Interrogation of a Long-Period Grating Sensor by a Thermally Tunable Arrayed Waveguide Grating

Honglei Guo, Gaozhi Xiao, Nezih Mrad, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—An interrogation technique for a long-period grating (LPG) sensor is studied theoretically and experimentally. By employing a thermally tunable arrayed waveguide grating (AWG), the center wavelength of the LPG sensor is successfully measured using the linear temperature dependence of the AWG transmission wavelengths. Initial results show that the proposed interrogation technique can provide a resolution of 1 pm and interrogation range of 25 nm. Furthermore, this technique has the potential of being packaged into a low-cost and compact-size device.**

***Index Terms*—Arrayed waveguide grating (AWG), long-period grating (LPG), sensor interrogation.**

I. Introduction

LONG-PERIOD grating (LPG) fiber-optical sensors have been well documented for the applications in bio-chemical detection, industrial process monitoring, and structural health monitoring due to their low back-reflection [1] and high sensitivities [2]–[4]. The key practical challenge for LPG sensors is without doubt the wavelength interrogation of their large spectral band. So far, many schemes have been developed, such as optical spectrum analyzers, fiber Bragg gratings (FBGs) [5], and the derivative spectroscopy technique [6]. However, these interrogation techniques are not practical for most applications and can only be used in the laboratory environment because of the bulky size, high cost, poor robustness, and nonportability. In recent years, arrayed waveguide grating (AWG) demultiplexers have shown great potentials in the wavelength interrogation of FBG sensors [7]–[9]. In this letter, a thermally tunable AWG is applied to interrogate an LPG sensor. As shown by both theoretical and experimental analysis, the transmission wavelength of an AWG can be linearly tuned by changing the AWG chip temperature. Curve fitting and its first-order derivative are performed to obtain the temperature corresponding to the minimum detected light intensity of the LPG sensor from one of the AWG channels. The center wavelength of the LPG is then calculated by interpolating the above obtained temperature in the temperature dependence curve of the AWG transmission wavelengths. Using this technique, 1-pm wavelength interrogation resolution and 25-nm interrogation range have been achieved. Since the AWG chip is fabricated on a semiconductor wafer and the thermal tuning package can be miniaturized, the demonstrated interrogation technique can potentially lead to the development of a palm-size AWG-based LPG sensor interrogation system at low cost and with high performance.

II. Theory

As a Gaussian apodized LPG can be considered as having a flip-flop Gaussian profile [10], its spectrum can be expressed as

$$I_{\mathrm{LPG}}(\lambda) = I_0 - I_L \exp\left[-4\ln(2)\frac{(\lambda-\lambda_L)^2}{\Delta\lambda_L^2}\right] \tag{1}$$

where I_0 is a constant, $I_0 - I_L$ is the transmittance at the center wavelength λ_L, and $\Delta\lambda_L$ is the full-width at half-maximum (FWHM) of the Gaussian profile.

An AWG is an integrated all-solid-state device consisting of two couplers connected by an array of waveguides. The phase increment in each waveguide should be equal to an integer multiplied by 2π, so that the light beams of certain wavelengths from the arrayed waveguides will constructively interfere at various output channels. As reported in [11], the transmission spectrum of an AWG channel can be described mathematically by

$$A_j(\lambda) = a_j \exp\left[-4(\ln 2)\frac{(\lambda-\lambda_{aj})^2}{\Delta\lambda_{aj}^2}\right] \tag{2}$$

where a_j, λ_{aj}, and $\Delta\lambda_{aj}$ are the peak transmittance, center wavelength, and FWHM of the jth output channel of the AWG.

The LPG and AWG are cascaded in tandem. The light intensity detected by the jth AWG channel is given by [7]

$$I_j(\lambda_{aj}) \approx I_c - P_j \exp\left[-4\ln(2)\frac{(\lambda_{aj}-\lambda_L)^2}{\Delta\lambda_L^2+\Delta\lambda_{aj}^2}\right] \tag{3}$$

where I_c is a constant and P_j is the peak of the second term on the right side of (3), which is dependent on the optical source power, photodetector (PD) sensitivity, and the FWHM of both AWG and LPG.

Manuscript received May 05, 2008; revised June 24, 2008. First published August 22, 2008; current version published October 15, 2008. This work was supported in part by the Canadian Institute for Photonics Innovations, National Research Council Canada and by the Department of National Defence Canada.

