Interrogation of a Long Period Grating Fiber Sensor With an Arrayed-Waveguide-Grating-Based Demultiplexer Through Curve Fitting

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

***Abstract*—Interrogation of a long period grating (LPG) fiber sensor with an arrayed-waveguide-grating (AWG)-based demultiplexer through curve fitting is investigated and experimentally demonstrated. In the interrogation system, the measured light intensities from the output of the AWG are used to reconstruct the selected resonant dip of the LPG sensor through curve fitting in the form of a linear combination of Gaussian functions. By monitoring the changes of the reconstructed LPG spectrum, including the center wavelength shift and the minimum attenuation variation, the sensor signals can be interrogated with good accuracy in real time. The center wavelength is obtained by calculating the first-order derivative of the fitting function. The minimum attenuation is obtained directly from the reconstructed spectrum. Since the interrogation system demonstrated is based on an all-solid-state optical device, it offers the advantages of compact size and high-speed interrogation with high potential for integration.**

***Index Terms*—Arrayed waveguide grating (AWG), curve fitting, long period grating (LPG), sensors, wavelength.**

I. Introduction

LONG-PERIOD-GRATING-(LPG)-based fiber-optic sensors have become an important tool for monitoring temperature [1], [2], strain [2], [3], and refractive index [4], [5]. These optic sensors are with the advantageous features such as small size, light weight, high sensitivity, long-term stability, and immunity to corrosion [6] and electromagnetic interferences. In an LPG-based sensor, environmental changes are reflected as the center wavelength shift and the minimum attenuation variation of the selected LPG resonant dip [3]. One of the challenges in using an LPG for environmental sensing is how to interrogate the signal from the LPG transmission spectrum, due to the large spectral range of the resonant dip. An optical spectrum analyzer (OSA) is usually adopted in an interrogation system together with a broadband optical source. However, this approach is not practical for most of the applications due to the large size and high cost of an OSA. Several other techniques have been proposed to interrogate the center wavelength of an LPG without using an OSA, such as the intensity interrogation scheme based on the reflection of a fiber Bragg grating (FBG) [7] and the derivative spectroscopy technique [8]. However, these techniques may not satisfy all the LPG interrogation requirements such as fast speed, immunity to harsh environments, compact size, and low cost. In addition, the techniques in [7] and [8] are not capable of interrogating the minimum attenuation variation of the selected resonant dip.

Arrayed waveguide gratings (AWGs) have been developed for wavelength division multiplexing/demultiplexing in DWDM optical communication systems [9]. An AWG is an integrated all-solid-state device with an array of narrow optical channels on a planar waveguide which can separate multiple wavelengths simultaneously without any mechanical movement [10], [11]. AWGs have been used to interrogate FBG sensors [12], [13] and have demonstrated superior performance. The difference between an FBG sensor and an LPG sensor is that an LPG has a much larger spectral range of the resonant dip. Therefore, to interrogate accurately the wavelength shift and the minimum attenuation variation, the sensing data must be processed. In this paper, an AWG-based demultiplexer is proposed to interrogate an LPG sensor by reconstructing the spectrum of the selected LPG resonant dip through curve fitting. Both theoretical analysis and experimental implementation are presented. It is found that the selected LPG resonant dip has a spectral profile that is a linear combination of Gaussian functions. Therefore, we propose to use a linear combination of Gaussian functions to reconstruct the spectral profile of the LPG resonant dip via curve fitting. We demonstrate that the form of the linear combination of Gaussian functions can be selected by the level of the root mean square (RMS) error. An experimental system that consists of an LPG and an AWG is constructed. Curve fitting is performed for a selected resonant dip of the LPG using the measured light intensities obtained from the multichannel outputs of the AWG. The center wavelength of the resonant dip is obtained by calculating the first-order derivative of the fitting function. The minimum attenuation is obtained directly from the reconstructed spectrum. The LPG interrogation system demonstrates the features of fast speed, high resolution, compact size, and low cost.

