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Development of Interrogators for Multiplexed Bragg Grating Sensors

Progress Report

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Technical Memorandum
DRDC Atlantic TM 2007-194
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Abstract

The increasing requirement for efficient and cost effective aircraft fleet management necessitates the integration of on-line health monitoring capability. Such capability must be reliable, robust and must easily respond to the physical and environmental constraints imposed by the aircraft environment. Highly multiplexed fibre optic Bragg grating sensors are assessed to meet this challenging environment. In an effort to develop a suitable small size, rugged, reliable data acquisition (demodulation) system to interrogate these highly multiplexed fibre optic sensors, a research and developmental activity has been initiated. This report documents the progress made towards such development. Preliminary results, demonstrated the suitability of the use of an Arrayed Waveguide Grating (AWG) demodulation system for monitoring five serially multiplexed gratings. The currently experienced limitation of this miniature demodulation system resides in its inability to perform high speed dynamic measurements.

Résumé

Le besoin croissant d’une gestion efficace et rentable d’une flotte d’aéronefs nécessite l’intégration d’une capacité de surveillance en direct de l’état des appareils. Une telle capacité doit être fiable et solide, et elle doit aisément réagir aux contraintes ambiantes et matérielles imposées par les conditions de fonctionnement des aéronefs. Des réseaux de capteurs de Bragg à fibres optiques fortement multiplexés font l’objet d’une évaluation visant à en déterminer le fonctionnement dans ces conditions exigeantes. Dans un effort pour mettre au point un système d’acquisition de données (de démodulation) qui soit fiable, robuste et d’une petite taille appropriée en vue de l’interrogation de ces capteurs à fibres optiques fortement multiplexés, des travaux de recherche et développement ont été entrepris. Le présent rapport documente les progrès réalisés à l’égard de cette mise au point. Les résultats préliminaires démontrent la pertinence d’utiliser un système de démodulation à réseau sélectif planaire (AWG) pour la surveillance de cinq réseaux multiplexés en série. La restriction que l’on connaît à l’égard de ce système de démodulation miniature réside dans son incapacité à prendre des mesures dynamiques à grande vitesse.

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Executive summary

Development of Interrogators for Multiplexed Bragg Grating Sensors: Progress Report

Mrad, N., G. Xiao; DRDC Atlantic TM 2007-194; Defence R&D Canada – Atlantic; July 2007.

Introduction

Maintaining and managing the health of air vehicles continues to be a challenge for aircraft owners and operators. Both aerospace industry and defence organizations have been continuously calling for the application of embedded sensors to provide in-situ aircraft health monitoring capability. One of the main issues impeding this development is the lack of a suitable, light-weight and miniaturized sensor system capable of monitoring multi-parameters simultaneously. Highly multiplexed fibre optic Bragg grating sensors are known to be the most suitable sensors for simultaneous in-situ multi-parameters measurements. In an effort to develop a suitable small size, rugged, reliable data acquisition (demodulation) system to interrogate these highly multiplexed fibre optic sensors an assessment of current technologies was conducted. As a result, an Arrayed Waveguide Grating (AWG) based demodulation concept for monitoring serially multiplexed gratings was identified and selected for development

Results

Preliminary results demonstrated the suitability of an Arrayed Waveguide Grating (AWG) demodulation system for statically monitoring five serially multiplexed gratings. The demodulation system was also demonstrated for temperature measurement, providing a resolution of 0.01^0C. The only experienced limitation of this small (12x8x5 cm^3) demodulation system resides in its inability to perform high speed (>1 min) dynamic measurements. This limitation is the topic of future investigation.

Significance

Development of a small/miniaturized fibre optic demodulation system is expected to provide additional capability to address current limitations for in-situ on-line health monitoring of aerospace structures and materials. This development is expected to benefit several aerospace and military platforms including the CH 149 cormorant, the CP 140 Aurora and the CC130 Hercules and would further benefit the continued development of diagnostics, prognostics and health management capabilities to support future CF aircraft fleets.

Future plans

This program is in its first phase and work will continue to refine the current development and address the encountered limitations.

Sommaire

Development of Interrogators for Multiplexed Bragg Grating Sensors: Progress Report

Mrad, N., G. Xiao ; DRDC Atlantic TM 2007-194 ; R & D pour la défense Canada – Atlantique ; July 2007.

Introduction ou contexte

Le maintien et la gestion de l'état de véhicules aériens ne cessent de poser des défis aux propriétaires et aux exploitants d'aéronefs. L'industrie de l'aérospatiale et les organismes œuvrant dans le domaine de la défense n'ont cessé de réclamer l'utilisation de capteurs intégrés pour assurer une capacité de surveillance embarquée de l'état des aéronefs. L'une des principales questions qui gênent les travaux de développement à cet égard est l'absence d'un système de détection pertinent, léger et miniaturisé capable de surveiller plusieurs paramètres simultanément. Des capteurs à fibres optiques et à réseaux de Bragg fortement multiplexés sont reconnus comme les capteurs qui conviennent le mieux aux mesures simultanées locales de plusieurs paramètres. Dans un effort pour mettre au point un système d'acquisition de données (de démodulation) qui soit fiable, robuste et d'une petite taille appropriée pour l'interrogation de ces capteurs à fibres optiques fortement multiplexés, une évaluation des technologies actuelle a été menée. Le principe de la démodulation reposant sur les réseaux sélectifs planaires (AWG) pour la surveillance de réseaux multiplexés en série a été identifié et choisi en vue de sa mise au point.

