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A planar lightwave circuit based micro interrogator and its applications to the interrogation of multiplexed optical fiber Bragg grating sensors

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ABSTRACT

Optical fiber Bragg grating sensors have found potential applications in many fields, but the lack of a simple, field deployable and low cost interrogation system is hindering their deployment. To tackle this, we have developed a micro optical sensor interrogator using a monolithically integrated planar lightwave circuit based echelle diffractive grating demultiplexer and a detector array. The design and development of this device are presented in this paper. It has been found that the measurement range of this micro interrogator is more than 25 nm with better than 1 pm resolution. This paper also reports the applications of the micro interrogator developed to the monitoring of commercial optical fiber Bragg grating (FBG) temperature sensors and mechanical sensors. The results obtained are very satisfactory and in some cases, they are better than those obtained using commercial bench top lab equipment.

1. Introduction

Optical fiber Bragg grating (FBG) sensors [1] are very compact. Their diameters generally range from 40 to 250 μm. This makes them ideal for the embedment in high value, critical structures and platforms including aircraft fuselage and civil engineering works where in situ health monitoring is desired [1–7]. These optical fiber sensors are usually produced from pure silicon dioxide glass and tiny amount of doping materials. They can withstand temperatures varying from few hundreds below zero to one thousand above zero, as well as other extreme environments. These characteristics render the optical fiber sensors particularly attractive for applications in chemical sensing, bio sensing, and temperature, pressure sensing in oil exploration and chemical processing etc. In addition, due to the high bandwidth of optical fiber, it is possible to multiplex hundreds, if not thousands, of Bragg grating sensors on a single fiber strand [8].

The simultaneous interrogation of such highly multiplexed Bragg grating sensors, however, presents a significant challenge. In addition to the stringent performance requirements, such as picometer measurement resolution [9], field implementation also requires that the interrogation systems be light weight and in a miniaturized form, particularly for air vehicle structure health monitoring [10]. Available systems are either bulky or heavy, or are not suitable for large number of Bragg grating sensor interrogation applications. Optical spectrum analyzers (OSA) are currently the most popular choice for the interrogation of optical fiber Bragg grating sensors. Though it offers large measurement range, their measurement resolution only reaches 10 pm. In addition they are bench top equipment, lab-oriented and not suitable for field applications. In recent years, several types of micro spectrometers have been developed and commercially available. But those spectrometers are targeting the large wavelength range spectrum measurement, their measurement resolutions are generally worse than that of OSA and are not suitable for optical fiber Bragg grating sensor interrogation applications. This has greatly hindered the deployment of the Bragg grating sensors in the field. For example, miniaturized, compact and light interrogator is needed for the structural health monitoring of solid rocket motors [10].

Based on field requirements and the industry's needs for advanced miniaturized sensing capabilities, in recent years, we have initiated the development of miniaturized, field deployable micro devices for the interrogation of optical fiber Bragg grating sensors using planar lightwave circuits technologies. Our recent publications reported on the novel fiber optical sensor interrogators based on arrayed waveguide gratings (AWG) demultiplexer [11,12], which shows a novel approach for the miniaturization of optical fiber sensor interrogators. Employing a similar interrogation principle, we have also prototyped a micro interrogator based on the integration of a planar lightwave circuit based echelle diffractive gratings (EDG) demultiplexer and a photodetector array, which will be presented in this paper. The sizes of the waveguides consisting of the device circuits are of micron scale and the circuits are patterned on Indium Phosphate (InP) wafer. The reliability of this integrated device has been proved by its successful

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deployments in the optical networks. Here we summarize the design and development of this micro interrogator and discuss its applications to optical fiber Bragg grating based temperature and strain sensors.