II. Interrogation Principle

We assume that the resonant dip of an LPG has a spectral profile that can be described as a linear combination of Gaussian

Manuscript received January 25, 2008; accepted April 01, 2008. Current version published October 22, 2008. This work was supported in part by the Canadian Institute for Photonics Innovations and in part by the Natural Sciences and Engineering Research Council of Canada (NSERC). The associate editor coordinating the review of this paper and approving it for publication was Prof. Gerald Gerlach.

H. Guo and J. Yao are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa ON K1N 6N5, Canada (e-mail: jpyao@site.uottawa.ca).

G. Xiao is with the Institute for Microstructural Science, National Research Council Canada, Ottawa ON K1A 0R6, Canada.

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

Digital Object Identifier 10.1109/JSEN.2008.2004472

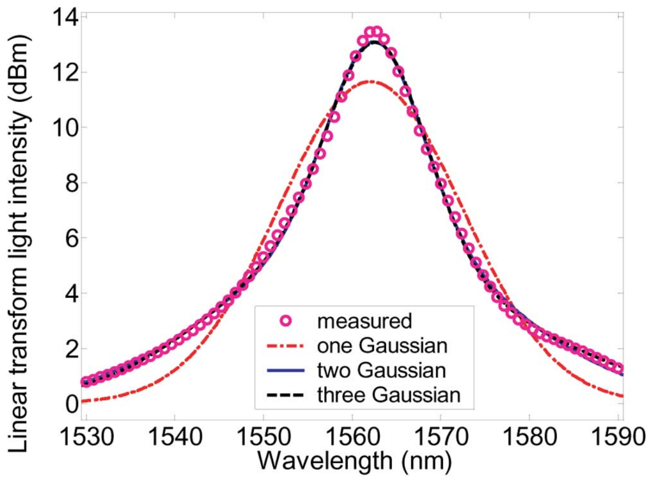

Fig. 1. Curve fitting of the spectra of the resonant dip of LPG1 using a linear combination of one, two, and three Gaussian functions.

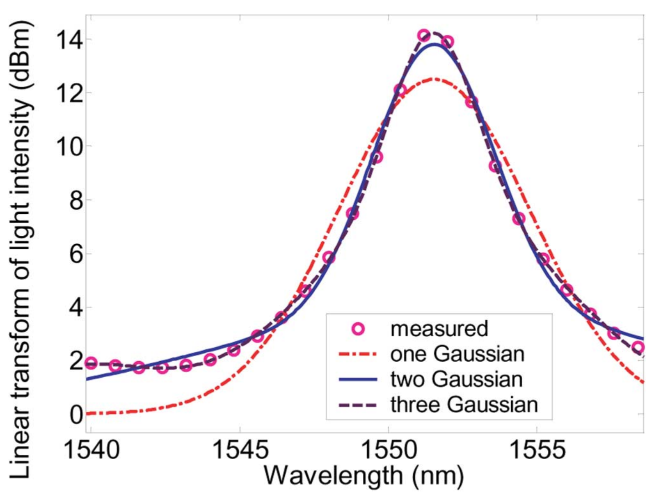

Fig. 2. Curve fitting of the spectra of the resonant dip of LPG2 using a linear combination of one, two, and three Gaussian functions.

functions. To simplify the analysis, we introduce a constant l_0 such that the spectral function of an LPG resonant dip can be written as

$$L(\lambda) = l_0 - \sum_{n=1}^{N} l_n \exp\left[-\frac{(\lambda - \lambda_{\text{ln}})^2}{\Delta\lambda_{\text{ln}}^2}\right] \quad (1)$$

where l_n, λ_{ln}, and $\Delta\lambda_{\text{ln}}$ are, respectively, the peak transmittance, the center wavelength, and the full width at half maximum (FWHM) of the Gaussian function, and N is the number of Gaussian functions in the linear combination.

The validity of the assumption in (1) is experimentally verified, where the spectra of two LPGs (LPG1 and LPG2) are reconstructed using the fitting function in (1) with N being 1, 2, and 3. The results are shown in Figs. 1 and 2.