Résultats

Les résultats préliminaires démontrent la pertinence d'utiliser un système de démodulation à réseau sélectif planaire (AWG) pour la surveillance statique de cinq réseaux multiplexés en série. Le système de démodulation a aussi fait l'objet d'une démonstration concernant les mesures de la température, avec une résolution de 0,01 °C. La seule restriction notée de ce système de démodulation de petite taille (12 cm x 8 cm x 5 cm) réside dans son incapacité à prendre des mesures dynamiques à grande vitesse (moins de 1 min). Cette restriction fera l'objet d'une étude ultérieure.

Portée

On s'attend à ce que la mise au point d'un système de démodulation à fibres optiques de petite taille/miniaturisé se traduise par une capacité additionnelle remédier aux restrictions que l'on connaît pour la surveillance embarquée de l'état de structures et de matériaux de l'industrie aérospatiale. On s'attend à ce que cette mise au point soit utile à plusieurs plates-formes militaires et aérospatiales, dont le CH-149 Cormorant, le CP-140 Aurora et le CC-130 Hercules, et ait d'autres retombées pour le perfectionnement des capacités de diagnostic, de prognostic et de gestion de l'état à l'appui des futures flottes d'aéronefs des FC.

Recherches futures

Le programme en est à sa première phase, et les travaux se poursuivront en vue du raffinement des mises au point en cours et de l'examen des restrictions constatées.

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Acknowledgements

The authors would like to acknowledge the technical support from their colleagues in the photonic systems group at the Institute for Microstructural Science (IMS) and Defence R&D Canada (DRDC). The financial contribution of the Director General of Air Equipment and Program Management (DGAEPM) is also acknowledged.

1. Introduction

Maintaining and managing the health of air vehicles has been and continues to be a challenge for aircraft owners and operators. Both aerospace industry and defence organizations have been continuously calling for the application of embedded sensors to provide in-situ health monitoring capability, such as integrity assessment of the aircraft structures or rocket motors. One of the main issues impeding such development is the lack of suitable, light-weight and miniaturized sensor system capable of monitoring multi-parameters simultaneously.

Fibre optic sensors are inherently passive to electricity and immune to electromagnetic interferences. Owing to the high bandwidth of optical fibres, it is possible to multiplex hundreds, if not thousands, of fibre optic sensors together and perform in-situ remote monitoring. In addition, fibre optic sensors are light-weight, of very small size and have very good long-term reliability [1]. These properties make fibre optic sensors particularly attractive for aerospace applications. Significant efforts have been devoted to the use of fibre optic sensors for aerospace vehicles, such as embedding fibre Bragg gratings into composite structures in order to monitor the health of aircraft [2-7].

However, simultaneous interrogation of fibre optic sensors at such a large scale, in the range of hundreds, is a daunting task. Besides performance requirements, aerospace applications require that the interrogation system be light-weight and of small size. The current available systems are either bulky and heavy, or not suitable for large number of sensors interrogation applications.

We have proposed and demonstrated a novel fibre optic sensor interrogation approach based on planar lightwave circuit technologies [8-9]. These circuits are of few microns in size and are patterned on silicon wafer using microfabrication technologies. This interrogation system, called micro-interrogator in our lab, is built upon planar lightwave circuits based demultiplexer, whose reliability has been proved by its successful deployments in optical networks.

The main goal of the current activity is to develop a fieldable sensor interrogator prototype based on the demonstrated approach for multiplexed fibre Bragg grating sensor applications. This report presents progress made this year including the following aspects:

- Evaluation of available sensor interrogation technologies
- Specification of prototype sensor system
- Development of interrogators lab prototypes

In addition, we also present other accomplishments and set the stage for the next and final phase of this project.

2. Evaluation of Sensor Interrogation Technologies

2.1 Fibre Bragg gratings

Fibre gratings are normally made by the side-illumination method using KrF lasers or frequency-doubled argon ion lasers (UV lasers). Depending on the needs, different type of gratings can be fabricated, such as Bragg, long period, blazed etc. Here we will focus only on standard fibre Bragg grating (FBG) sensors, which are the most mature and widely available grating type. As illustrated in Figure 1 [10], when a light with a broadband spectrum is launched into the FBG sensor, the optical wave is partially reflected from each part of the grating. Only a specific wavelength of light, which is called the Bragg wavelength (λ_B), is reflected. The optical waves partially reflected from each part can interfere constructively with each other. For a given broadband light, only a narrow spectrum at the Bragg wavelength is reflected, while other wavelength components are transmitted through the FBG only to traverse other gratings, in the case of multi-gratings. The Bragg wavelength is given by

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the fibre core and Λ is the grating period.

