Simultaneous Interrogation of a Hybrid FBG/LPG Sensor Pair Using a Monolithically Integrated Echelle Diffractive Grating

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***Abstract*—A simultaneous interrogation technique of a hybrid fiber Bragg grating (FBG) and long-period grating (LPG) sensor pair is proposed and demonstrated using a monolithically integrated echelle diffractive grating (EDG). The operation principle that is based on the monotonic temperature dependence of the EDG transmission wavelengths is presented. Initial results show that a 1-pm resolution and 24-nm interrogation range are achieved by using the proposed interrogation technique, which can effectively be implemented to interrogate hybrid FBG/LPG-based sensor pairs for the discrimination of refractive index (RI)/temperature in RI measurement. The specially designed EDG-based interrogator has the added features of low cost and compact size.**

***Index Terms*—Echelle diffractive grating (EDG), fiber Bragg grating (FBG), long period grating (LPG), refractive index (RI) measurement, sensor interrogation, temperature measurement.**

I. INTRODUCTION

ONE of the technical problems associated with long-period grating (LPG)-based refractive index (RI) sensors is the inability to distinguish wavelength shifts produced by the cross-sensitivity between RI and temperature measurements [1], [2]. Considerable effort has been devoted to develop techniques for the RI/temperature discrimination, such as dual-wavelength LPG sensors [3], [4], LPG sensors packaged in two sections with different coatings [5], sandwiched LPG sensors [6], and hybrid FBG/LPG sensor pairs [7], [8]. All the proposed techniques are based on having the ratio of RI response to that of the ratio of temperature response of the two gratings or two sections of a single grating be different. As a consequence, the RI/temperature discrimination effect dramatically depends on these ratios. Due to the larger RI and temperature response of LPG sensors, as compared to FBG sensors [7], [8] and the configuration simplicity, the hybrid FBG/LPG is believed to be the most suited approach for RI/temperature discrimination in RI measurements. However, the key challenge for such effective hybrid approach is the availability of wavelength interrogation technique that is capable of simultaneously providing both high resolution and large wavelength range [1], [9]. In their investigation [10], Patrick *et al.* used a second FBG to obtain the wavelength shift of the LPG by analyzing the reflectance signals of the two FBG sensors, which increases the complexity and instability of the configuration design. In this paper, we propose a simple interrogation technique for the potential applications in the RI/temperature discrimination in hybrid FBG/LPG sensor pairs. This technique is based on a thermally tunable echelle diffractive grating (EDG) interrogation approach, which is capable of providing both high resolution and large wavelength range. Results of both theoretically and experimentally studies are reported.

II. THEORY

Similar to the operation principle of an arrayed waveguide grating (AWG) described in [11], the transmission spectrum of the ith channel of an EDG interrogator can be expressed as [12]

$$A_i(\lambda) = a_i \exp\left[-4(\ln 2)\frac{(\lambda - \lambda_{Ei})}{\Delta\lambda_{Ei}^2}\right] \tag{1}$$

where a_i, λ_{Ei} and $\Delta\lambda_{Ei}$ are the peak transmittance, center wavelength, and full-width at half-maximum (FWHM) of the ith output channel of an EDG.

Assuming that the transmission wavelength of the EDG interrogator changes monotonically with respect to the EDG chip temperature, the thermal tunability of the transmission wavelength of the ith channel of the EDG can be described by

$$\lambda_{Ei} = f(T) + \lambda_0 \tag{2}$$

where $f(T)$ is the monotonic temperature-dependent function, T is the EDG chip temperature, and λ_0 is a constant.

As a Gaussian apodized FBG and LPG can be considered as having a flip-flopped Gaussian spectrum profile [13], the transmission spectrum of a Gaussian apodized FBG or LPG can be expressed as

$$I_{\text{Hybrid}}(\lambda) = I_0 - I_{B/L} \exp\left[-4\ln(2)\frac{(\lambda - \lambda_{B/L})^2}{\Delta\lambda_{B/L}^2}\right] \tag{3}$$

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where I_0 is a constant, $I_{B/L}$ is the transmittance at the center wavelength $\lambda_{B/L}$, and $\Delta\lambda_{B/L}$ is the FWHM of the Gaussian profile. The notation adopted for FBG/LPG is expressed by B/L. It is further assumed that the light intensity detected by the ith channel of the EDG is mainly from the FBG, while the contribution from the LPG is very small and can thus be neglected. The latter assumption can be easily realized by proper design of the operation wavelengths of both hybrid FBG/LPG sensor pairs.