2. Micro interrogator design and development

The design of our micro interrogator is based on the layout of typical micro spectrometer. As illustrated in Fig. 1, a typical micro spectrometer consists of two components, i.e. a light disperser (or a light demultiplexer), and a linear photo detector array [13,14]. When a light signal coming into the micro spectrometer, the light is dispersed into its spectral components by the disperser and is directed to the detector array. Through suitable calibration, each detector can be assigned a certain wavelength range. However, due to the physical limitation of the number of the photo detectors that can be fabricated on a single array area, the spectrometer measurement resolution and range become two competing factors in the design. Depending on the spectrometer's operational and performance requirement, one parameter must be sacrificed at the expense of the other. As the commercial micro spectrometers are generally developed for large wavelength range spectrum measurement applications, their measurement resolution is normally around 1 nm or worse. This number is about 1000 times larger than that required by the interrogation of Bragg grating sensors [9]. To develop our micro sensor interrogator, we used a tunable demultiplexer to replace the light disperser. This approach would overcome the above discussed limitations of typical micro spectrometer design and offer our interrogator with good measurement resolution without sacrificing its measurement range.

For the micro sensor interrogator reported in this paper, a planar lightwave circuit based echelle diffractive grating (EDG) demultiplexer is used. It is a device fabricated on InP chip [15], which measures few millimeters to few millimeters. The reliability of its performance has been proved by its deployment in the telecommunication field. The transmission wavelengths and spectra of the device can be designed as required [16,17].

As discussed in [18], the transmission wavelength of an EDG demultiplexer can be tuned by controlling the refractive index of the lightwave circuits, i.e.

$$\Delta\lambda_i = f(x)\Delta x \quad (1)$$

where $\Delta\lambda_i$ is the wavelength change of the ith EDG channel, $f(x)$ is the controlling function for the refractive index of the circuits and Δx is the change of the controlling parameter. There are several ways to control the refractive index of the circuits, such as by doping the circuits with some special elements, then using current injection to control the refractive index of the circuits [19], or by simply changing the temperature of the circuits [18,20]. Due to the simplicity of the latter method, the temperature tuning approach is adopted in this work. To this end, a thermo electric cooler (TEC) was bonded to the back of the InP chip. By changing the current input to the TEC, the temperature of the device chip can be precisely controlled and scanned. A resistive temperature sensor (RTD) was also bonded to the chip for the purpose of the monitoring of the device temperature. As the refractive index of the InP changes (in the wavelength range from 1200 nm to 1600 nm) linearly with the chip temperature within the range of 10–60 °C [20], the transmission wavelength of the EDG demultiplexer changes linearly with the temperature of the chip as reported in [18].

To further provide size reduction in our design, the photo detector array is monolithically integrated with the EDG demultiplexer [16]. Using this integrated planar lightwave circuit chip, a micro sensor interrogator based on the above discussion, as shown in Fig. 2, was developed, which mainly consists of an EDG device chip, a TEC, the electronic control circuits, the signal amplification circuits and few other components. The working principle of this micro interrogator is illustrated in the block diagram shown in Fig. 3. The prototype is about palm size and measures $125 \times 73 \times 50\ mm^3$. The device control is achieved via the use of executable Lab view programs with user friendly Graphic user interface (GUI).

In this work, fifteen EDG demultiplexer channels are used. The channel spacing is set to be 1.6 nm and it is used to measure a spectrum of wavelength range of 1.6 nm. Fig. 4 shows the measurement range of the fifteen channels, their spacing, their wavelength range and the tuning temperature range as well. Results illustrate that the rate of change (wavelength vs. chip temperature) of all channels is the same and is about 0.09 nm/°C. Due to the efficient design of the electronic circuits that can be tuned to control temperature steps of less than 0.01 °C, a better than 1 pm wavelength tuning step can be achieved using the developed micro interrogator prototypes. In addition, a new but better temperature controlling mechanism compared to the one used in [18] is used.

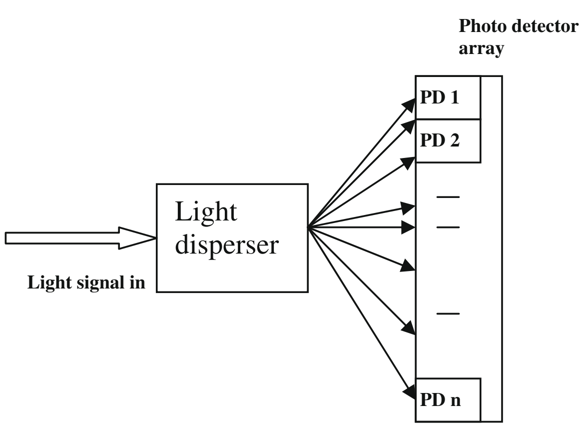


Fig. 1. Illustration of a typical micro spectrometer.