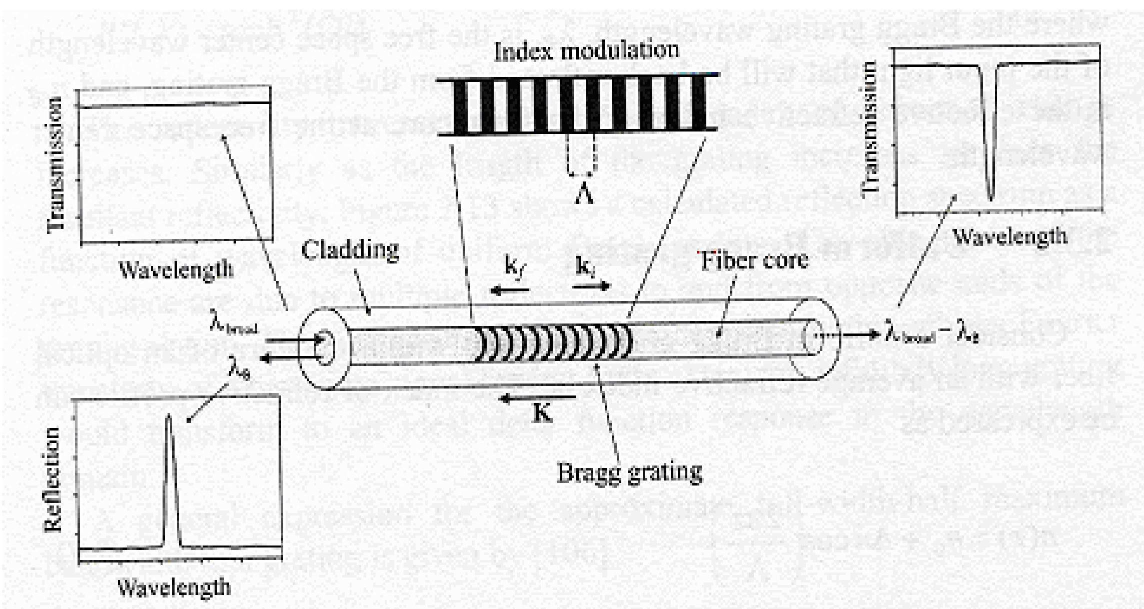


Figure 1 Illustration of the functioning of a Bragg grating

As the effective refractive index of the fibre and the grating period change with the environment, such as temperature, strain etc., FBGs can be used as strain or temperature sensors. They can also be used for probing a variety of other parameters, such as pressure, erosion, liquid level, chemicals, bending, and even magnetic fields [11]. For smart structure applications, FBG sensors offer many advantages including the following [11].

- The Bragg wavelength is a linear function of the measurands over large ranges.
- The measurand information is spectrally encoded; hence, the sensor signals are basically unaffected by environmental noise or power loss.
- The FBGs have inherent advantages over fibre devices such as signal transmission capability with small loss over fibre channels.
- The FBGs can be low in price and are readily available.
- The FBGs have high reflectivity for selected Bragg wavelength, small gauge length (~10 mm, typically), and can be quasi distributed.
- The FBGs are light-weight and because of their small diameters, they can be inserted into composite materials without any structural degradation.
- Various types of sensor multiplexing such as spatial division multiplexing (SDM), wavelength division multiplexing (WDM), time division multiplexing (TDM), and code division multiple access (CDMA) etc., and their combination, can be implemented to form quasi-distributed or quasi-point sensor array systems.

To extract measurand information from the light signals coming from the sensor heads, signal interrogators (also referred as demodulators or conditioners) are needed. As mentioned earlier, the measurand is typically encoded spectrally for FBG sensors, hence the interrogators for FBG sensors have to be able to measure the Bragg wavelength shifts and convert the results to useful data descriptive of the physical phenomena being evaluated.

2.2 Interrogation techniques

A variety of interrogation techniques have been studied [11], but only few of them are practical and can be used in the field. Here, we only discuss these few techniques: linearly wavelength-dependent optical filters, CCD Spectrometer Interrogator, Fabry-Perot filter interrogator, matched fibre Bragg grating pair interrogator and the use of wavelength tunable sources.

2.2.1 Linearly wavelength-dependent optical filters

As illustrated in Figure 2 [11-12], wavelength change is obtained by the intensity monitoring of the light at the detector.

$$\frac{I_S}{I_R} = A(\lambda_B - \lambda_0 + B) \qquad (2)$$

where I_S is the intensity of the light coming out of the filter, I_R is the intensity of the light received by the reference detector, A is a constant determined by the slope of the filter and B is a constant arising from the nonzero reflection bandwidth of the FBG, and λ_0 is a constant related to the filter function. Equation (2) is linearly dependent on the Bragg wavelength change but independent of light intensity variation due to the source fluctuation, etc. [12]. That is because the intensity variations are cancelled out by comparing the signal I_S with the reference I_R [12].