For the FBG sensor, for instance, the light intensity detected by the ith channel is described by [14]

$$I_i(\lambda) = I_c - P_i \exp\left[-4\ln(2)\frac{(\lambda_B - \lambda_{Ei})^2}{\Delta\lambda_B^2 + \Delta\lambda_{Ei}^2}\right] \tag{4}$$

where I_c is a constant representing the output dc level, λ_B is the FBG center wavelength, P_i is dependent on the optical source power, photodetector sensitivity, and the FWHM of the EDG channel and the FBG.

It is observed from (2) and (4) that by tuning the EDG chip temperature, the detected light intensity of the ith channel of the EDG reaches a minimum value when λ_{Ei} reaches λ_B. Therefore, the center wavelength of the FBG can be obtained by knowing the temperature corresponding to the minimum value of the detected light intensity in the ith channel and the monotonic temperature dependence of the EDG transmission wavelengths.

The operation principle of interrogating an LPG is the same as that of the above presented FBG sensor. Combining the two separated interrogation processes into one single measurement, by monitoring the light intensity of several EDG channels at the same time, the simultaneous interrogation of the hybrid FBG/LPG can be achieved.

III. EXPERIMENTAL SETUP AND RESULT

Fig. 1 illustrates a monolithically integrated EDG chip [15], which consists of a 1 × 15 EDG demultiplexer, an array of photodetectors (PD), a thermal electric cooler (TEC), a resistance temperature detector (RTD), and a heater dissipater packaged in a butterfly configuration. The TEC and RTD that has a resolution of 0.01°C are integrated in the chip for controlling and monitoring the EDG chip temperature. The proposed EDG interrogation technique is developed based on this chip, which weighs 60 g and has dimension of $45 \times 30 \times 15$ mm^3.

In this paper, a special temperature controlling approach was developed for the EDG interrogator, which is different from the one reported in [15]. The relationship between the EDG chip temperature and the transmission wavelengths of the 15 EDG channels are tested and the results are shown in Fig. 2.

An Agilent tunable laser source (TLS, Agilent 81640B) is used to perform the wavelength scanning with tuning step of 5 pm. From Fig. 2(a), it is determined that the EDG-based interrogator has a spectral tunable range of ~24 nm. Although a polynomial curve fitting would yield best result for the curves shown in Fig. 2, a linear approximation has been found acceptable due to the small variation and simplicity in the data processing. Fig. 2(b) shows such linear fitting for channel 3 of the EDG with temperature sensitivity of ~ 86 pm/°C. All other EDG transmission channels possess the same wavelength tuning behaviour due to the uniformity of EDG devices. Thus, the monotonic relationship between the EDG transmission wavelengths and the EDG chip temperature expressed in (2) is demonstrated.

To further demonstrate the feasibility of the proposed interrogation technique an experimental setup is established, as shown in Fig. 3.