The performance of the curve fitting is evaluated by calculating the RMS error. For LPG1, the measured spectrum of the selected resonant dip is shown in Fig. 1 (dotted line). Curve fitting using one Gaussian function (dash-dotted line), a linear combination of two Gaussian functions (solid line), and three Gaussian functions (dashed line) are performed to reconstruct the selected resonant dip. The parameters of the peak transmittances, the center wavelengths, and the FWHMs of the Gaussian functions in the fitting functions are $\{11.65, 1562, 14.7\}$, $\{(7.073, 1563, 7.511); (6.042, 1561, 22.06)\}$, and $\{(7.334, 1563, 7.705); (2.49, 1569, 24.34); (3.802, 1557, 18.85)\}$ for the one Gaussian, two Gaussian, and three Gaussian functions, respectively. The RMS errors are calculated to be 0.116, 0.094, and 0.092, respectively. As can be seen the use of a combination of two or three Gaussian functions presents a better curve fitting than one Gaussian function. For LPG2, the measured spectrum of the selected resonant dip is shown in Fig. 2 (dotted line). Curve fitting using one Gaussian function (dash-dotted line), a linear combination of two Gaussian functions (solid line) and three Gaussian functions (dashed line) are performed, with the results also shown in Fig. 2. The parameters of the peak transmittances, the center wavelengths, and the FWHMs of the Gaussian functions in the fitting functions are $\{12.51, 1552, 4.578\}$, $\{(10.05, 1552, 2.88); (3.763, 1552, 11.85)\}$, and $\{(1.687, 1540, 3.674); (7.76, 1552, 6.083); (6.468, 1551, 2.044)\}$ for the one Gaussian, two Gaussian, and three Gaussian functions, respectively. The RMS errors are calculated to be 1.198, 0.352, and 0.115. Again, a better curve fitting is achieved with a fitting function that is a combination of two or three Gaussian functions. The experiments have verified that the spectrum of a LPG resonant dip can be approximated using a linear combination of Gaussian functions. The level of RMS errors provides a measure to evaluate the curve fitting accuracy when different number of Gaussian functions is applied.

In the proposed interrogation system, an AWG is used to sample the spectrum of the resonant dip. The dip spectrum is measured at discrete wavelengths which are fixed with a given AWG. For an AWG with n channels, n light intensities at n different wavelengths are obtained through only a one-time measurement. Based on the sampling theory, a sampled signal can be completely reconstructed if the sampling frequency is twice the maximum frequency of the signal. Mathematically, the sampling function is a Dirac delta function, which has an infinite height, but a unity area. For real implementation, however, we may use a sampling function which is narrow in width with a unity area. This can be realized by an AWG. For a state-of-the-art AWG, the transmittance and the FWHM of all the channels are considered identical. In addition, the FWHM is much smaller than that of the LPG dip spectrum. Therefore, it is feasible to use an AWG to sample the LPG dip spectrum and to reconstruct the spectrum through curve fitting with the use of the sampled light intensities. The center wavelength of the resonant dip is obtained by calculating the first-order derivative of the fitting function. The attenuation is obtained directly from the reconstructed spectrum.

III. Experimental Result and Discussions

The proposed interrogation system is experimentally evaluated. The experimental setup is shown in Fig. 3, which consists of an optical broadband source (BBS), an AWG, and a photodiode array. Two erbium-doped fiber amplifiers (EDFAs) are

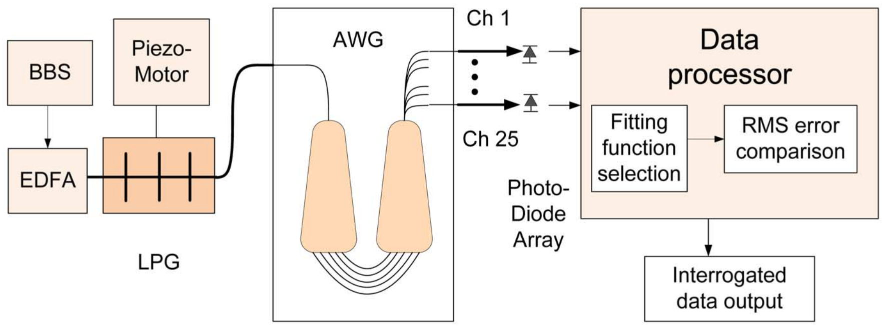

Fig. 3. An LPG sensor interrogation system using an AWG.