This technique is very simple and reliable. But its measurement range is generally limited due to the availability of the linear transmission range (as illustrated in Figure 1(a), usually few nanometers wavelength range) of the filter. Also the optical signal to noise ratio (OSNR) is an issue when the Bragg wavelengths of the sensors fall in the low transmission end of the filter. This technique is suitable for the monitoring of one or a few gratings, depending on the measurement range.

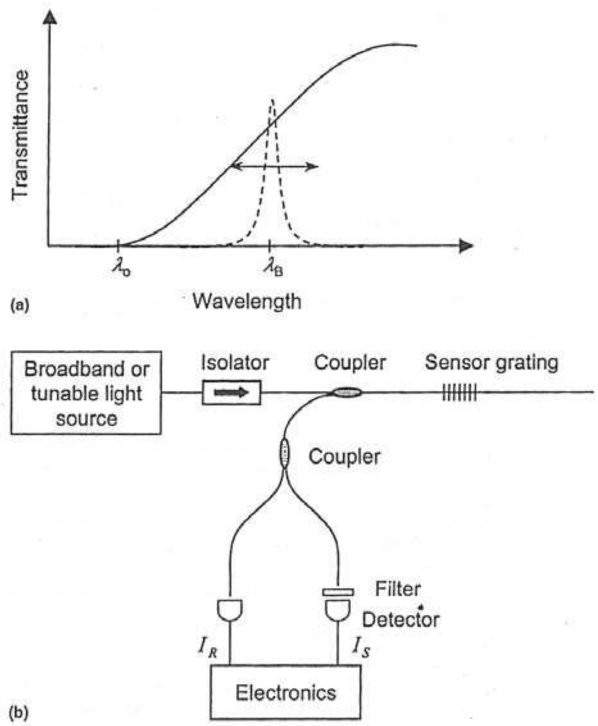


Figure 2 Illustration of wavelength interrogation by an optical filter

(a)Transmittance of the linearly wavelength-dependent optical filter interrogator (The dashed peak shows the light reflected by a FBG sensor), (b) Illustration of the sensing system

2.2.2 CCD spectrometer interrogator

This method is suitable for multipoint fibre grating sensors. As illustrated in Figure 3 [13], lights reflected from FBGs are directed to a fixed diffractive element such as finely ruled diffraction gratings and then focused to a CCD. For light incident to the diffraction grating, the diffraction angle is dependent on the wavelength of the light. Therefore, lights with different wavelengths illuminate different areas of pixels. The change in the light wavelength results in the shift of the light at the detector array of the CCD.

The main advantages of this technique are its suitability for multi-sensor interrogation and compact configuration. Since this approach collects all the light returned by each FBG over the entire scan period of the CCD, it is able to detect weak sensor signals. The main drawback of this technique is that the measurement resolution is limited. The resolution of the commercial available interrogators that are based on this approach is usually a few tens of picometers.

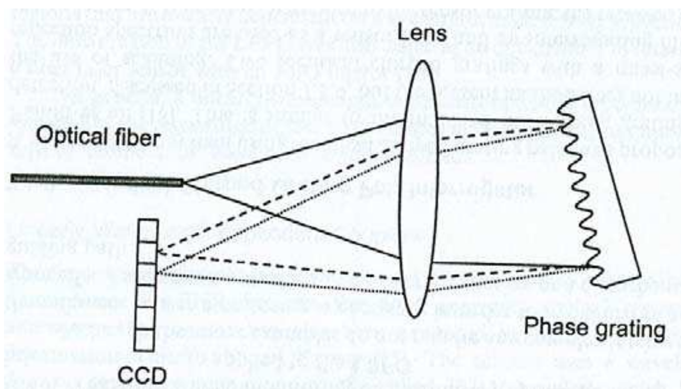


Figure 3 Schematic diagram of the wavelength interrogation system using a CCD and a plane phase grating. The dashed and dotted lines indicate lights with different wavelength

2.2.3 Fabry-Perot filter interrogator

One of the most successful techniques for wavelength-change interrogation of FBG sensors is based on the use of the tunable band pass filter. The most commonly used technique employs a fibre-pigtailed Fabry-Perot tunable filter as a narrow band pass filter [14]. The filter is sometimes referred to as a fibre Fabry-Perot (FFP) interferometer. Figure 4 [11], illustrates a typical transmittance versus wavelength of a FFP.

Figure 5(a) [14] shows the concept for a single FBG element. Light from a broadband source is input into the system, and the component reflected by the FBG is directed via a coupler to a tunable FFP filter, which has a bandwidth comparable with that of the FBG (the bandwidth of a FBG can be designed and fabricated according to the requirements) and a free spectral range (FSR) larger than the operational wavelength domain of the FBG (typically less than ±5 nm). The narrow pass band of the FFP filter is locked to the narrow-band FBG return signal, ***R,*** with a simple feedback-loop arrangement to the tuning mechanism of the FFP (e.g., with piezoelectric adjustment of the FFP cavity spacing). Consequently, the FFP control voltage (feedback voltage) is a measure of the mechanical or thermal perturbation of the FBG. One obvious limitation of this approach is that it can only be used to interrogate a single FBG, and multiplexing of the sensors is not possible in this locked mode. Operating the FFP in a wavelength-scanning mode, however, provides a means for addressing several FBG elements. In this case, as shown in Figure 5(b), several FBG sensor elements are placed along a fibre path (a star or branching arrangement would be equally applicable). The nominal Bragg wavelengths and operational wavelength domains of the FBG□s are chosen not to be overlapped, and all fall within the spectral envelope of the source and the FSR spacing.