H. Guo and J. Yao are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, ON K1N 6N5, Canada.

G. Xiao is with the Institute for Microstructural Science, National Research Council Canada, Ottawa, ON K1A 0R6, Canada (e-mail: George.Xiao@nrc-cnrc.gc.ca).

N. Mrad is with the Air Vehicles Research Section, Defence R&D Canada, Department of National Defence, National Defence Headquarters, Ottawa, ON K1A 0K2, Canada.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2004692

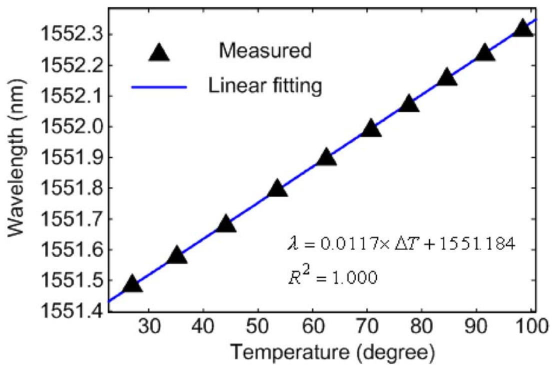

Fig. 1. Experimental result of the temperature dependence of a selected AWG channel.

It has been noted that the transmission wavelengths of an AWG changes linearly with the temperature [9], i.e.,

$$\lambda_{aj} = \beta \times T + \lambda_0 \tag{4}$$

where T is the AWG chip temperature, and β and λ_0 are constants, respectively.

By substituting (4) into (3), we obtain

$$I_j(T) \approx I_c - P_j \exp\left[-4\ln(2)\frac{(\beta \times T + \lambda_0 - \lambda_L)^2}{\Delta\lambda_L^2 + \Delta\lambda_{aj}^2}\right]. \tag{5}$$

Equation (5) shows that the $I_j(T)$ has a flip-flop Gaussian profile with the minimum value of $I_c - P_j$, which is achieved when $\lambda_L = \beta\times T + \lambda_0$. Hence, by knowing the temperature corresponding to the minimum of the detected light intensity and the temperature dependence of AWG transmission wavelengths, the center wavelength of an LPG can be determined.

III. Experimental Results and Discussion

To verify the temperature effect on the transmission wavelengths expressed by (4), one AWG channel (Channel 8 in this case) is selected and tested. The experimental result is shown in Fig. 1. In this test, the chip temperature is changed from 25.4 °C to 98.8 °C, while the transmission wavelengths are measured by an Agilent tunable laser source [(TLS) Agilent 81640B] with a tuning step of 1 pm and a PD. A linear fitting is applied to the results shown in Fig. 1 to obtain the constants β and λ_0. It is observed that the transmission wavelength of the AWG channel varies linearly with the temperature providing a tunable spectral range of ~0.8 nm for the temperature change of ~75 °C. Due to the uniformity of the AWG [12], all the other transmission channels possess the same tuning performance. Therefore, a 32-channel AWG with an interrogation range of ~25 nm is achieved and has the capability to interrogate most LPG sensors.

Furthermore, to evaluate the feasibility of the proposed interrogation scheme, an experimental interrogation setup illustrated in Fig. 2 is built.

The experimental setup shown in Fig. 2 consists of a broadband light source (BBS), an erbium-doped fiber amplifier

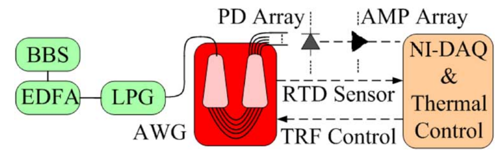

Fig. 2. Experimental setup for LPG interrogation based on a thermally tunable AWG.

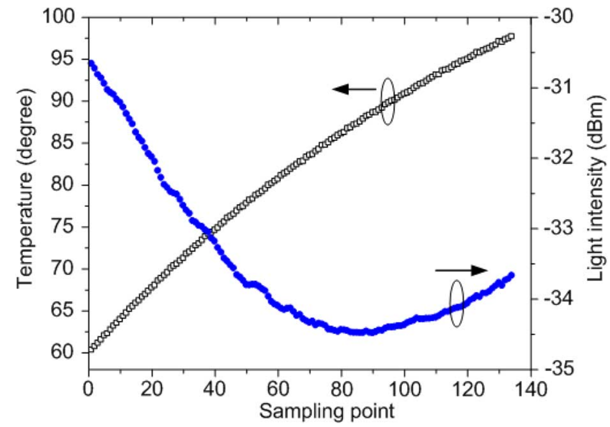

Fig. 3. Experimental results for LPG interrogation measured from the DAQ card.

