



Spectrum Analysis and Data Processing with Automated Multiple-channel Measurements

Plamen Balzhiev¹, Wojtek Bock², Tinko Eftimov³, Rumen Arnaudov⁴

¹Plamen Balzhiev is with the Faculty of Telecommunications at Technical University of Sofia, 8 Kl.Ohridski Blvd, Sofia, Bulgaria
baljiev@gmail.com

²Wojtek Bock is with the Canada Research Chair in Photonics Université du Québec en Outaouais, Québec, Canada
Wojtek.Bock@uqo.ca

³Tinko Eftimov is with the Faculty of Physics Plovdiv University, Bulgaria
tinkoeftimov@yahoo.ca

⁴Rumen Arnaudov is with the Faculty of Telecommunications Technical University of Sofia, Bulgaria
ra@tu-sofia.bg

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ABSTRACT

In this paper, we present techniques for analyzing spectrum and processing data. We introduce a system for automated measurement of multiple channels, featuring controlled fibre-optic signal switching and analysis of spectra using a linear CCD photodiode array, diffraction grating, and an accurate stepper motor. This system requires sophisticated techniques for measurement and data processing. The work outlines the techniques used for automated measurement across multiple channels, enhancing accuracy, eliminating noise, and measuring fibre-optic grating signals.

Keywords: Long-period Grating Sensors, Fiber-optic Sensor Interrogation and Multi-channel Spectrum Measurement

1. 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 an 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..

2. Multi-channel Spectrum Measurement System

2.1. 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].

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, Ch.2 and Ch.3 investigate single LPG and Ch.4 is utilized to perform reference signal measurement and system calibration with the ASE light source.

2.2. 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 (Δ), 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].