This method gives very high measurement resolution and accuracy, in some cases to the level of sub-picometer. But the number of the sensors can be monitored is limited due to the limit of FSR (usually few nanometers). If we need to monitor many sensors simultaneously, then several FFP interrogators need to be stacked. This should significantly increase the dimensions and the cost.

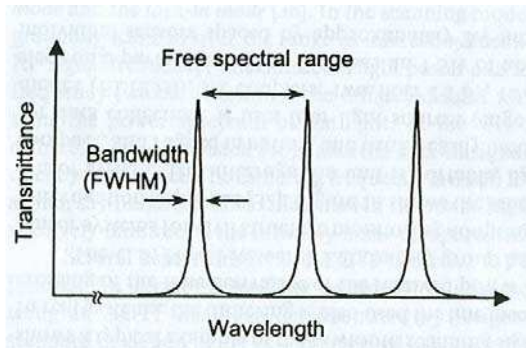


Figure 4 Typical transmittance versus wavelength of the Fabry-Perot filter (FWHM: fullwidth at half-maximum)

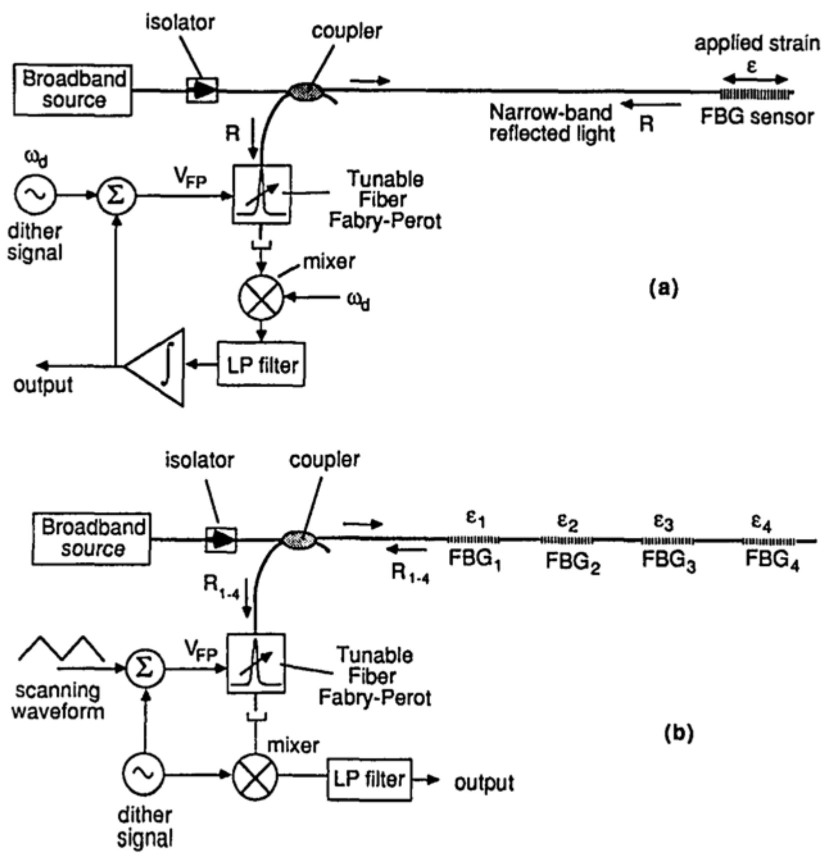


Figure 5 Strain sensor with a FFP interrogator

(a) Single FBG strain sensor with a FFP interrogator in wavelength locked mode.
(b) Multiplexed FBG array with a scanning FFP interrogator in wavelength-scanning mode

2.2.4 Matched Fibre Bragg grating pair interrogator

This interrogation technique, proposed by Jackson *et al.* [15] is based on matching a receiving grating to a corresponding sensor grating. The basic concept of the sensor-receiver grating pair is that the Bragg wavelength of the sensor grating is monitored by filtering the light reflected from the sensor grating with a receiver grating that is nearly identical to the sensor grating at rest. When a strain or a temperature variation is applied to the sensor grating, the matched condition of the Bragg wavelength between the grating pair is not satisfied. But the condition can be easily recovered by tuning the receiver grating with a suitable method. It is possible to utilize a piezoelectric stretcher, to tune the receive grating [15]. The resultant resolution is largely dependent on the bandwidth of the gratings and the resolution of piezoelectric stretcher. Figure 6 [15] illustrates such concept of matched fibre Bragg grating pair interrogator in parallel configuration.

