Interrogation of a long-period grating using a mechanically scannable arrayed waveguide grating and a sampled chirped fiber Bragg grating

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A novel technique to interrogate a long-period grating (LPG) using a mechanically scannable arrayed waveguide grating (AWG) is proposed. This technique is implemented based on space-to-wavelength mapping by mechanically scanning the input light beam along the input coupler facet of an AWG. By employing a sampled chirped fiber Bragg grating with multiple peaks as a reference, the central wavelength of the LPG is measured. An interrogation system with a resolution of 10 pm at a speed of 10 Hz is demonstrated. Furthermore, the technique proposed can potentially offer subpicometer resolution at a speed of 500 Hz.

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Long-period-grating (LPG) sensors have found extensive applications ranging from temperature monitoring, mechanical measurement, to chemical sensing thanks to such advantageous features as high sensitivity and low backreflections [1]. The key challenge in employing an LPG for sensing applications is the large spectral band, which is hard to interrogate with high resolution and fast speed [2]. A few LPG sensor interrogators have been developed, with most of them based on an optical spectrum analyzer (OSA). The use of an OSA would make the system very bulky and costly, which is only suitable for use in a laboratory environment. In the past few years, the arrayed waveguide grating (AWG), originally developed for optical wavelength division multiplexed (WDM) communications, has been used in sensing systems to interrogate fiber Bragg grating (FBG)-based sensors [3,4]. The technique proposed by Sano and Yoshino [3] provides a simple solution with good performance but suffers from a limited spectral interrogation range, which is not suitable for the interrogation of an LPG-based sensor. To increase the spectral interrogation range, Xiao *et al.* [4] proposes to tune the AWG via thermal tuning. The major difficulty involved in this technique is the low speed limited by the response time of the thermal-resistant heating film. The use of interferometric wavelength shift detection could provide both a large spectral interrogation range and fast speed, but the system is complicated and costly [5].

In this Letter, we propose and demonstrate a novel technique to interrogate an LPG sensor. The technique is implemented based on space-to-wavelength mapping by mechanically scanning the input light beam along the input coupler facet of an AWG. By employing a sampled chirped FBG (SCFBG) with multiple peaks as a reference, the central wavelength of the LPG is measured. Since the AWG is mechanically tuned, the speed of the interrogation can be faster than that based on thermal tuning. In addition, the use of an SCFBG as a wavelength reference makes the measurement of the central wavelength of an LPG accurate.

The AWG is a type of device based on planar lightwave circuits. Its design principle and waveguide layouts have been described in the literature [6,7]. What is relevant to this work is the relationship [7] between the spectral wavelength shift $\Delta\lambda$ of the wavelength λ_c from the center output channel and the focal position change Δx_1 at the input coupler,

$$\Delta\lambda = \frac{n_s d_1 \lambda_c}{N_c f_1 \Delta L}\Delta x_1, \tag{1}$$

where ΔL is the physical length difference between two adjacent waveguides; d_1 and f_1 are the array waveguide separation and the curvature radius in the input coupler, respectively; n_s is the effective refractive index in the couplers; and N_c is the group index of the effective refractive index of the array waveguides.

From Eq. (1) it is seen that the center wavelength shifts monotonically with the position of the input light beam at the input coupler. In this case, we can simply obtain the transmission wavelength by knowing the position of the input light beam. However, the input coupler is fabricated with the profile of a Rowland circle and the insertion loss is high if the input light beam is coupled directly into the input coupler. In the experiment, the input coupler used in this proposed technique is slightly cut so that part of the Rowland circle is changed into a slab waveguide, as shown in Fig. 1. In the system an SCFBG is used as a reference to build a mapping relationship between the wavelength and the number of sampling points.

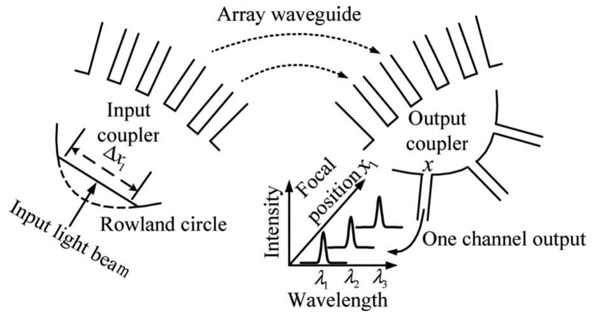

Fig. 1. Mechanically scannable AWG methodology.