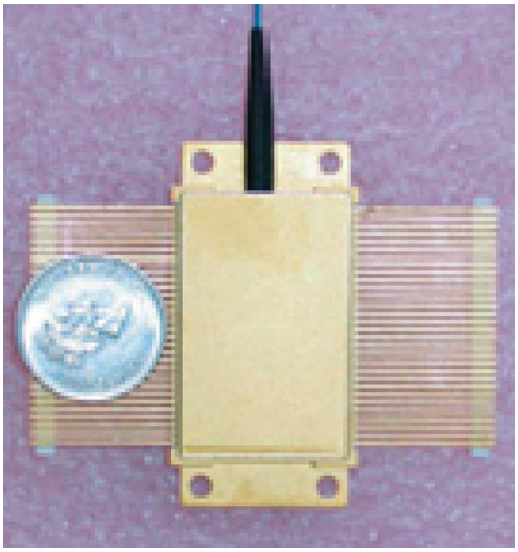
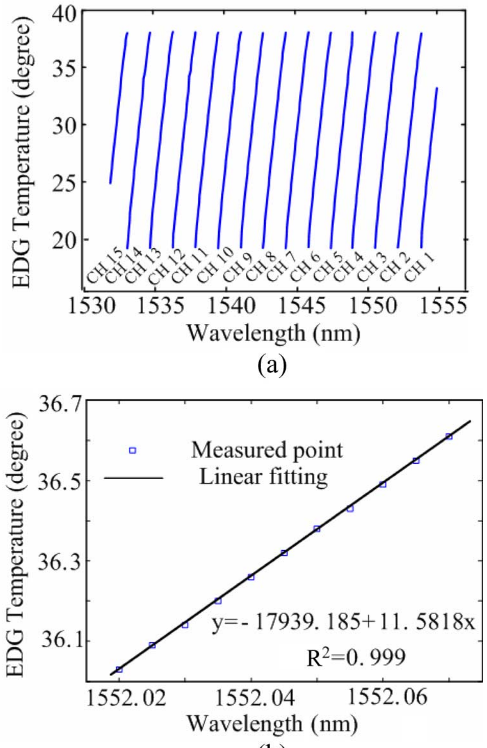


Fig. 1. Illustration of the EDG interrogator prototype.



(a)

(b)

Fig. 2. Temperature changes as a function of the wavelength. (a) All 15 channels. (b) Part of the temperature changes in Channel 3.

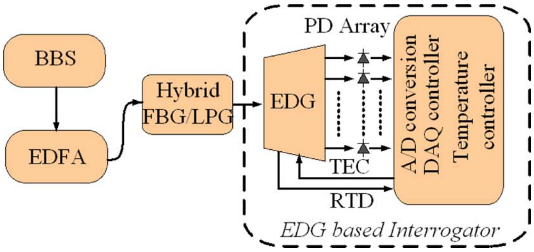


Fig. 3. Experimental setup for the hybrid FBG/LPG interrogation using a thermally tunable EDG.

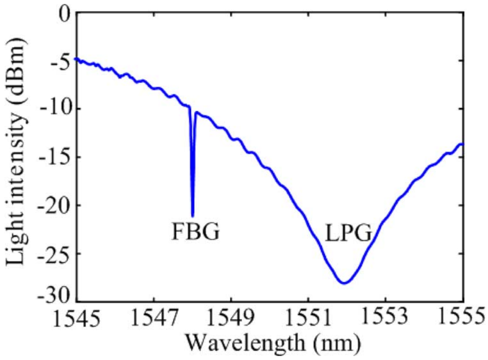


Fig. 4. Spectrum of the hybrid FBG/LPG measured by an OSA.

The setup consists of a broadband source (BBS), an erbium-doped fiber amplifier (EDFA), and an EDG-based interrogator. The EDG-based interrogator, which has a channel spacing of 1.6 nm, is controlled by a Labview program that performs the analog-to-digital conversion, data acquisition, temperature detection, and control.

Considering the 86 $\mathrm{pm}/^\circ\mathrm{C}$ EDG temperature sensitivity, shown in Fig. 2(b), the proposed interrogation technique presents a wavelength resolution of better than 1 pm due to the temperature resolution of 0.01°C provided by the TEC and RTD. Meanwhile, a transmission wavelength shift of 1.7 nm at each EDG channel can be obtained by tuning the EDG chip temperature of 20°C. Since the tunable range of each channel is larger than the channel spacing, the proposed interrogation system can provide a continuously scanning spectral range of 24 nm. Therefore, the proposed interrogation technique can meet the challenges posed by the hybrid FBG/LPG-based RI sensors and would be able to make the RI/temperature discrimination.

Fig. 4 shows the spectrum of the hybrid FBG/LPG measured by an optical spectrum analyzer (OSA) with wavelength resolution of 10 pm. It is noted that the wavelength spacing between the FBG and LPG (4.2 nm) is larger than an EDG channel (1.6 nm). Therefore, the spectra of the two gratings are located in two different EDG transmission channels.