This approach offers very high resolution and accuracy, to the level of sub-picometer [15], and can monitor multi-sensors simultaneously. In theory, it can monitor tens of sensors. The only draw back is every receiver gratings need to be controlled individually and it makes the package bulky and expensive.

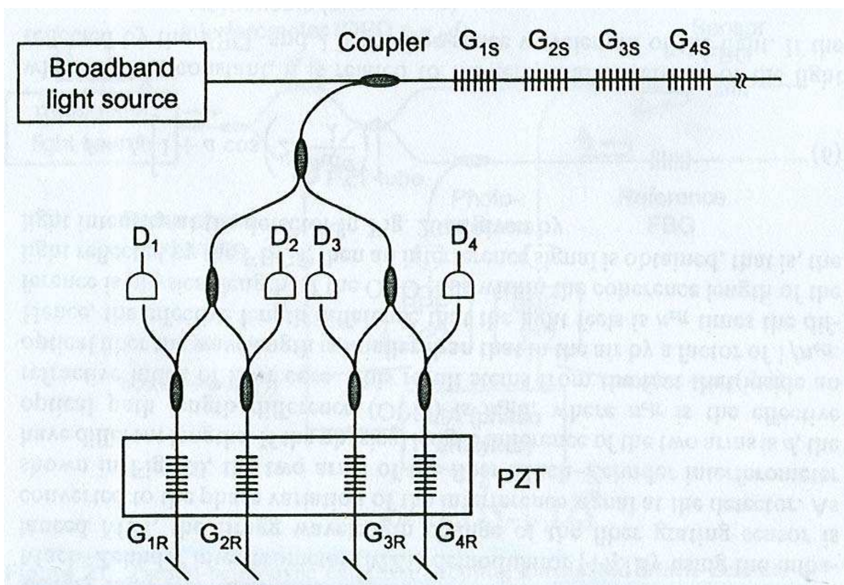


Figure 6 Schematic diagram of matched fibre Bragg grating pair interrogator in parallel configuration

2.2.5 The use of wavelength tunable sources

Many configurations of interrogation systems for the multiplexed arrayed sensors include broadband sources and appropriate filtering devices for detecting spectral change in reflected light from the sensor gratings. However, most of the broadband sources are not high-power devices, and the receivable optical powers are reduced considerably after the broadband light is reflected from the narrow-band sensor gratings. The low power leads to low signal to optical noise ratios (OSNRs), which might reduce the reliability of the interrogation and increase the interrogation time.

If we launch a light with very narrow bandwith, but of known wavelength, to a sensor grating, the detected optical power reflected from the sensor grating indicates the spectral response of the sensor at that given wavelength. As a result, it is possible to fully interrogate the spectral change in the sensor grating by tuning the wavelength of the laser source over a spectral range of interest. Both the tunable fibre laser and tunable semiconductor laser are readily utilized. However, this type of interrogators is currently very expensive and bulky and can only be found in the lab. Figure 7 [16] illustrates the use of a tunable laser source for interrogation of multi FBG sensors.

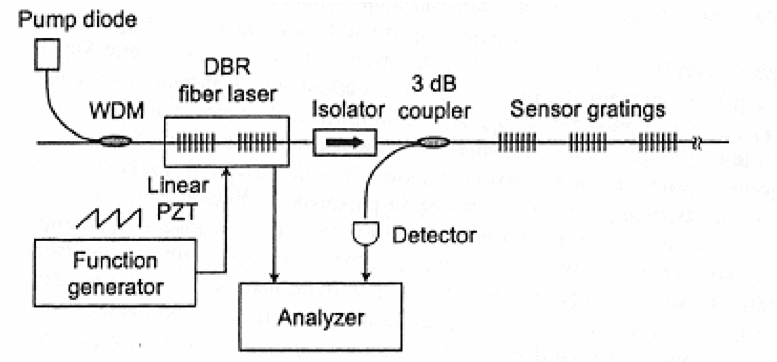


Figure 7 Example of a tunable laser source for interrogation of multi FBG sensors

From the above presentation, it can be observed that each method has its own advantages and disadvantages for a specific requirement. To develop a sensor interrogator suitable for Defence R&D Canada (DRDC) needs, we plan to use the operation principle of the matched Bragg grating pairs approach discussed above and shown in Figure 6. However, instead of using receiver gratings, we will use planar lightwave circuits based demultiplexers, which would overcome the disadvantages associated with the approach.

3. Specifications of sensor interrogator prototypes

Based on the needs of DRDC, project timeline and the funding level, we have identified, as shown in table 1, preliminary specifications for a sensor interrogator prototype slated for development and demonstration. Besides meeting the requirements, the targeting specifications are comparable with those being developed by competitors (e.g.. Ibsen), but with a much more compact size and lower cost.

The selected specifications will meet many application needs, including temperature monitoring, corrosion monitoring, and environmental monitoring. For monitoring rapidly changing parameters (such as dynamic and fatigue events monitoring), the scanning speed of the interrogator needs to be increased. We plan to start the development of this fast sweeping interrogator after we finish the current phase of the developmental work (i.e. development of the fieldable prototype). The targeting specifications for this next generation sensor interrogator are shown in Table 2. These specifications are comparable with those of the bench-top lab equipment but with faster scanning speed, miniaturized size and lower cost. The long-term goal of this work will be to integrate the above interrogators with an optical power source and wireless communication functions without increasing the device dimension and significantly impacting the cost and the reliability.

