Automated multichannel broadband spectrum analysis of fiber-optic grating sensors

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***Abstract* – In this paper we report methods for spectrum analysis and data processing algorithms. An automated multi-channel spectrum measurement system is introduced with controlled fiber-optic signal switching and spectra analysis with linear CCD photodiode array, diffraction grating and precise stepper motor. The designed system demands advanced measurement and data processing techniques. The paper reports the implemented methods for automated multi-channel measurements, accuracy improvement, noise cancellation techniques and fiber-optic grating sensor measurements**

Keywords – **long-period grating sensors, fiber-optic sensor interrogation and multi-channel spectrum measurement.**

I. INTRODUCTION

Over the past decade optical fiber-based sensors are gaining significant progress and popularity. Optical fiber gratings are often classified as Fiber Bragg gratings (FBGs) and Long Period gratings (LPGs) [5]. Because of the large periodicity, LPGs are usually easier to fabricate in mass production in comparison with FBGs. LPGs have found applications in various devices like equalizers for erbium doped fiber amplifiers, band-rejection filters and sensors for strain and temperature [3]. Because of their great width, spectral multiplexing is limited; the absence of a reflected signal demands detection of center wavelength shifts in a noisy minimum; and since resonance coupling in LPGs is to a cladding mode, the fiber typically has to be stripped, which creates challenges for long-term reliability and packaging.

On the other hand, LPGs are sensitive to a number of physical quantities such as surrounding refractive index, hydrostatic pressure, bending and twisting. They therefore offer significant application opportunities. However, in order to reduce the effective price per sensor, simple and efficient multiplexing systems must be developed. Wavelength and time-division multiplexing are well advanced with FBG sensor networks [1,2], but comparatively little has been reported on the multiplexing of LPGs [10]. Also a precise stepper motor is introduced to extend measured spectrum range and resolution by rotating the diffraction grating. Precise stepping drives are presented in [12, 13], where improvement in position accuracy and micro-stepping control is applied.

In this paper we report on the further development of a previously proposed spectrally and spatially multiplexed sensor network using an InGaAs CCD photodiode array and opto-mechanic switches. We also present results on the implemented methods for automated multi-channel measurements, accuracy improvement and noise cancellation techniques and fiber-optic grating sensor measurements..

II. MULTI-CHANNEL SPECTRUM MEASUREMENT SYSTEM

A. System description

The basic scheme of the multi-channel spectral measurement system is shown in Fig. 1. The radiation of a C+L band amplified spontaneous emission (ASE) broadband source (Joinwit) is coupled to port 1 of a 3-port optical circulator. Light reflected from the end of each channel is redirected from port 2 to port 3 and then to the diffraction-grating-based spectrometer and the CCD photodiode array detector [4].

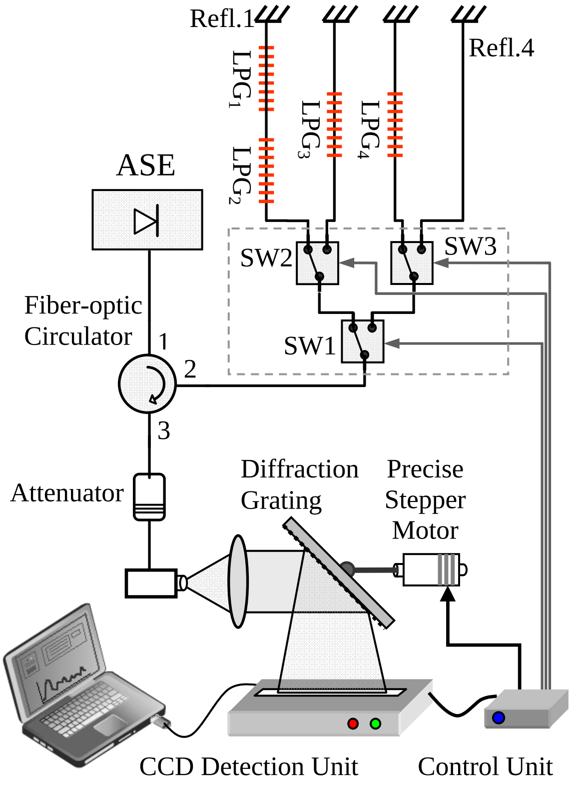

Fig. 1. Multi-channel spectrum measurement system

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At port 2 there is an arrangement of three electrically controlled 1x2 fiber optic switches that allow an arbitrary access to four sensing channels, which can accommodate up to four LPGs depending on their bandwidth and sensitivity to a particular physical quantity [9, 14]. At the end of each channel there is a tunable reflector which returns light back to the sensing channel and through port 3 the light is collimated onto a 600 lines/mm diffraction grating so the spectrum is observed by a CCD photodiode array.