(EDFA), a thermal resistant film (TRF), a resistance temperature detector (RTD), and a 32-channel AWG with 0.8-nm uniform channel spacing. The TRF is bonded at the back of the AWG chip and controlled by a Labview program. The RTD is implemented for the purpose of monitoring the temperature variation. Also, an array of PDs and operational amplifiers (AMPs) are used to acquire and amplify the light intensity from the AWG channels. A data acquisition (DAQ) card is used to perform the data acquisition for both temperature and light intensity. For simultaneous data acquisition, the LabView based triggering function is initiated so that temperature and light intensity are obtained at the same sampling points for each AWG output channel.

As shown in Fig. 3, one dedicated channel (Channel 8 in this case) with the tuning temperature from 60 °C to 98 °C is capable of obtaining the center part of the LPG spectrum, which is decided by the 3-dB bandwidth of the LPG being studied and the temperature dependence of the AWG transmission wavelengths. As to the other LPG with larger 3-dB bandwidth, the proposed interrogation technique allows for the use of two, three, or more AWG channels to obtain the LPG spectrum, since a continuous 25-nm scannable range can be achieved as discussed above.

Curve fitting of the detected light intensity and its first-order derivative with respect to the temperature are shown in Fig. 4 in solid and dashed lines, respectively. The temperature corresponding to the minimum light intensity is measured as 86.98 °C by analyzing the first-order derivative. Using the temperature dependence of the AWG transmission wavelengths discussed above, an LPG center wavelength of 1552.202 nm is obtained. The obtained results correlate well with the ones provided by the manufacturer and denoted as 1552.2 nm. Five repeating tests within 2 h show that the maximum variation obtained is 26 pm, which is believed to be partly attributed to

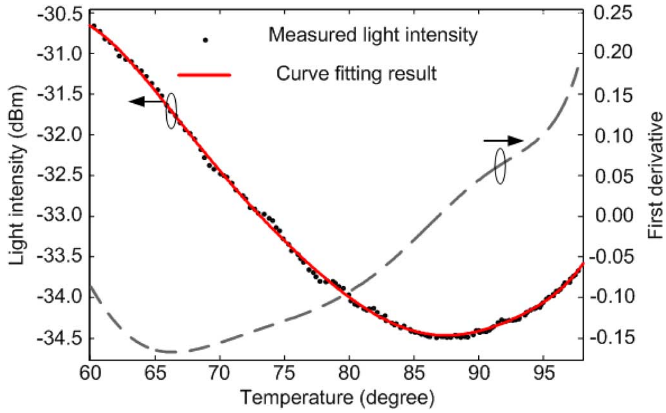

Fig. 4. Detected light intensity, curve fitting, and the first-order derivative versus the chip temperature.

the drifting of the ambient conditions during the experiment period, since a typical LPG has the sensitivity to strain and temperature almost an order-of-magnitude higher than 1 pm$/\mu\varepsilon$ and 10 pm$/^{\circ}$C, respectively, denoted as that of an FBG [1].

Additionally, an AWG transmission spectrum of a Dirac delta function with an infinite height and a unity area would be ideal for the scanning of the LPG spectrum. In this work, a commercial AWG demultiplexer chip from IgnisPhotonyx is used. The chip has a 3-dB bandwidth of $\sim$0.4 nm (a typical performance of commercially available AWG devices). This could also contribute to the measurement variation discussed above. According to the analysis in [13], the narrower the AWG transmission bandwidth, the less the measurement error will be. Therefore, using an AWG with a narrower transmission bandwidth could potentially improve the measurement accuracy.

Moreover, it can be deduced from Fig. 3 that AWG chip temperature dependence coefficient is 11.7 pm$/^{\circ}$C and its resolution is 3.16 pm for a TRF temperature increment step of 0.27 °C. If the curve fitting is employed, calculating its first-order derivative with the temperature increment step of 0.1 °C, an interrogation resolution of 1 pm can be achieved. A better than 1-pm resolution will be theoretically achieved by reducing the temperature increment step in calculating the first-order derivative and increasing the resolution of the TLS.