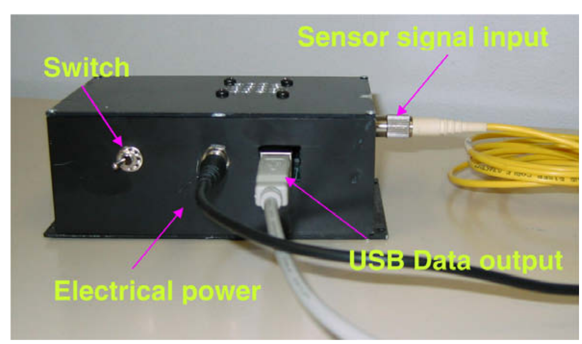


Fig. 2. Example of a micro interrogator prototype.

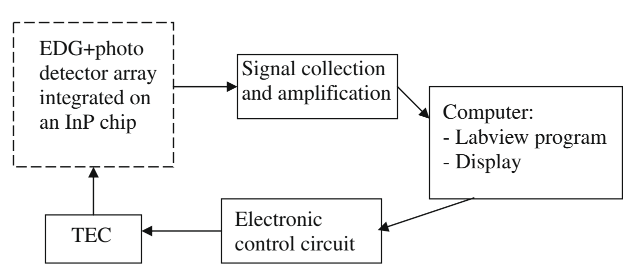


Fig. 3. Illustration of the operation of the micro interrogator.

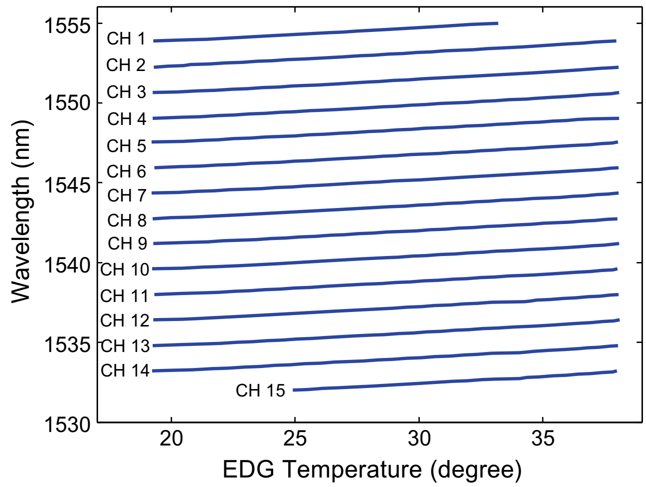


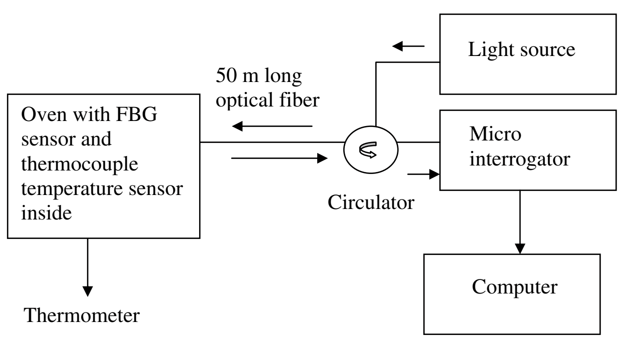
Fig. 4. Measurement range of each EDG channel and the relationship between EDG chip temperature and the transmission wavelength.

3. Applications of the micro interrogator: multi Bragg grating sensor monitoring

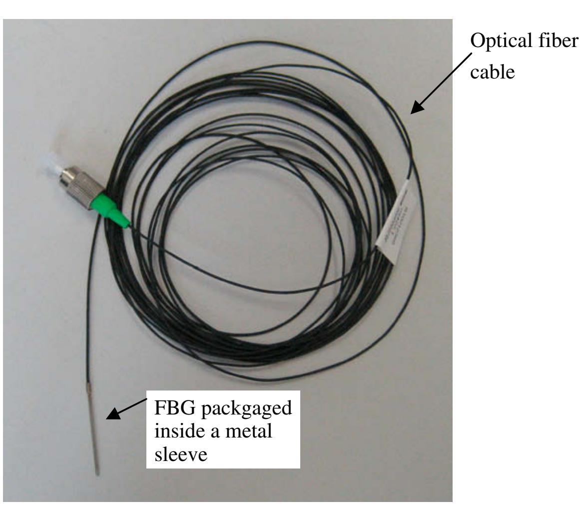
To demonstrate the suitability of the developed micro interrogator in the monitoring of fiber Bragg grating sensors, an experimental activity is initiated and conducted. The selection of Bragg grating sensors is a result of the significant interest presented by the structural health monitoring community in this technology. The two most significant parameters of interest to this community are assessed in this section.