Basically, an SCFBG can be regarded as a multichannel comb filter that is fabricated by sampling a regular chirped FBG with a specific sampling period to achieve the required wavelength spacing [8]. Owing to the position uncertainty introduced by the hysteresis and the scanning speed nonuniformity, a space-to-wavelength mapping should be established for each scan, which is realized by comparing the SCFBG peak wavelengths with the measured sampling points.

Assuming that the center wavelength of an LPG is designed close to one of the transmission channels of an AWG, when the input light beam is scanning along the input coupler facet of the AWG, the received light intensity will reach its minimum when the transmission wavelength of the AWG is located at the center wavelength of the LPG. Thus, by knowing the position of the input light beam corresponding to this minimum light intensity with the assistance of the reference SCFBG, the center wavelength of the LPG can be measured.

To evaluate the feasibility of the proposed scheme an experimental interrogation setup, illustrated in Fig. 2, is built. The system consists of a broadband source (BBS), an erbium-doped fiber amplifier (EDFA), an AWG, a piezomotor, an SCFBG, and two photodetectors (PDs). The fiber tail at the output of the EDFA is mounted on a piezomotor, which is moving along the input coupler facet of the AWG. The output from the AWG is split into two channels via a 3 dB fiber coupler, with one channel connected to the LPG under interrogation and the other connected to the SCFBG. A thermal electrical cooler (TEC) is used to control the temperature of the SCFBG to eliminate its wavelength drifts due to the environmental temperature variations. The position uncertainty introduced by the hysteresis of the open-loop piezomotor and nonuniformity of the scanning speed are overcome by the space-to-wavelength mapping implemented by the SCFBG. Thus, a mapping between the wavelengths and sampling points is established within each scan. A data acquisition (DAQ) card provides two physical input channels, which are employed to record the electrical voltages representing the light intensities from the two channels. Since the two physical input channels share the same trigger provided by the DAQ card itself, the measured data are acquired from the two channels at the same time. Finally, the center wavelength of the LPG is interrogated by interpolating the measured data to find a sampling point representing the LPG dip with the space-to-wavelength mapping.

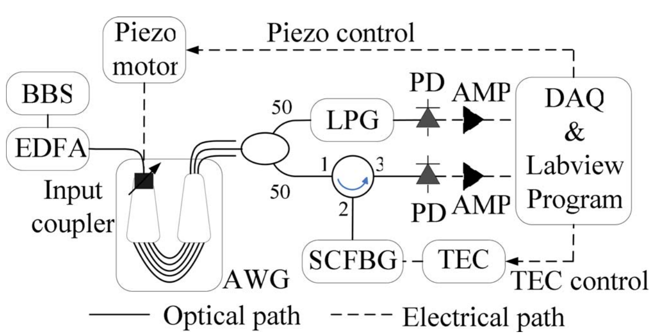

Fig. 2. (Color online) Experimental setup for the wavelength interrogation of an LPG sensor based on mechanically scannable AWG.

The dependence of the wavelength tunability on the change of the input light beam position is measured to be 0.0478 nm/μm, as shown in Fig. 3. Figure 4 shows the reflection spectrum of the SCFBG measured by an OSA with a resolution of 10 pm, with the selected peak wavelengths labeled in the figure.

Figure 5 shows the experimental results. The peak wavelengths and their corresponding sampling points are obtained by comparing Fig. 5 with Fig. 4. The DAQ sampling point corresponding to the minimum value of the electrical voltages in Fig. 5 is measured as 3576. The center wavelength of the LPG is measured to be 1552.083 nm. Compared with the center wavelength of 1552.080 nm at room temperature supplied by the manufacturer, a good agreement is achieved.

The piezomotor applied in this experiment has a maximum speed of 500 mm/s. A physical distance along the input coupler of 1 mm is required to achieve a spectral scanning range of 50 nm based on the AWG wavelength tunability of ~0.05 nm/μm. If the piezomotor works at its maximum speed, a physical scanning distance of 1 mm can be completed within 2 ms. Therefore, the scanning speed can be as high as 500 Hz with a spectral scanning range of 50 nm, which would make the proposed interrogation technique feasible for most applications where a large measurement range and fast speed are re-

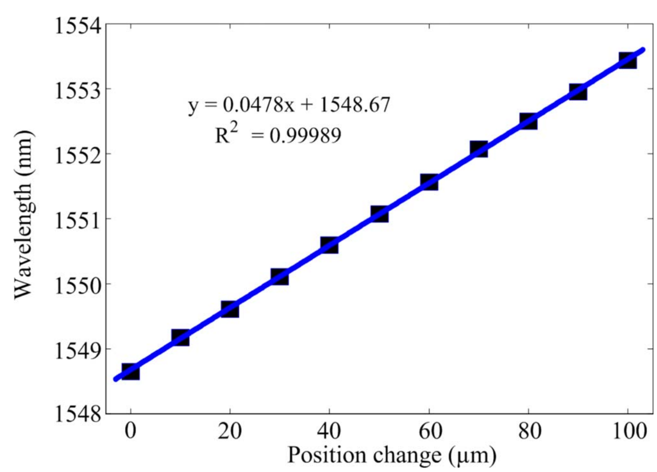

Fig. 3. (Color online) Wavelength shift of an AWG output channel as a function of the position of the input light beam.