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

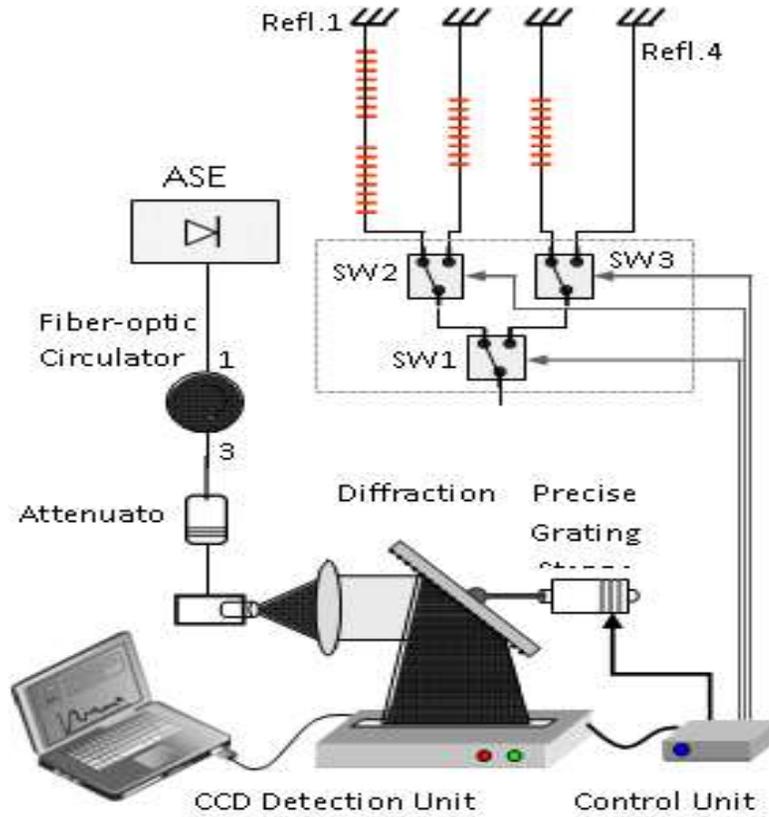


Figure 1. Multi-channel spectrum measurement system

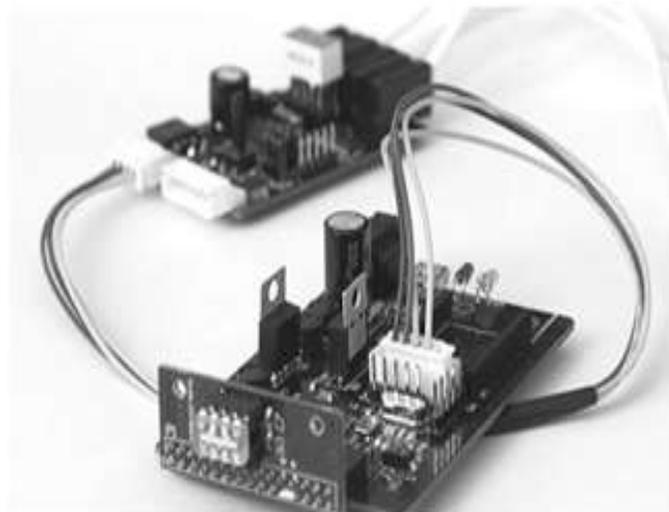


Figure 2. Photographs of CCD Detection Unit and control device

precise stepper motor and the measured channel. After the current channel is measured and visualized, the program automatically configures the next channel for measurement.

$$R(\tau) = \sum_{\tau} f_1(n)f_2(n + \tau) \tag{1}$$

$$R(\tau_{\max}) = \max$$

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

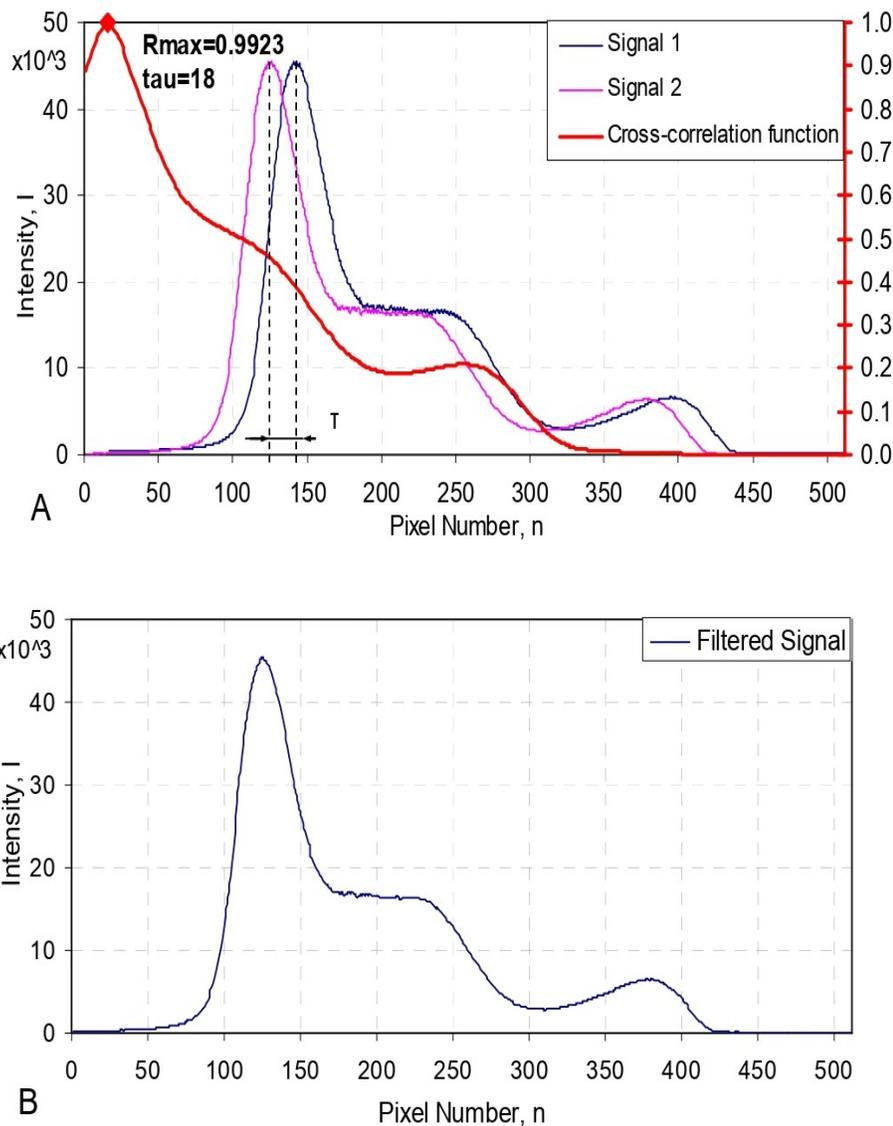


Figure 3. Correlation analysis of two shifted spectrum measurements-A, Noise suppression with spatially shifted measurements-B

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

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

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

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 Figure 3b.