3.1. Remote temperature monitoring

Fig. 5a illustrates a controlled experimental setup for remote temperature sensing within an oven environment. The setup consists of a light source, which is a broadband light source amplified by an Erbium doped fiber amplifier, an optical circulator, a 50 m long standard single mode optical fiber, two fiber Bragg grating temperature sensors (an example is shown in Fig. 5b) with the Bragg wavelength of 1543 nm and 1547 nm, respectively, a Fisher isotherm oven, a thermo coupler and an Omega thermometer, our developed micro interrogator prototype, and a computer for data processing and display. When the broadband light enters the circulator, it is transmitted to its transmission port and to the FBG sensors through optical fiber cables. The light signals of the Bragg wavelengths are reflected back from the sensors to the circulator and then transmitted to the micro interrogator through the reflection port of the circulator. The sensor signals are converted to electric signals and fed into the computer through the micro interrogator. The National Instrument's Labview program is used for data acquisition, data display, data analysis as well as for controlling the micro interrogator.

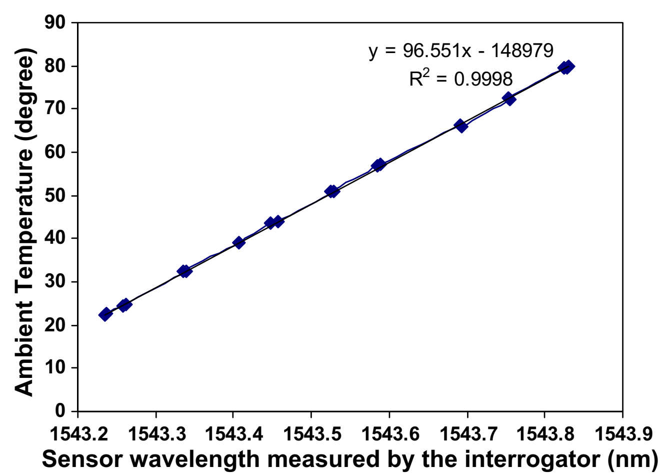


(a) Illustration of the experimental setup

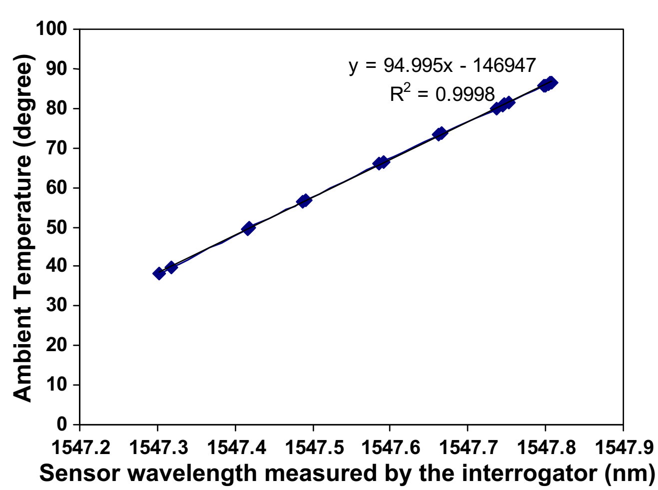


(b) Picture of a FBG temperature sensor

Fig. 5. Illustration of the remote temperature sensor monitoring set up.



(a) 1543 nm FBG sensor



(b) 1547 nm FBG sensor

Fig. 6. Results of temperature sensor monitoring (two sensors).