Table 1 Preliminary specifications for miniaturized fieldable fibre Bragg grating sensor interrogator

Parameters	Target Specifications (2006-2008)
Optical	
Number of Channels	1
Wavelength Range	1530 nm~1555 nm
Wavelength resolution	<±1 pm
Wavelength accuracy	<±10pm
Dynamic range	>25 dB
Scan frequency	1 Hz
Maximum sensor per channel	4
Optical Connector	FC/APC
Mechanical	
Dimension	12 cm x 8 cm x 5 cm
Weight	500 g
Environmental	
Operating temperature	-65°C to 65°C
Operating Humidity	0 to 80%, non-condensing
Storage temperature	-65°C to 65°C
Storage humidity	0 to 80%, non-condensing
Electrical	
Input voltage	+5 VDC
Data Management	
Remote Software	Data logger, peak tracking and instrument control
LabVIEW source code	

Γ. Long-term goal of this prototype will be to integrate the above interrogator with an optical power source and a wireless communication functions without increasing the device dimension.

Table 2 Preliminary specifications for the high speed miniaturized Fibre Bragg Grating sensor interrogator

Parameters	Target specifications (Phase 2)
Optical	
Number of Channels	4
Wavelength Range	1520nm~1590nm
Wavelength resolution	<±1 pm
Wavelength accuracy	<±2 pm
Dynamic range	> 25 dB
Scan frequency	1 KHz
Maximum sensor per channel	80
Optical Connector	FC/APC
Mechanical	
Dimension	12 cm x 8 cm x 5 cm
Weight	500 g
Environmental	
Operating temperature	-65°C to 65°C
Operating Humidity	0 to 100%
Storage temperature	-65°C to 65°C
Storage humidity	0 to 100%
Electrical	
Input voltage	+5 VDC and/or 9V battery
Data Management	
Remote Software	Data logger, peak tracking and instrument control
LabVIEW source code	

4. Development of fieldable (lab) prototype

4.1 Operation principles

Figure 8 illustrates a typical power output signal of distributed FBG sensors (three gratings in this case), each peak's intensity (I_{Si}) can be approximated as a Gaussian distribution, i.e.

$$I_{Si}(\lambda) = S_i \exp[-4(\ln 2)\frac{(\lambda-\lambda_{Si})^2}{\Delta\lambda_{Si}^2}] \tag{3}$$

where S_i, λ_{Si} and $\Delta\lambda_{Si}$ are the peak transmittance, center wavelength and full width at half maximum (FWHM) of the Gaussian profile of the i^{th} sensor in a sensor network, respectively. The error caused by this assumption is quite small and can be neglected according to the analyses given in [17]. As the Bragg wavelength (the center wavelength shown in Equation 3) of a FBG sensor drifts with the variations of the parameters of interested, the key to monitor this sensor is to measure the drift of its Bragg wavelength.

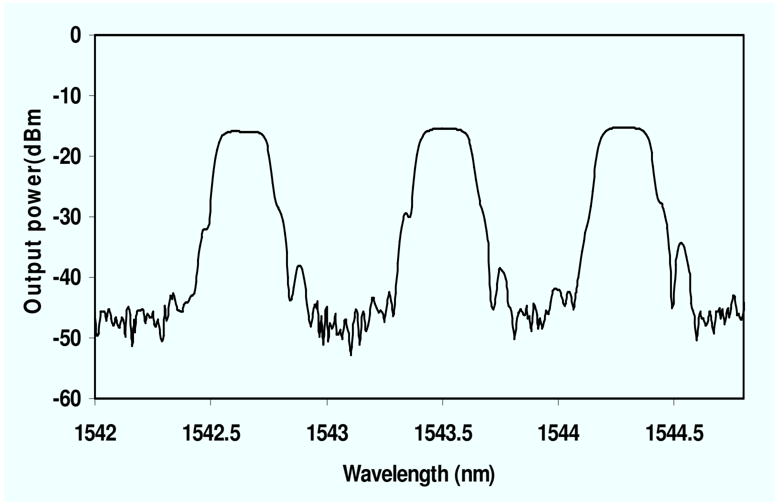


Figure 8 Typical experimental measured reflection spectra of three FBG sensors

Planar lightwave circuits based demultiplexer, such as echelle diffractive gratings (EDG) and arrayed waveguide gratings (AWG), were initially developed for telecommunication applications. Their reliability has been proved by their deployment in optical networks. The transmission spectra (I_{Ej}) of those demultiplexers can be designed as Gaussians (Figure 9) and are expressed as

$$I_{Ej}(\lambda) = E_j \exp[-4(\ln 2)\frac{(\lambda - \lambda_{Ej})^2}{\Delta\lambda_{Ej}^2}] \tag{4}$$

where E_j, λ_{Ej}, and $\Delta\lambda_{Ej}$ are the peak transmittance, center wavelength, FWHM of the Gaussian profile of the j^{th} channel of the demultiplexer, respectively.