3. 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 Figure 4 with relative measurement to the reference signal.

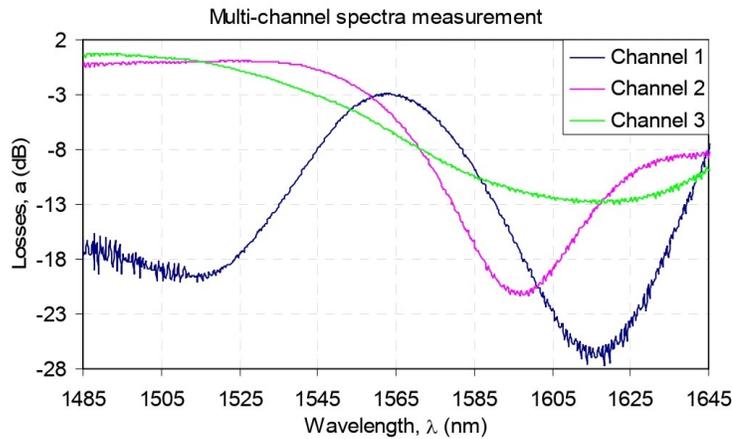


Figure 4. Joint multi-channel spectral response measurement

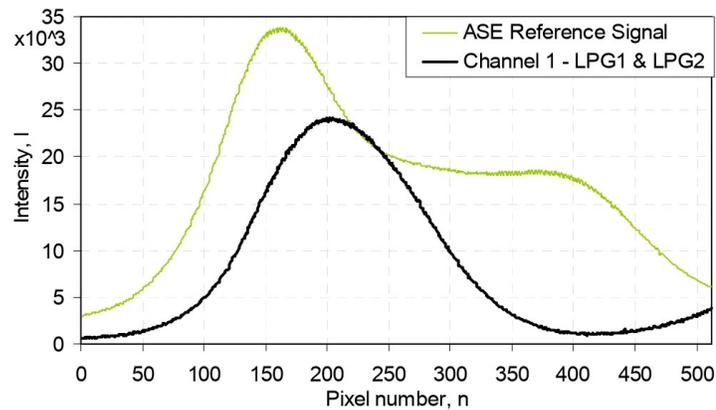


Figure 5. Channel 1 LPGs' signal compared to reference spectrum

The results from measurements of the transmission spectra in Channel 1 are shown in Figure 5. Figure 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 Figure 7-8 and Figure 9-10. The spectrum change in Ch.1 when sensors are under stress (bending) is presented on Figure 6, where two LPGs are simultaneously measured.

