interrogation of the four-FBG-based sensor is performed by measuring its temperature sensitivity, in which the sensor temperature is modified by an oven. As shown in Fig. 7(b), the temperature sensitivity is measured to be $\sim$ 10 pm/°C near the wavelength of 1550 nm for each FBG based sensor, which accords well with the results reported in [13].

The experimental results in Fig. 7 show that the proposed interrogation technique has the capability of multichannel measurement and all the channels are able to constitute a zoom-in spectrum to reflect a small-scale wavelength shift. As shown in (3), a broader wavelength range can be achieved by increasing the travel range of the closed-loop piezo motor. In the experiment, we extend the travel range to 540 μm instead of 15 μm to cover a broader wavelength interrogation range of 18 nm (selected according to the TFBG sensor in this experiment).

Next, the proposed interrogation technique is tested to achieve a large-scale wavelength range by reconstructing the reflected spectrum of a tilted-FBG sensor. A comparison of the obtained transmission spectrum of a TFBG is shown in Fig. 8.

Fig. 8(a) shows the transmission spectrum of a TFBG obtained using an optical spectrum analyzer (OSA) as a reference, and Fig. 8(b) shows the transmission spectrum obtained using our proposed interrogation technique. Comparing the results shown in Fig. 8(a) and (b), we can see that the transmission spectrum of a TFBG can be accurately reconstructed, which validates the ability of the proposed interrogation technique to operate in a large-scale wavelength range. The wavelength range of 18 nm is limited by the specific TFBG we used in this experiment rather than the proposed interrogation technique. Broader wavelength interrogation range can be achieved by extending the travel range of the closed-loop piezo motor over 540 μm.

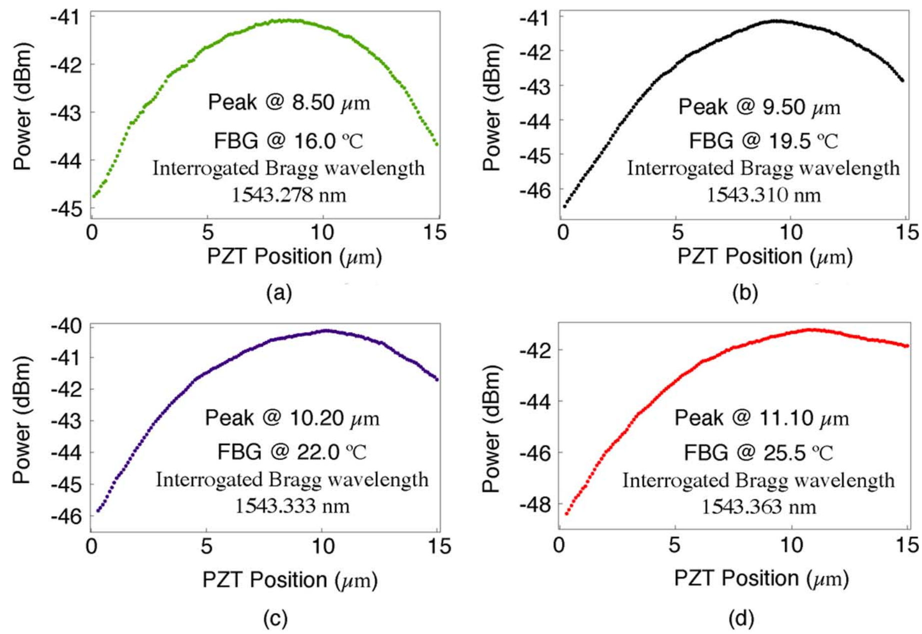

Fig. 5. Interrogation result of a single FBG sensor under four different temperatures, (a)–(d), as a function of the beam position.

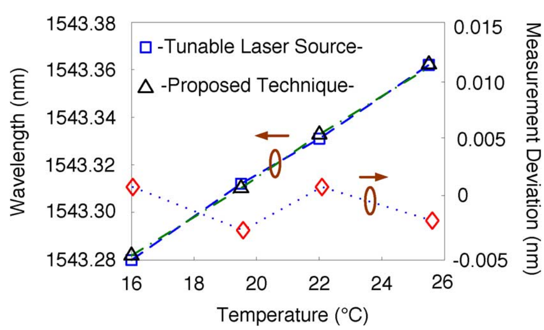

Fig. 6. Measured Bragg wavelength by the proposed technique and the use of a PD and a tunable laser source.

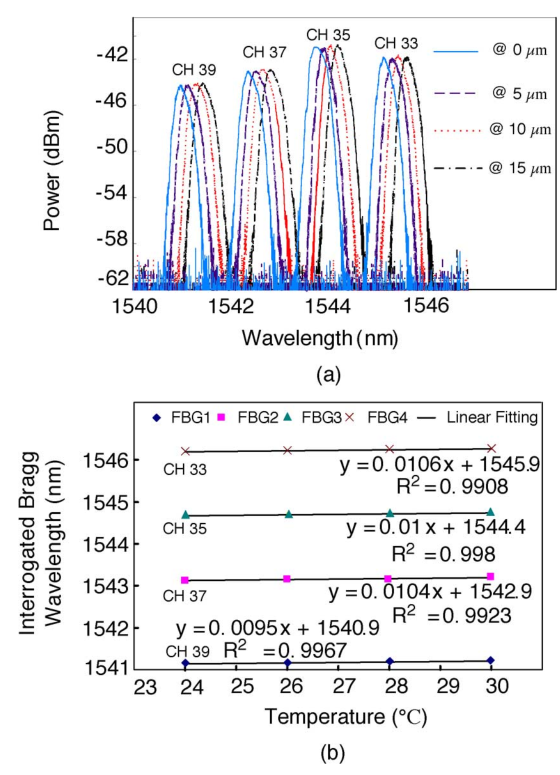

Fig. 7. Interrogation of a four-distributed-FBG sensor. (a) Shifted spectrum of each AWG channel with changed position of the input light beam. (b) Measured temperature sensitivity.