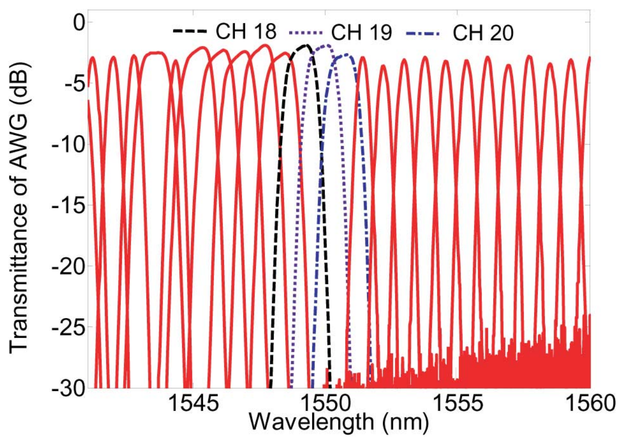

Fig. 4. The transmission spectrum of the AWG. The dashed line, dotted line and dash-dot line show the spectra for Channels 18, 19, and 20, respectively.

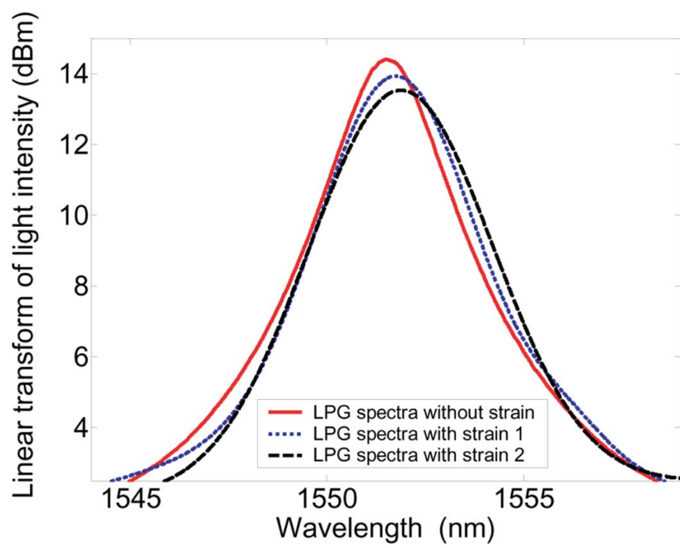

Fig. 5. LPG spectra with different strains.

incorporated in the system before the LPG to boost up the optical power. The measured light intensities at the outputs of the photodiode array are sent to a digital data processor. The data processor performs the functions including curve fitting, RMS error calculation, and the estimation of the center wavelength shift and the minimum attenuation variation.

As the BBS available in the lab has an output power of about -45 dBm, the two EDFAs with a total gain of about 45 dB are used to increase the power level to about 0 dBm before the light enters into the LPG. A Piezo motor is used to control the strain applied to the LPG to shift the spectrum of the resonant dip. The proposed interrogation scheme is then used to interrogate the spectrum of the LPG resonant dip with different strains. The AWG has 32 channels with a wavelength spacing of 0.8 nm. The transmission spectrum of the AWG is shown in Fig. 4. In the experiment, 25 channels that have their center wavelengths within the spectrum range from 1540.32 to 1561.64 nm, same as that of the LPG resonant dip, are used to measure the light intensities with a photodiode array.

In processing the sensing data, the RMS error is used to select the number of Gaussian functions in the linear combination, since the curve fitting functions might be only one Gaussian function, a linear combination of two or three Gaussian functions. In Figs. 1 and 2, it is seen that the RMS error is dependent on the number of Gaussian functions used in the curve fitting. In most of the cases, a linear combination of two Gaussian functions provides the best tradeoff in terms of the simplicity and the accuracy to reconstruct the spectrum, while maintaining a small RMS error. In addition, the use of a linear combination of two Gaussian functions would make the fitting more robust than the use of three or more Gaussian functions, to ensure that the fitting process will converge [14]. Then, the center wavelength of the resonant dip is obtained by calculating the first-order derivative. The minimum attenuation is obtained by linearly transforming the peak transmittance of the reconstructed spectrum.