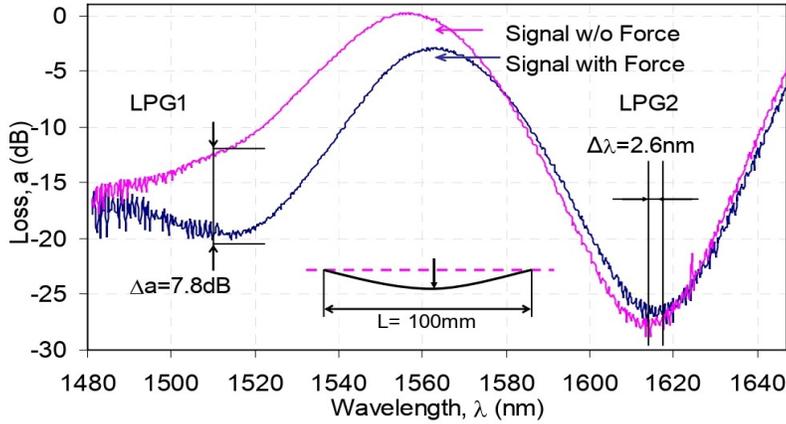


Figure 6. Channel 1 relative measurement with LPG sensor under stress

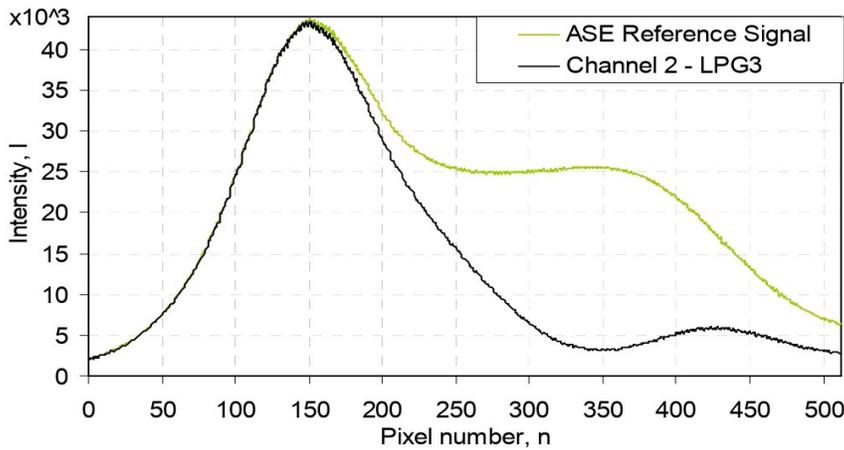


Figure 7. Channel 2 LPGs' signal compared to reference spectrum

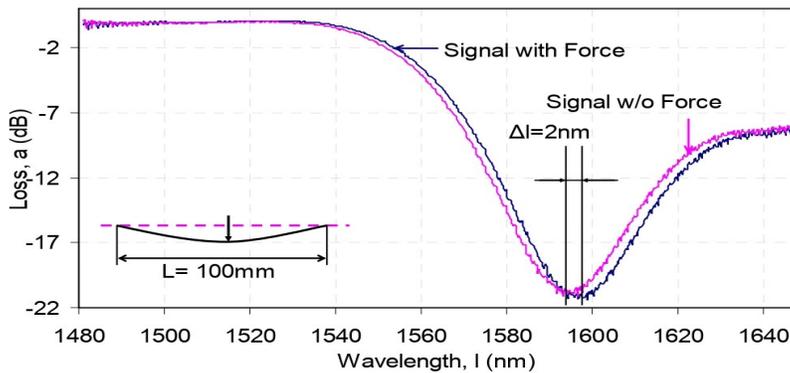


Figure 8. Channel 2 relative measurement with LPG sensor under stress

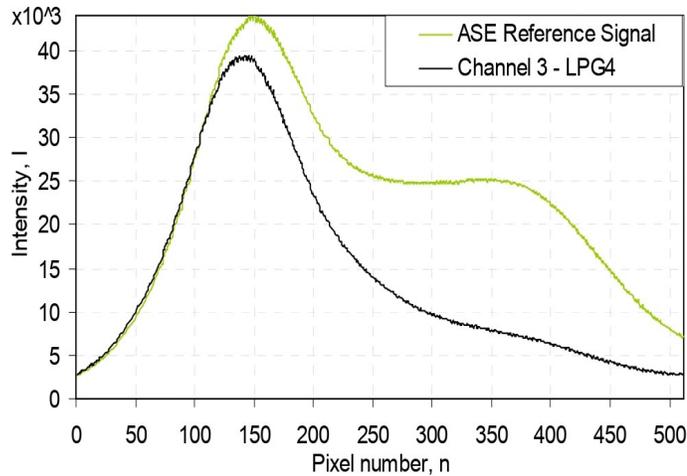


Figure 9. Channel 3 LPGs' signal compared to reference spectrum

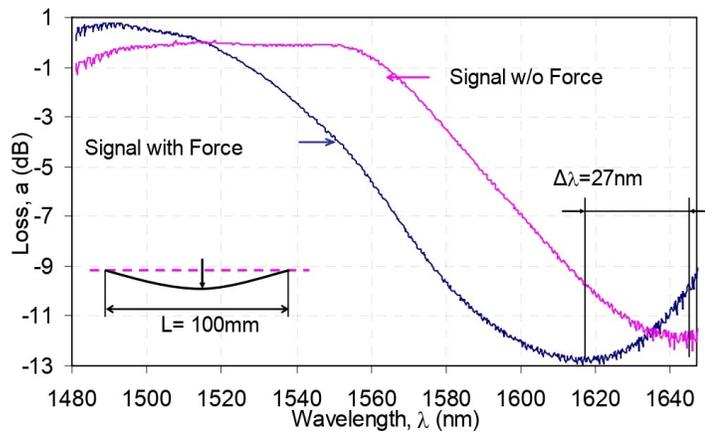


Figure 10. Channel 3 relative measurements with LPG sensor under stress

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

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

4. 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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