The four measured fiber-optic channels are set in the following configuration – in Ch.1 two LPG sensors are placed, Ch2 and Ch.3 investigate single LPG and Ch.4 is utilized to perform reference signal measurement and system calibration with the ASE light source.

B. Detection and control devices

The detection unit is based on a 512-pixel InGaAs CCD (G9204-512D – Hamamatsu Photonics) linear array with an integrated low-noise charge-amplifier featuring high sensitivity, a low dark current and high stability in the 800-1750 nm spectral range Two high-speed capacitive-based analog-digital converters (ADCs) transform the analog data from the CCD sensor into 16-bit corresponding digital values.

The obtained data from the CCD array is filtered and further transmitted via USB interface to a personal computer. The interrogation system is operated and configured by an application using a Lab-View programming environment [8] which allows an individual settings for the parameters - integration time (τ), sensor sensitivity (s), conversion speed, data communication speed (r)., has start, stop and pause functions to be manually configured. Dark current can be subtracted after averaging, reference and the current signal can be read, and the signal-to-reference ratio will be presented in dB on the screen [11].

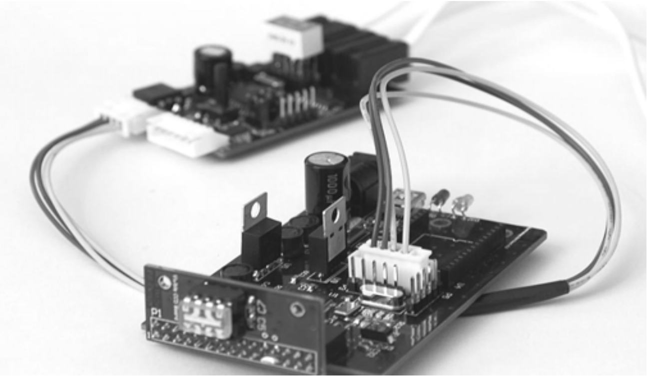

Fig. 2. Photographs of CCD Detection Unit and control device

The communication protocol between personal computer and devices is command-based – via the LabView application a command is transmitted to the CCD detection unit and it responds with corresponding packet of data or device status. If command is intended to adjust or acquire status for fiber-optic switches' position or stepper motor position then the CCD detection unit retransmits the command to the control device.

The LabView application automatically configures diffraction grating angle position via the precise stepper motor and the measured channel. After the current channel is measured and visualized, the program automatically configures the next channel for measurement.

C. Correlation analysis for accuracy improvements and noise cancellation

Correlation analysis in two separate spatially shifted signals is introduced to increase accuracy of spectral measurement and to reduce signal noises. The measured broadband signals from fiber-optic sensors are spectrally resolved on the linear CCD photodiode array. To perform a spatial shift of the signal a precise stepper motor is implemented. It rotates the diffraction grating with 0.1deg accuracy.

$$\begin{aligned} R(\tau) &= \sum_{\tau} f_1(n) f_2(n+\tau) \\ R(\tau_{\max}) &= \max \end{aligned} \qquad (1)$$

With cross-correlation function (1) the exact signal shift is calculated and any difference in signals is analyzed [6, 15]. In this way the multiple spatially shifted measurement of an identical signal may result in increased spectral measurement resolution.

On Fig.3a two measurements with spatial shift are presented. The cross-correlation function (R(τ)) and exact shift are calculated. The optimal signal match is achieved at maximum of R(τ) and the exact shift (τ) is calculated.