LPG2 shown in Fig. 2 is used in the experiment. To verify the validity of this interrogation technique, a Piezo motor is introduced to apply strain to the LPG. Three different transmission spectra with three different strains applied to the LPG are observed, as shown in Fig. 5.

The solid curve in Fig. 5 shows the LPG spectrum without applying any strain, the center wavelength is 1551.65 nm measured using an OSA with a minimum attenuation of -14.7 dB; the dotted and the dashed curves show the LPG spectrum with two different strains (Strain 1 and Strain 2), the center wavelengths are, respectively, 1551.85 and 1552.05 nm measured using the OSA with the minimum attenuations of -14 and -13.2 dB. The attenuation variations between the two adjacent measurements are 0.7 and 0.8 dB.

For the three cases, the light intensities are measured using a photodiode array that is connected to the 25 output channels

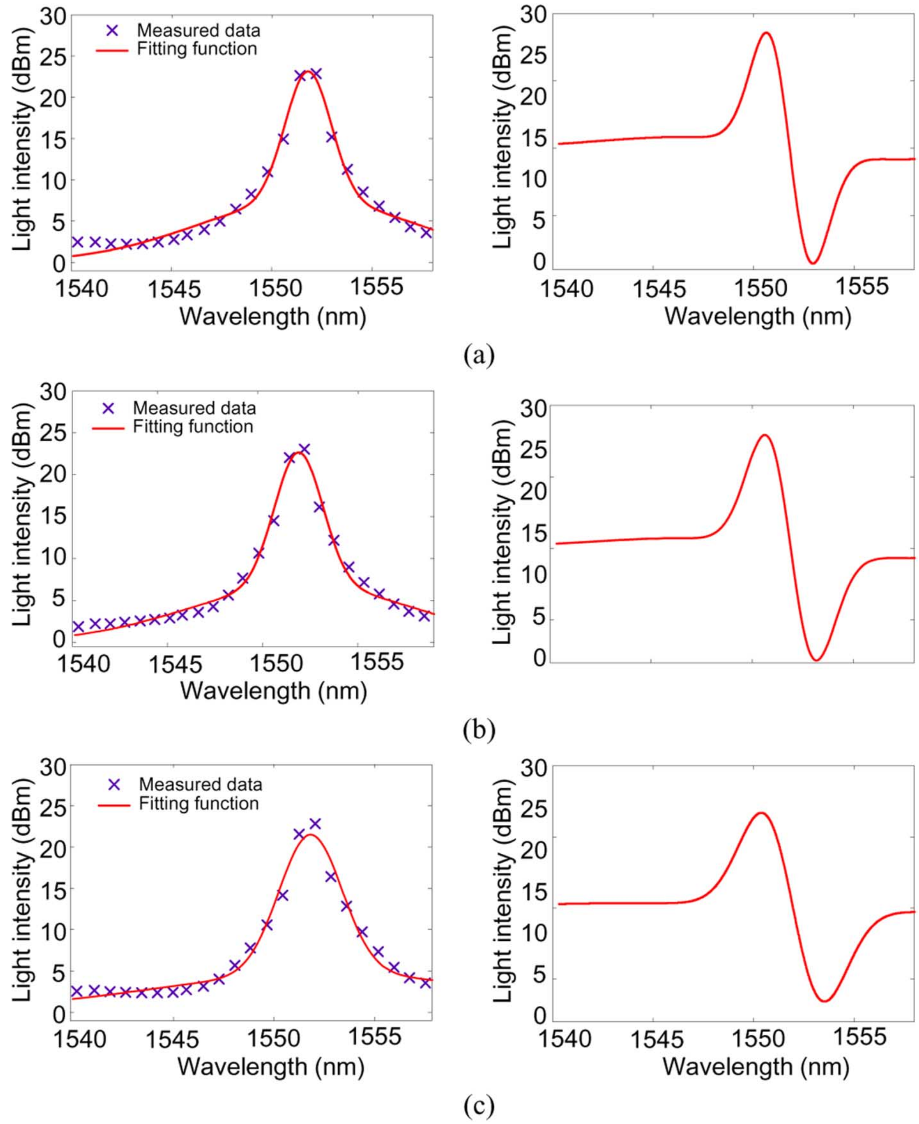

Fig. 6. Curve fitting functions (left) and the first-order derivatives (right) for three different strains applied to the LPG. (a) LPG without strain. (b) LPG with Strain 1. (c) LPG with Strain 2.