For temperature variations ranging from room temperature to about 80 °C, FBG sensors are monitored employing the developed interrogator. Results showing the relationship between the oven temperature and the Bragg wavelengths of the two FBG temperature sensors measured by the micro interrogator using the above set up are shown in Figs. 6 and 7. In both figures, the results show that the ambient temperature has a monotonic relationship with the Bragg wavelength. The rate of increase in these relationships is different between the two sensors used. This is believed to be due to the packaging of the FBG sensors, which applied different type or levels of the stress on the gratings. During the experiment, both gratings were secured to a metal plate by tape and left on the shelf inside the oven, for the purpose of avoiding any possible strain condition changes on the sensor during the experiments.

Fig. 7 shows the temperature drifting inside the oven during several hours time frame monitored by the micro interrogator prototype. The change of the temperature shown in the curve was caused by the manual adjustment of the oven temperature to test the response of the sensor and the micro interrogator. The horizontal axis in the figure is the times of the scanning. The interval between each scan is about 30 s.

3.2. Mechanical sensing

Similar to the above discussed application to temperature sensor monitoring, the employment of the micro interrogator prototype to the monitoring of the load applied to a standard mechanical coupon is examined in this section. Fig. 8 shows the mechanical sensing test set-up. Two FBGs of 3 mm length were serially written on a standard Corning SMF-28 optical fiber with a 10 mm physical spacing between them. The Bragg wavelengths of these two gratings are 1539 nm and 1544 nm, respectively. The outer diameter of the optical fiber is 125 m. The gratings were bonded to the surface of an aluminum 2024-T3 testing coupon using a standard M-bond AE10 adhesive. The dimension of this coupon is $304.8 \times 50.8 \times 6.35\ mm^3$ and the gratings were placed at its mid-span where the stress distribution is known to be uniform. The coupon was then placed in a 20 kips MTS Load Frame.

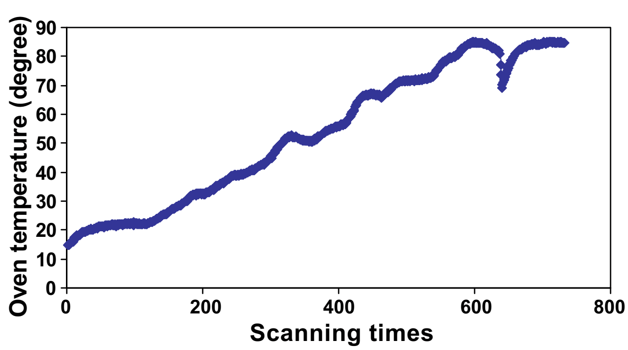


Fig. 7. Remote monitoring of temperature change inside an oven.

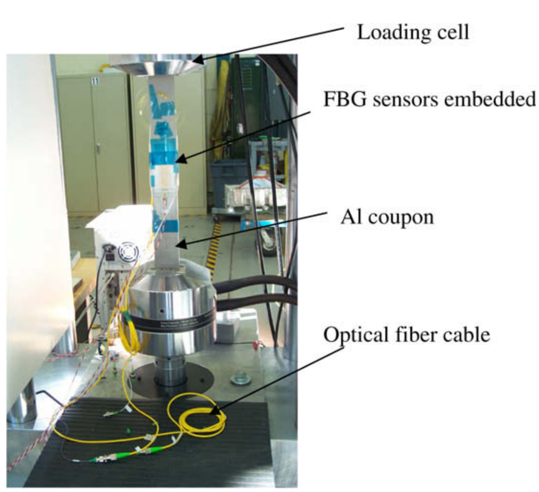


Fig. 8. Mechanical sensing test set-up.