The presented high-resolution AWG-based approach employed for the interrogation of LPG would be particularly attractive for the refractive index estimation in chemical sensors, such as a chemical concentration sensor which requires a spectral resolution of 10 pm in a 60-nm range [14]. The 25-nm interrogation capacity of the presented device in this letter can be increased by stacking several properly designed AWGs, providing added flexibility for the applications requiring wide spectral interrogation range. Moreover, this technique has the potential of being packaged into a low-cost and compact-size device.

IV. Conclusion

The interrogation of an LPG sensor was achieved by thermally scanning an AWG. The experimental results showed that the transmission wavelengths of AWG channels shifted linearly with the temperature. By calculating the temperature corresponding to the minimum of the detected light intensity and employing the temperature dependence curve of the AWG transmission wavelengths, the center wavelength of the LPG sensor was successfully measured. It was also shown that the use of the proposed thermally tunable AWG technique provided a 25-nm interrogation range at resolution of 1 pm with the additional features of compact size, low cost, and suitability for practical applications.

References

[1] V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors," *Opt. Lett.*, vol. 21, pp. 692–694, 1996.
[2] B. H. Lee and J. Nishii, "Temperature sensor using the self-interference of a long-period fiber grating," *Proc. SPIE*, vol. 3746, pp. 418–421, 1999.
[3] S. W. James and R. P. Tatam, "Optical fibre long-period grating sensors: Characteristics and application," *Meas. Sci. Technol.*, vol. 14, pp. R49–R61, 2003.
[4] S. Khaliq, S. James, W. Stephen, and R. P. Tatam, "Fiber-optic liquid-level sensor using a long-period grating," *Opt. Lett.*, vol. 26, pp. 1224–1226, 2001.
[5] C. C. Chiang, C. S. Shin, and S. K. Liaw, "An intensity modulation based high-speed and high-resolution long-period fiber grating sensor interrogating system," *Proc. SPIE*, vol. 6377, pp. 63770W1–63770W7, 2006.
[6] T. Allsop, T. Earthrowl, R. Reeves, D. J. Webb, and I. Bennion, "The interrogation and multiplexing of long period grating curvature sensors using a Bragg grating based, derivative spectroscopy technique," *Meas. Sci. Technol.*, vol. 15, pp. 44–48, 2004.
[7] Y. Sano and T. Yoshino, "Fast optical wavelength interrogator employing arrayed waveguide grating for distributed fiber Bragg grating sensors," *J. Lightw. Technol.*, vol. 21, no. 1, pp. 132–139, Jan. 2003.
[8] M. Teshima, M. Koga, and K. Sato, "Multiwavelength simultaneous monitoring circuit employing wavelength crossover properties of arrayed-wave-guide grating," *Electron. Lett.*, vol. 31, pp. 1595–1597, 1995.
[9] G. Z. Xiao, P. Zhao, F. G. Sun, Z. G. Lu, Z. Y. Zhang, and C. P. Grover, "Interrogating fiber Bragg grating sensors by thermally scanning a demultiplexer based on arrayed waveguide gratings," *Opt. Lett.*, vol. 29, pp. 2222–2224, 2004.
[10] T. Erdogan, "Fiber grating spectra," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1277–1294, Aug. 1997.
[11] H. Takahashi, K. Oda, H. Toba, and Y. Inoue, "Transmission characteristics of arrayed waveguide $N \times N$ wavelength multiplexer," *J. Lightw. Technol.*, vol. 13, no. 3, pp. 447–455, Mar. 1995.
[12] K. Okamoto, "Recent progress of integrated optics planar lightwave circuits," *Opt. Quantum Electron.*, vol. 31, pp. 107–129, 1999.
[13] F. G. Sun, G. Z. Xiao, Z. Y. Zhang, and Z. G. Lu, "Modeling of arrayed gratings for wavelength interrogation application," *Opt. Commun.*, vol. 271, pp. 105–108, 2007.
[14] T. Allsop, L. Zhang, and I. Benion, "Detection of organic aromatic compounds by a long period fibre grating optical sensor with optimized sensitivity," *Opt. Commun.*, vol. 191, pp. 181–190, 2001.