of the AWG. As discussed above, by considering the simplicity, the accuracy, and the convergence of the fitting, a linear combination of two Gaussian functions is selected to provide the best tradeoff. The fitting function consisting of two Gaussian functions has a form of

$$L(\lambda)=a_1\exp\left\{-\left[\frac{(\lambda-b_1)}{c_1}\right]^2\right\}+a_2\exp\left\{-\left[\frac{(\lambda-b_2)}{c_2}\right]^2\right\} \quad (2)$$

Applying the fitting function in (2) for the three cases in our experiment, we obtain the reconstructed spectrum, which are shown in Fig. 6(a)–(c). The parameters in (2) for the three cases are shown in Table I.

The center wavelength is then obtained from the first-order derivative of (2). In the data processing, a 0.01 nm wavelength resolution is employed to calculate the derivative. Fig. 6 shows the curve fitting functions and the first-order derivatives for three different strains applied to the LPG.

TABLE I
PARAMETERS IN THE LINEAR COMBINATION OF TWO GAUSSIAN FUNCTIONS

LPG spectra	a_1	b_1	c_1	a_2	b_2	c_2
Fig. 6(a)	15.61	1552	1.615	7.514	1552	7.754
Fig. 6(b)	15.911	1552	1.787	6.741	1552	8.351
Fig. 6(c)	16.85	1552	2.21	4.675	1553	12.2

The center wavelengths estimated based on the proposed technique are 1551.72, 1551.92, and 1552.02 nm. The differences between these center wavelengths and the values obtained from an OSA are 0.07, 0.07, and 0.03 nm. Directly from the fully reconstructed spectra in Fig. 6, we obtain the minimum attenuations, which are −23.1, −22.5, and −21.3 dB. Compared with the attenuations measured using the OSA, the differences between these minimum attenuations and the values obtained from the OSA are all smaller than 0.1 dB.

The channel spacing of the AWG used in the experiment is 0.8 nm. The FWHM of the LPG resonant dip is around 8 nm, within which only 8 to 10 channels of the AWG outputs are employed in the curve fitting. If more output channels are located in the range of the resonant dip, the sampling spacing would be decreased with more sampling points introduced in the curve fitting, which would improve the fitting accuracy. Taking an AWG with a channel spacing of 0.4 nm, for an example, the sampling spacing is reduced to half, with twice the number of sampling points included in the curve fitting. Therefore, the estimation errors would be significantly decreased. In addition, the AWG used in the experiment has nonuniform transmission spectra throughout the channels, as shown in Fig. 4, especially channels 18–20. The nonuniform channel spectra would cause measurement errors in obtaining light intensities, with which the curve fitting would lead to a large estimation error. Comparing Figs. 4 and 5, we find that the three channels contribute more to the measurement errors in the spectra of solid and dotted curve than that of dashed curve in Fig. 5. This is the reason why the spectra of dashed curve in Fig. 5 have a better measurement result than the other two spectra. Therefore, an AWG with a uniform transmission spectrum can furthermore reduce the measurement errors.

In the proposed system, the intensities at the sampling points are obtained in real-time thanks to the use of a high-speed photodiode array. Thus, the LPG itself is assumed not affected by the environmental changes in such a short time.

IV. Conclusion

An interrogation system for an LPG sensor based on an AWG was demonstrated using curve fitting in the form of a linear combination of Gaussian functions. The light intensities at different wavelengths were sampled by the AWG and were used to perform the curve fitting. An experiment was performed to demonstrate the proposed system. In the experiment, an LPG with three different strains was successfully interrogated, with a wavelength estimation error as small as 0.07 nm. The measured minimum attenuation variations from the reconstructed spectra were 0.6 and 0.8 dB, compared with 0.7 and 0.8 dB from an OSA. The proposed system could be improved if an AWG with smaller wavelength spacing is employed.

References

[1] 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, Sep. 1999.