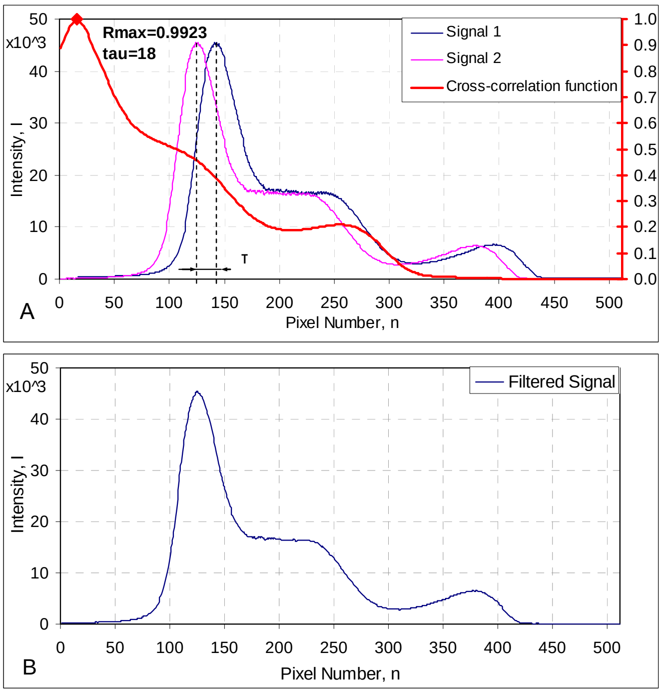

Fig.3. Correlation analysis of two shifted spectrum measurements-A, Noise suppression with spatially shifted measurements-B

To filter any noise resulting from signal conversion or in photodiode array and channel inequalities an averaging low-pass filter with respect to the spatial signal shift is designed (2). It averages N-shifted spectral measurements with the initial signal [7]. Since the correlation function is preliminarily calculated and the exact shift is acknowledged, the average signal is calculated and noises are filtered

$$S(n)=\frac{1}{N+1}\sum_{k=0}^{N}S_k(n-\tau_k) \qquad (2)$$

$$\tau_{k=0}=0$$

By introducing this filtering scheme the acquired spectrum preserves any narrow minima in measured grating sensors but also suppresses noises due to conversion or channel inequalities in CCD array. The resulting filtered signal is presented on Fig.3b.

III. EXPERIMENTAL SET-UP AND MEASUREMENT RESULTS

The designed multi-channel broadband spectrum measurement system is tested by analysing four different long period grating sensors arranged in three channels. On Ch.4 only a tuneable reflector was connected and this channel was utilized as reference signal. A joint multiple channel graphic is presented on Fig.4 with relative measurement to the reference signal.

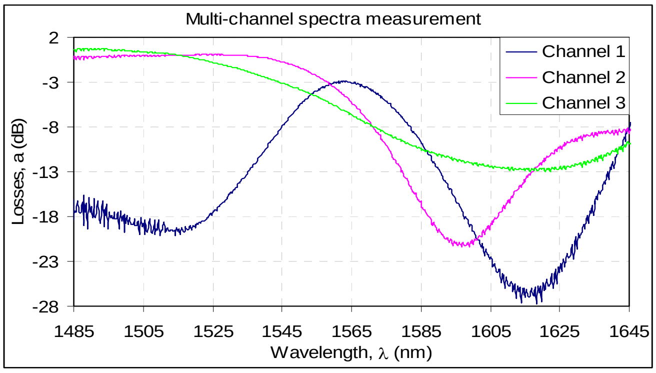

Fig. 4. Joint multi-channel spectral response measurement

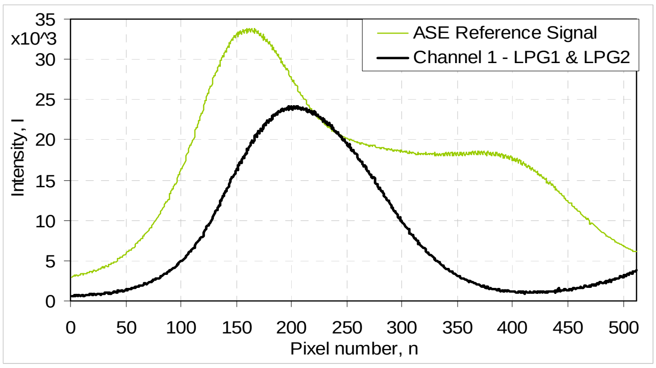

Fig. 5. Channel 1 LPGs' signal compared to reference spectrum

The results from measurements of the transmission spectra in Channel 1 are shown in Fig.5. Fig.6 presents linear change of spectrum change with two LPG sensors compared to the reference ASE broadband light source. The same results are shown for Ch.2 and Ch.3 respectively in Fig.7-8 and Fig.9-10. The spectrum change in Ch.1 when sensors are under stress (bending) is presented on Fig.6, where two LPGs are simultaneously measured.