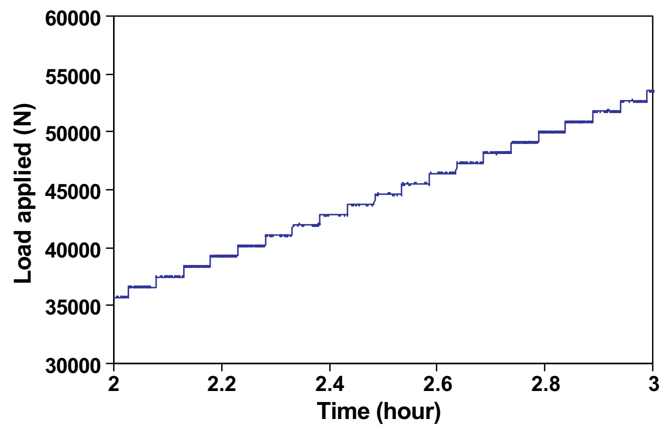
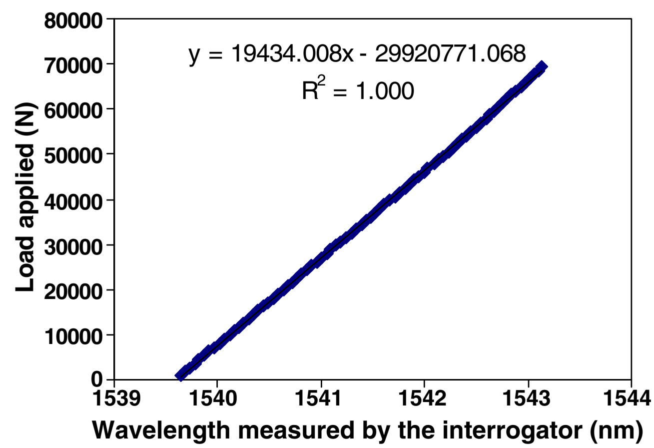
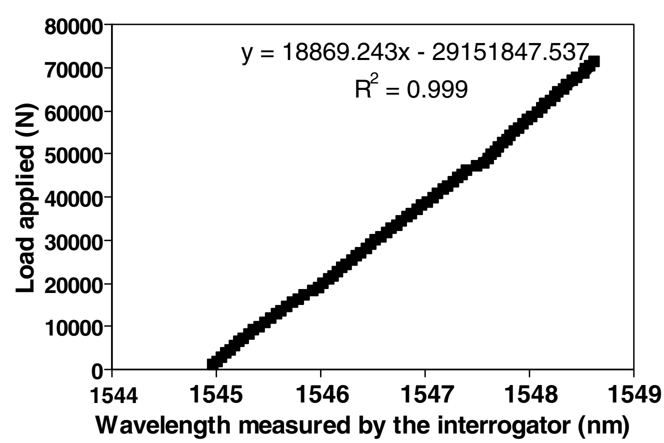


Fig. 9. Example of the mechanical testing load profile.



(a) 1539 nm FBG sensor



(b) 1544 nm FBG sensor

Fig. 10. Change of FBG sensor wavelength monitored by the micro interrogator vs. load applied.

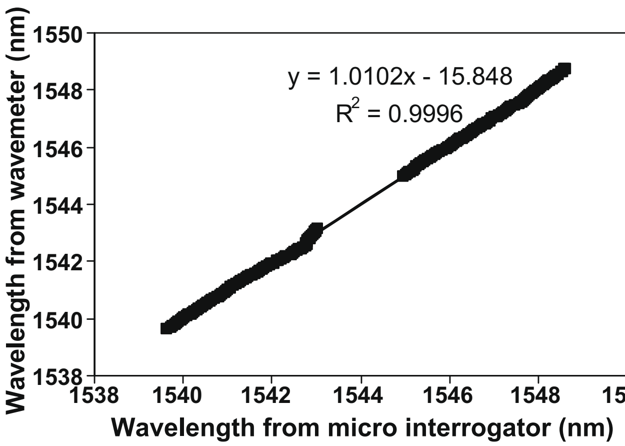


Fig. 11. Correlation between the wavelength measured by the micro interrogator and the wavelength meter.

A load profile as shown in Fig. 9 was applied to the coupon and wavelengths measurements were obtained using the micro interrogator. To verify the performance of the micro interrogator, a HP wavemeter was also connected to the sensors. Loads are applied linearly with a 3 min hold at each step of 892.857 N for a maximum load of 71528 N (∼3200 με of the coupon). Fig. 10 shows the relationship between the load applied and the Bragg wavelengths of the sensors measured by the micro interrogator.

In order to assess the suitability of the developed system, the collected data is also compared to data obtained using a conventional HP 86120C multi-wavelength meter. Fig. 11 demonstrates the strong correlation obtained between the two systems confirming the expected suitability of the micro-sized Echelle Diffractive Gratings based micro interrogator for mechanical sensing and FBG monitoring.