[2] J. A. Besley, T. Wang, and L. Reekie, "Fiber cladding mode sensitivity characterization for long-period gratings," *J. Lightwave Technol.*, vol. 21, pp. 848–853, Mar. 2003.

[3] S. W. James and R. P. Tatam, "Optical fiber long-period grating sensors: Characteristics and application," *Meas. Sci. Technol.*, vol. 14, pp. R49–R61, Mar. 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, no. 16, pp. 1224–1226, Aug. 2001.

[5] M. N. Ng, Z. Chen, and K. S. Chiang, "Temperature compensation of long-period fiber grating for refractive-index sensing with bending effect," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 361–362, Mar. 2002.

[6] K. R. Cooper, J. Elster, M. Jones, and R. G. Kelly, "Optical fiber-based corrosion sensor system for health monitoring of aging aircraft," *Proc. AUTOTESTCON*, pp. 847–856, Aug. 2001.

[7] 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, Nov. 2006.

[8] 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, Jan. 2004.

[9] Y. Sano and T. Yoshino, "Fast optical wavelength interrogator employing arrayed waveguide grating for distributed fiber Bragg grating sensors," *J. Lightwave Technol.*, vol. 21, pp. 132–139, Jan. 2003.

[10] H. Takahashi, K. Oda, H. Toba, and Y. Inoue, "Transmission characteristics of arrayed waveguide $N \times N$ wavelength multiplexer," *J. Lightwave Technol.*, vol. 13, pp. 447–455, Mar. 1995.

[11] K. Okamoto, "Fundamentals, technology and applications of AWGs," *Proc. 24th ECOC.*, vol. 2, pp. 7–47, Sep. 1998.

[12] M. Teshima, M. Koga, and K. Sato, "Multiwavelength simultaneous monitoring circuit employing wavelength crossover properties of arrayed-wave-guide grating," *Electron. Lett.*, vol. 31, no. 18, pp. 1595–1597, Aug. 1995.

[13] 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, no. 19, pp. 2222–2224, Oct. 2004.

[14] Y. Hu, J. Liu, and W. Li, "Resolution of overlapping spectra by curve-fitting," *Analytica Chimica Acta*, vol. 538, no. 1–2, pp. 383–389, May 2005.

Honglei Guo (S'08) received the M.S. degree in optics from Nankai University, Tianjin, China, in 2006. He is currently working towards the Ph.D. degree in the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada.

His current research interests include fiber-optic sensors, sensor interrogation systems, and microwave photonics.

Gaozhi (George) Xiao received the Ph.D. degree from Loughborough University of Technology, Leicestershire, U.K., in 1995.

He is currently a Senior Research Officer with the Institute for Microstructural Science, National Research Council of Canada. His research work mainly focuses on the development of micro fiber-optic sensor systems for aerospace applications and physical-chemical sensing applications.

Jianping Yao (M'99–SM'01) received the Ph.D. degree in electrical engineering from the Université de Toulon, Toulon, France, in 1997.

He joined the School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada, in 2001, where he is currently a Professor, Director of the Microwave Photonics Research Laboratory, and Director of the Ottawa–Carleton Institute for Electrical and Computer Engineering. From 1999 to 2001, he held a faculty position with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He holds a guest professorship at Shantou University and Sichuan University, China. He spent three months as an Invited Professor in the Institut National Polytechnique de Grenoble, France, in 2005. He is an Associate Editor of the *International Journal of Microwave and Optical Technology*. He is on the Editorial Board of the IEEE Transactions on Microwave Theory and Techniques. He has published over 100 papers in refereed journals and over 90 papers in conference proceeding. His research has focused on microwave photonics, which includes all-optical microwave signal processing, photonic generation of microwave, mm-wave and THz, radio over fiber, UWB over fiber, fiber Bragg gratings for microwave photonics applications, and optically controlled phased array antenna. His research interests also include fiber lasers, fiber-optic sensors and biophotonics.

Dr. Yao received the 2005 International Creative Research Award from the University of Ottawa. He was the recipient of the 2007 George S. Glinski Award for Excellence in Research. He was named University Research Chair in Microwave Photonics in 2007.

Dr. Yao is a registered Professional Engineer of Ontario. He is a member of SPIE and OSA.