Fig. 5 presents the light intensity from the FBG with respect to the sampling points detected from Channel 5 of the EDG with the help of the data acquisition system.

Since the bandwidth of the FBG is relatively small, as shown in Fig. 4, one dedicated channel (Channel 5) is capable of obtaining the spectrum. Although the bandwidth of the LPG is larger than the EDG channel spacing, the flexibility of the proposed interrogation technique allows for the use of three or more EDG channels (Channel 2–4 in this case) to obtain the LPG spectrum, as shown in Fig. 6(a)–(c), where the minimum light intensity is obtained at Channel 3.

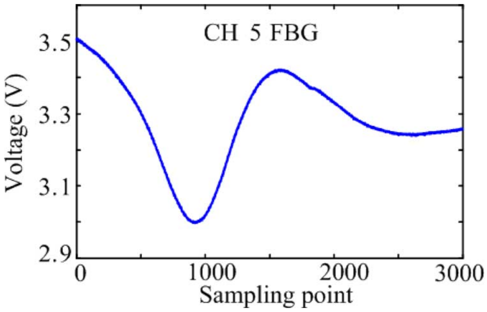
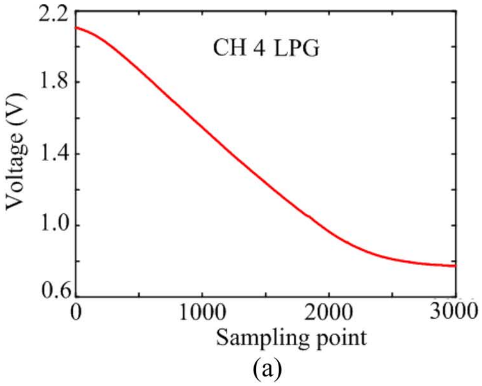
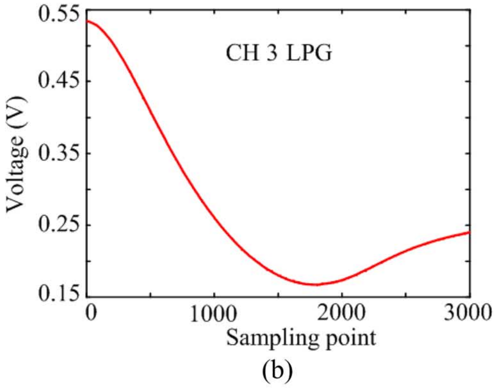


Fig. 5. Experimental result of the light intensity from the FBG.





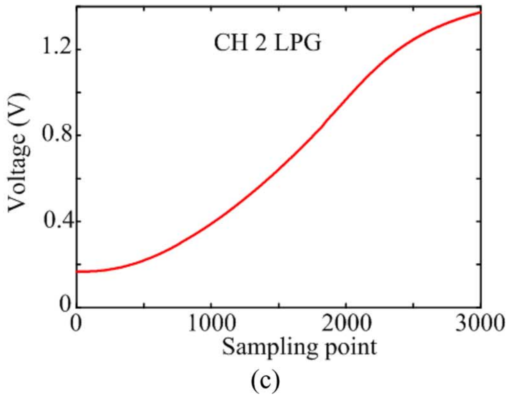


Fig. 6. Experimental result of the light intensity from the LPG. (a) EDG Channel 4. (b) EDG Channel 3. (c) EDG Channel 2.

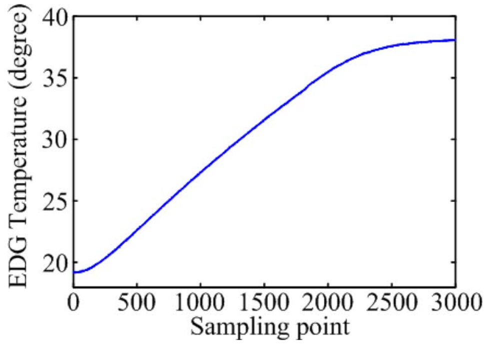


Fig. 7. Measured EDG chip temperature.