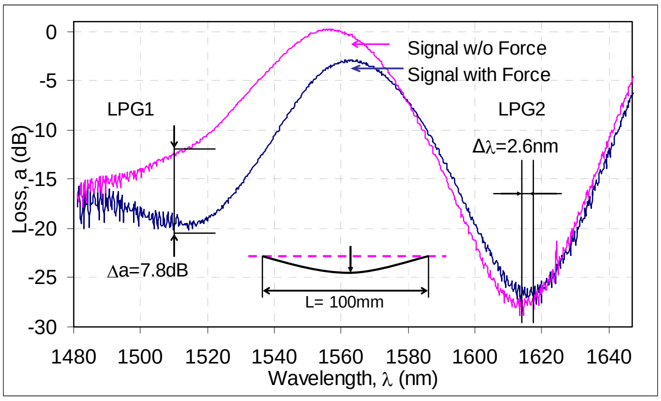

Fig. 6. Channel 1 relative measurement with LPG sensor under stress

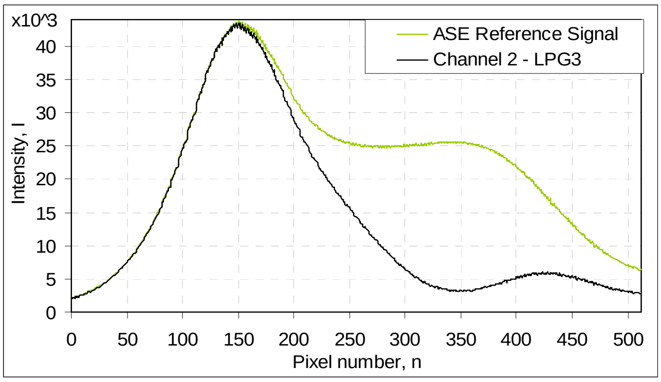

Fig. 7. Channel 2 LPGs' signal compared to reference spectrum

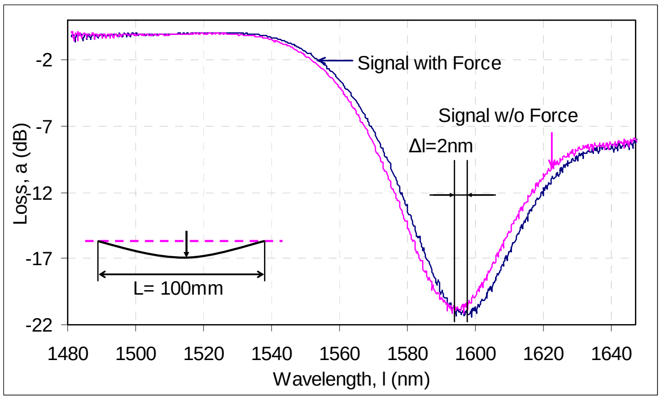

Fig. 8. Channel 2 relative measurement with LPG sensor under stress

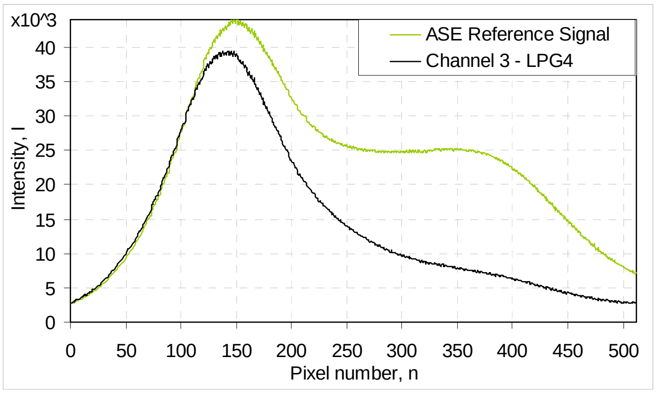

Fig. 9. Channel 3 LPGs' signal compared to reference spectrum

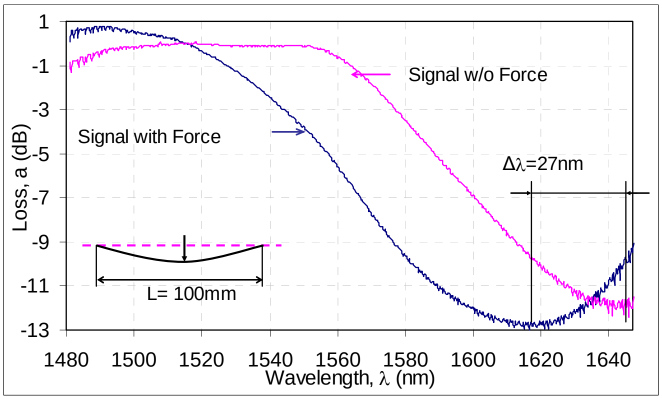

Fig. 10. Channel 3 relative measurements with LPG sensor under stress

They are particularly selected not to interfere with each others' spectra. LPG_1 shows significant depth change in its transmission minimum at λ=1515nm, while LPG_2 results in minimum shift of $\Delta\lambda$=2.6nm.