4. Conclusions

We have developed a micro interrogator, which covers a wavelength range of more than 25 nm with a resolution of better than 1 pm for optical fiber Bragg grating sensor interrogation applications. The device is based on an integration of an echelle diffractive grating demultiplexer and a photo detector array fabricated on an InP chip. We have also demonstrated the suitability of the developed micro interrogator for the remote monitoring of FBG sensors as well as the monitoring of FBG mechanical sensors.

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References

[1] A. Othonos, in: K.T.V. Grattan, B.T. Meggitt (Eds.), Optical Fiber Sensor Technology, Kluwer Academic Publishers, 2000, p. 79.
[2] N. Mrad, G.Z. Xiao, The 2005 International Conference on MEMS, NANO, and Smart Systems, July 24–27, 2005, Banff, Alberta – Canada, p. 359.
[3] J.-R. Lee, C.-Y. Ryu, B.Y. Koo, S.-F. Kang, C.-S. Hong, C.-Gon Kim, Smart Mater. Struct. 12 (2003) 147.
[4] G.Z. Xiao, N. Mrad, Caneus 2006 Conference on Micro and Nano Technologies for Aerospace Applications, Toulouse, France, 11028, August 27–September 1, 2006.
[5] K. Wood, T. Brown, R. Rogowski, B. Jensen, Smart Mater. Struct. 9 (2000) 163.
[6] F. Mennella, A. Laudati, M. Espostio, A. Cusano, A. Cutolo, M. Giordano, S. Campopiano, G. Breglio, EWOFS 2007, Proc. SPIE 6619, p. 66193H.
[7] H.F. Lima, R. Vicente, R.N. Nogueira, I. Abe, P. Andre, C. Fernandes, H. Rodrigues, H. Varum, H. J. Kalinowski, A. Costa, L. Pinto, EWOFS 2007, Proc. SPIE 6619, p. 661941-1.
[8] P. Lefebvre, A. Vincelette, C. Beaulieu, P. Ficocelli, Automated manufacturing of fiber Bragg grating arrays, <http://www.lxsix.com/en/technology/white-papers/Automation-Technology-White-Paper.pdf>.
[9] B. Lee, Y. Jeong, in: F.T.S. Yu, S. Yin (Eds.), Fiber Optic Sensors, Marcel Dekker, New York, 2002, p. 295.
[10] C. Lopatin, S. Mahmood, E. Mendoza, B. Moslehi, R. Black, K. Chau, L. Oblea, EWOFS 2007, Proc. SPIE 6619, p. 66193X.
[11] G.Z. Xiao, P. Zhao, F. Sun, Z. Lu, Z. Zhang, IEEE Photon. Technol. Lett. 17 (2005) 1710.
[12] G.Z. Xiao, P. Zhao, F.G. Sun, Z.G. Lu, Zhiyi Zhang, C.P. Grover, Opt. Lett. 29 (2004) 2222.
[13] D. Brennan, J. Alderman, L. Sattler, J. Walshe, J. Huang, B. O'Connor, C. O'Mathuna, Infrared Phys. Technol. 43 (2002) 69.
[14] O. Liver, P. Kiesel, M. Bassler, N. Johnson, Int. J. High Speed Electron. Syst. 17 (2007) 661.
[15] J.J. He, B. Lamontagne, A. Delage, L. Erickson, M. Davies, E.S. Koteles, J. Lightwave Technol. 16 (1998) 631.
[16] V.I. Tolstikhin, A. Densmore, K. Pimenov, Y. Logvin, F. Wu, S. Laframboise, S. Grabtchak, J. Lightwave Technol. 22 (2004) 146.
[17] R. Marz, Integrated Optics: Design and Modeling, Artech House, Norwood, MA, 1994.
[18] G.Z. Xiao, N. Mrad, F. Wu, Z. Zhang, F. Sun, IEEE Sensors Journal 8 (2008) 1202.
[19] K. Wakao, K. Nakai, M. Kuno, S. Yamakoshi, IEEE J. Select. Area Commun. 6 (1988) 1199.
[20] E. Gini, H. Melchior, in: Proceedings of the Eighth International Conference on Indium Phosphide and Related Materials, 1996, Germany, p. 594.