The key difference between the proposed technique and the one reported in [8] is that the wavelength is accurately interrogated here by reading the beam position provided by the closed-loop control. While in [8], since the beam position was not known, a wavelength reference must be used to estimate the Bragg wavelength. Clearly, the use of the proposed technique in this paper would increase the interrogation accuracy and resolution. Since no wavelength reference device is needed, the proposed system has a smaller size with a reduced system complexity and an increased system robustness.

To increase the wavelength interrogation range, a solution is to extend the travel range of the piezo motor, as discussed above. If the travel range is extended to 2 mm, a wavelength range of $\sim$ 65 nm will be achieved, which covers the entire C band and part of the L band—a wavelength range that is wide enough for most of FBG sensor applications. The wavelength interrogation range can also be extended by cascading multi-AWG-channels. Our current AWG has a channel spacing of 0.8 nm. Since all the AWG channels have the same wavelength tuning capability, a PZT motor travel range of 25 μm will allow each AWG channel cover an interrogation range of 0.8 nm. In such a case, cascaded multi-AWG-channels will cover a broader interrogation range. Compared to the first method to increase the interrogation range, this method is not vulnerable to the size of the cut Rowland Circle and it further decreases the requirements of the PZT motor and the fiber-to-waveguide coupling due to reduced PZT motor travel range. Furthermore, the reduced PZT

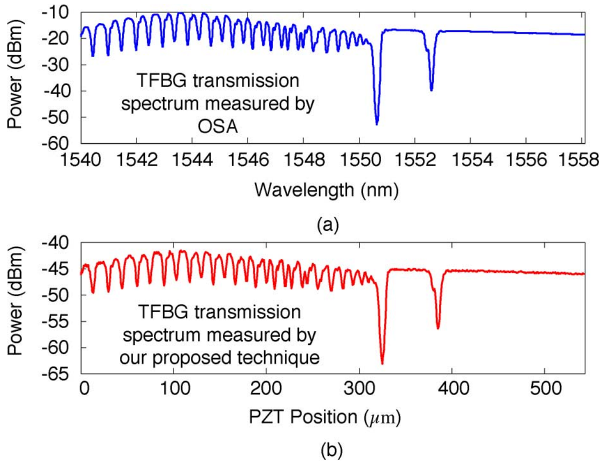

Fig. 8. Measured transmission spectrum of a TFBG. (a) Measured by an OSA. (b) Measured by the proposed interrogation technique.

motor travel range can increase the interrogation speed. Our current PZT motor has a maximum travel speed of 400 mm/s (PI, M-663.465). It could provide an interrogation speed of 16 kHz if a travel range of 25 μm is needed as discussed above. The broad interrogation range and fast interrogation speed are particularly suitable for the vibration measurement using a TFBG sensor [14].

In this paper, a positioning stage is still required for the light coupling from the input fiber into the input coupler of an AWG. The butt-to-butt coupling results in a high attenuation of 25 dB, as shown in Fig. 8, which reduces the performance of the entire interrogation system. The use of a recently developed subwavelength grating coupler could be a solution. In a subwavelength grating coupler, the light is designed to be coupled into the input coupler of an AWG from its top surface with the coupling grating structure fabricated directly onto the input coupler. As a result, positioning stage is no longer required. A simple configuration with better robustness and higher coupling efficiency has been reported [15].

The AWG chip and the piezo motor are compact in size (e.g., the AWG is about $30 \times 50 \times 3$ mm and the piezo motor is about $30 \times 90 \times 15$ mm without the controller). The weight for both AWG chip and piezo motor (controller included) is less than 500 g. Furthermore, the cost for a closed-loop piezo motor with 2-mm travel range (60 nm as the wavelength range) and 0.1-μm spatial resolution (3 pm as the wavelength resolution) is significantly reduced, making the proposed interrogation technique cost-efficient. Therefore, in addition to an increased performance, the proposed interrogation technique also features a smaller size, lighter weight and lower cost, which enables the design and package of the proposed interrogation system in a hand-held and light-weight device at a low cost.

IV. Conclusion

We have demonstrated a wavelength interrogation technique based on space-to-wavelength mapping implemented by an AWG and a closed-loop controlled piezoelectric motor. The interrogation was performed by scanning the light beam along the AWG input coupler, with the beam position controlled by a closed-loop piezoelectric motor. A fixed relationship between the beam position and the transmission wavelength of the AWG channel was established, making it possible to interrogate the wavelength by simply measuring beam positions. The key contribution of this technique was the use of a closed-loop controlled piezoelectric motor which could increase the wavelength range and resolution of the interrogation system. Since no additional wavelength reference device was needed, the system was greatly simplified. The interrogation of distributed FBGs and a TFBG to show respectively its performance in small- and large-scale wavelength range was experimented. Four-distributed FBGs were successfully interrogated, which confirmed the multichannel measurement capability of the proposed technique. The proposed AWG-based interrogation technique has a high potential to be packaged into a miniaturized, light weight and cost-efficient device with high performance.

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