Corresponding transmission minimum shifts for Ch.2 and Ch.3 are presented on Fig.8 and Fig.10. The latter sensor is particularly sensitive resulting in a larger minimum shift of $\Delta\lambda$=27nm.

IV. CONCLUSION

The reported automated multi-channel broadband analysis system for measurement of fiber-optic grating sensors is capable of simultaneously monitoring up to 12 long period gratings in groups of three spectrally multiplexed sensors per channel. An advanced signal processing and analysis is demonstrated using cross-correlation function and adaptive filtering techniques which effectively suppress noises while preserving the spectral resolution.

It is also possible to extend significantly the measured spectrum range by rotating the diffraction grating with the precise stepper motor and the wide sensitivity range of the linear CCD photodiode array (800-1750 nm).

The measurement results demonstrate the high sensitivity of implemented long period grating sensors to external strain forces on the fibers and also the ability of the demonstrated system to detect and analyze those spectral changes.

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REFERENCES

[1] Murphy, D. F., Flavin, D. A., McBride, R., and Jones, J. D. C., Interferometric Interrogation of In-Fiber Bragg Grating Sensors Without Mechanical Path Length Scanning, J. Lightwave Techn., 19, 1004-1009 (2001).
[2] Alves, J., Santos, J.L., Carvalho, A., and Lage, A. Fiber Bragg Sensor Interrogation System Based on a CCD Spectrometer, Proceedings of IEEE, Sensors, 1, 909-913 (2003)..
[3] J. Choi, Adaptive and Iterative Signal Processing in Communications, Cambridge Press, 2006.
[4] C.G. Askins, M.A. Putnam E.J. Friebele, Instrumentation for Interrogating Many-element Fiber Bragg Grating Arrays, SPIE vol.2444 p.257-266, 1995.
[5] K. Srimannarayana1, M. Shankar,R.S. Prasa, Fiber Bragg Grating And Long Period Grating Sensor For Simultaneous Measurement And Discrimination Of Strain And Temperature Effects, Optica Applicata, Vol. 38,No. 3, 2008
[6] S. Vaseghi, Advanced Digital Signal Processing and Noise Reduction, 4th Edition, Wiley, 2009.
[7] Farhang-Boroujeny, B., Adaptive Filters – Theory and Applications, Wiley, 1998.
[8] Bitter, R., Mohiuddin, T., Nawrocki, M., LabVIEW – Advanced Programming Techniques, 2nd Edition, CRC Press, 2007.
[9] Zahariev P., Hristov G., Iliev M., Tsvetkova I., "Extending the lifetime of wireless sensor networks by mechanisms for routing the information in more energy efficient ways", Mosharaka International Conference on Communications, Computers and Applications MIC-CCA, Istanbul, Turkey, pp. 73 – 78
[10] Guan, Z.G., Zhang, A.P., Liao, R., "Wavelength Detection of Coherence-Multiplexed Fiber-Optic Sensors Based on Long-Period Grating Pairs", IEEE Sensors Journ., 7, 36-37, 2007.
[11] Tamhane, A. C., "Statistical Analysis of Designed Experiments: Theory and Applications", Wiley, 2009.
[12] M. Mikhov, P. Nakov,"A Hybrid Step Motor Drive System with High Positioning Accuracy", Proceedings of the International Conference on Electronic Devices and Systems, pp. 59-64, Brno, Czech Republic, 2005, ISBN 80-214-2990-9.
[13] M. Mikhov, P. Nakov, "Stepping Motor Drive for Precise Positioning Applications", Proceedings of the International Scientific Conference on Information, Communication and Energy Systems and Technologies, Vol. 1, pp. 227-230, Nish, Serbia, 2008, ISBN 978-86-85195-59-4.
[14] Zahariev P., Hristov G., "Performance evaluation of data delivery approaches for wireless sensor networks", World Conference on Information Technology WCIT 2010, Istanbul, Turkey; Procedia Computer Science, Volume 3, 2011, Elsevier, pp. 714 – 720
[15] Tsvetkova I., Aleksandrov Y., Hristov G., Zahariev P., Iliev M., "Comparison of target tracking algorithms in hierarchical WSNs", World Conference on Information Technology WCIT 2011, Antalya, Turkey