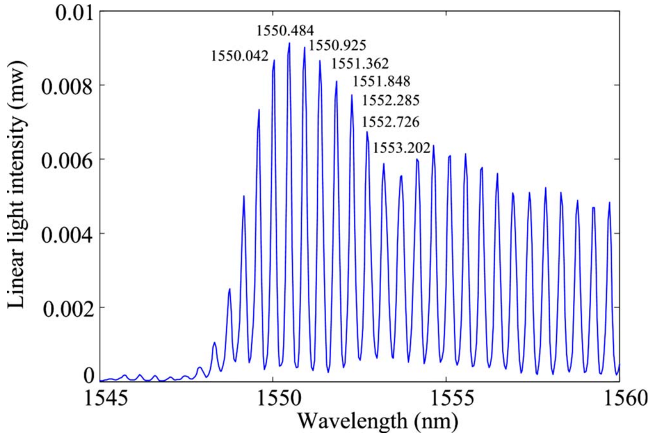

Fig. 4. (Color online) Reflection spectrum of the SCFBG measured by an OSA.

quired. The scanning speed could be further increased if the required spectral scanning range was reduced.

In this experiment, the DAQ card is set at a sampling speed of 60,000 samples per second. For the sake of simplicity of demonstrating the concept, 6000 sampling points representing a spectral range of ~4 nm, as shown in Figs. 4 and 5, are obtained within 100 ms, which provides a resolution of 0.67 pm and a scanning speed of 10 Hz. However, since the spectrum of the SCFBG is measured by an OSA with a resolution of 10 pm, the resolution achieved in this experiment is restricted to 10 pm. The resolution of the proposed interrogation technique can be highly improved if the reference SCFBG

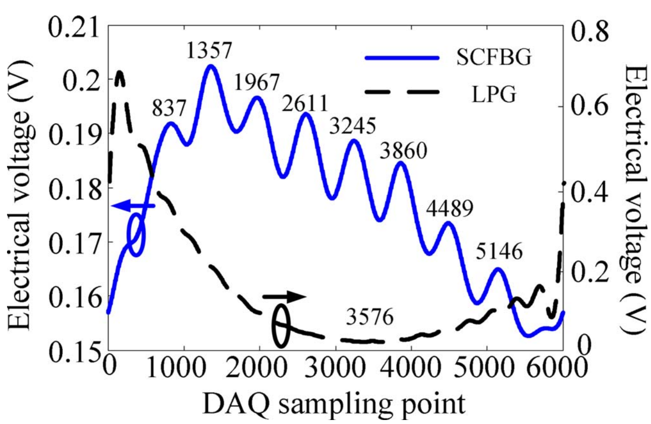

Fig. 5. (Color online) Experimental interrogation results of an LPG sensor by mechanically scanning an AWG.

spectrum is calibrated by an equipment of subpicometer resolution. Meanwhile, the resolution, as well as the accuracy, can be improved if an AWG with a smaller than 3 dB bandwidth is applied. The AWG used in this experiment has a 3 dB bandwidth of 0.4 nm, which is the maximum value that is suitable for the scanning of the current SCFBG, because the wavelength spacing of the SCFBG is around 0.4 nm. If an SCFBG with smaller wavelength spacing is employed, an AWG with an equal to or smaller than 3 dB bandwidth should be used. Furthermore, the maximum sampling speed of the current DAQ card is ~300,000 samples per second on the condition that only two input channels are in operation. Compared with the sampling speed of 60,000 samples per second incorporated in this work, the resolution will be five times higher if the DAQ card is working at 300,000 samples per second.

In summary, a new technique to interrogate an LPG sensor by mechanically scanning the input light beam along the input coupler facet of an AWG has been demonstrated. By using the space-to-wavelength mapping provided by an SCFBG as a wavelength reference, the center wavelength of the LPG with a resolution of 10 pm was interrogated. The proposed system has the potential to operate at an interrogation resolution better than 1 pm and an interrogation range of 50 nm with a scanning speed up to 500 Hz.

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