TABLE I
Interrogation Results of the Hybrid FBG/LPG

Measurement	1	2	3	Actual*
FBG (nm)	1548.021	1548.019	1548.023	1548.01
LPG (nm)	1552.214	1552.210	1552.180	1552.20

* supplied by the manufacturer

* supplied by the manufacturer

In this experiment, the EDG chip temperature, measured by the RTD, is simultaneously fed back to the Labview program together with the light intensity. Fig. 7 shows the measured EDG chip temperature with respect to the sampling points.

In the data processing, the sampling points representing the minimum value of the detected light intensity in the dedicated channels are obtained from Figs. 5 and 6(b) for the FBG and LPG, respectively. Then, the EDG chip temperatures are calculated by interpolating the above obtained sampling points in the processed curve in Fig. 7. Finally, the center wavelengths of the hybrid FBG/LPG pair are achieved by correlating the obtained EDG chip temperatures to the wavelengths using the linear temperature dependence obtained in Fig. 2. Three experiments were performed within 1 h to verify the proposed interrogation technique. Table I presents the results obtained and it shows that very good agreement is achieved with those data provided by the manufacturer, proving the feasibility of the proposed interrogation technique.

IV. MEASUREMENT ERRORS AND EVALUATION

In this section, we estimate the sources of the resultant measurement errors and evaluate the performance of the proposed interrogation technique.

The small variation, at a maximum value of 14 pm, among the measurement results and the manufacturer's number shown in Table I is believed to be partly attributed to the drifting of the ambient conditions, such as strain and temperature, during the testing processes. A typical FBG has sensitivity to strain and temperature of 1 $\mathrm{pm}/\mu\varepsilon$ and 10 $\mathrm{pm}/^{\circ}\mathrm{C}$, respectively, for a Bragg wavelength of 1550 nm, whereas the ones of a typical LPG is almost an order-of-magnitude higher [1]. In addition, even though the spectra of the gratings are assumed to be of Gaussian profiles in the theoretical analyses, practically, they are not an absolute requirement. As can be seen from Fig. 4, the spectrum of the hybrid FBG/LPG is not truly Gaussian but closely resembles a Gaussian distribution. This is described in detail in [16] from the mathematical view. Thus, the assumption of the grating spectra with the Gaussian profiles might slightly induce error in the measurement. Finally, the Gaussian profile of the EDG transmission spectrum might also induce some errors. Mathematically, an EDG transmission spectrum of a Dirac delta function with an infinite height and a unity area is preferable in scanning the spectrum of the hybrid FBG/LPG. However, for real implementation, the EDG involved in this experiment has a 3-dB bandwidth of ~0.8 nm. Compared with the ideal Dirac delta function, it might slightly affect the measurement accuracy. Better measurement accuracy could be achieved by introducing an EDG with a smaller 3-dB bandwidth according to the analysis presented in [17].

The proposed interrogation technique was shown to be capable of providing a better than 1-pm resolution and 24-nm interrogation range. It has the potential to stack several EDG-based interrogators together to increase the interrogation capacity beyond the current device capability for increased flexibility, in the use of the hybrid FBG/LPG for RI/temperature discrimination, at reduced weight, size, and cost.

V. CONCLUSION

A simultaneous interrogation technique based on a monolithically integrated EDG was proposed and demonstrated for the interrogation of hybrid FBG/LPG-based sensor pairs to perform discrimination of refractive index (RI)/temperature in the RI measurement. It has been noted that the transmission wavelength of an EDG can be monotonically tuned by changing the EDG chip temperature. Therefore, by knowing the monotonic temperature dependence of the EDG transmission wavelengths and the temperatures representing the dips of the transmission spectra of the FBG and LPG, respectively, the center wavelengths of the hybrid FBG/LPG sensor pair can be determined by a single measurement. A resolution of 1 pm and wavelength range of 24 nm are achieved by the proposed interrogation technique. This type of performance would be ideal for the RI/temperature discrimination of a hybrid FBG/LPG refractive index sensor pair. Furthermore, the interrogator presented here is capable of being applied in interrogating other sensor systems, such as tilted FBG sensors, superstructure FBG sensors, and Fabry–Perot-based sensors.

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