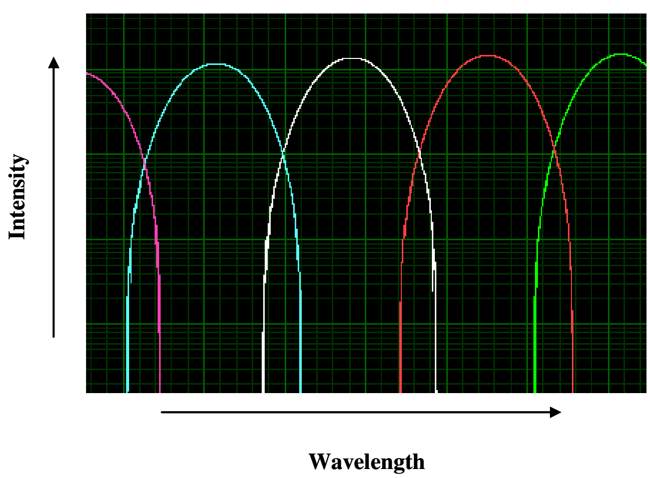


Figure 9 Typical transmission spectra of a Gaussian EDG demultiplexer

Therefore, similar to those matching principles discussed in the literature [9,15,17], If we can match the j^{th} channel of the demultiplexer to that of the i^{th} FBG sensor, in principle we would be able to interrogate the Bragg wavelengths of the sensors using the planar lightwave circuit based demultiplexer. Figure 10 shows a set-up for the demonstration of the concept. The setup includes a broadband light source, an optical circulator, a planar lightwave circuits based demultiplexer, photodetector arrays, and an electronic controller.

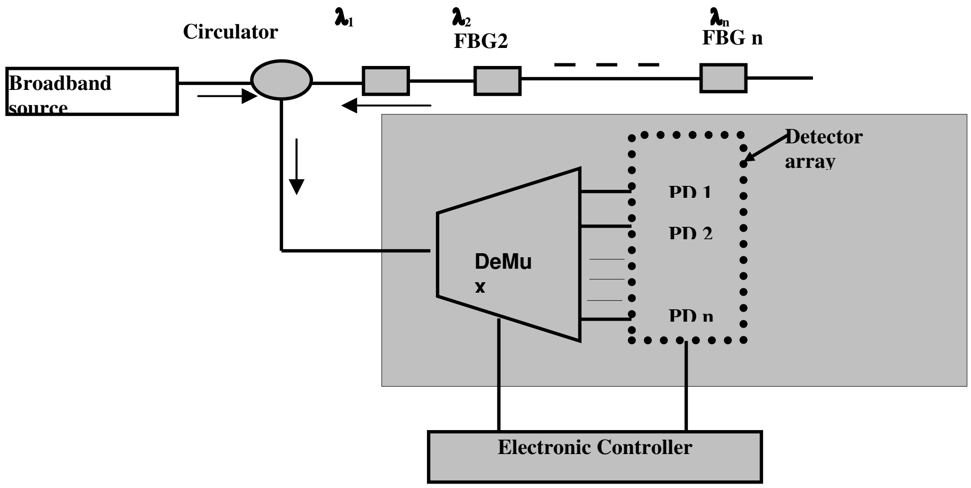


Figure 10 Illustration of the setup for the demonstration of the operation principle of the proposed planar lightwave circuit based interrogator

It is assumed that the signal collected by the j^{th} EDG channel is mainly from the i^{th} FBG sensor while the contributions from other sensors are very small and can be neglected. This assumption can be easily satisfied by proper design of the sensor□s working wavelength range. Hence, the power detected by the j^{th} EDG channel can be described by [9,17,18]

$$I_{ji}(\lambda_{Ej}) \approx k_j E_j S_i \Delta\lambda_{Ej} \Delta\lambda_{Si} \times \sqrt{\frac{\pi}{(\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2) 4 \ln 2}} \times \exp[-4(\ln 2) \frac{(\lambda_{Ej} - \lambda_{Si})^2}{\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2}] \tag{5}$$

where k_j is a constant related to the source power, detector sensitivity and etc. From this equation we know that the $I_{ji}(\lambda_{Ej}) \sim \lambda_{Ej}$ curve is a Gaussian with the FWHM equalling $\sqrt{(\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2)}$ and the peak value equalling K_j, (which is achieved when $\lambda_{Ej} = \lambda_{Si}$).

$$K_j = k_j E_j S_i \Delta\lambda_{Ej} \Delta\lambda_{Si} \times \sqrt{\frac{\pi}{(\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2) 4 \ln 2}} \tag{6}$$

Assuming that the transmission wavelengths of the planar lightwave circuits based demultiplexer can be tuned by a simple and linear manner, i.e.

$$\lambda_{Ej}(X) = B * X + C \tag{7}$$

where B and C are constants and X is the tuning parameter. Combining equations (5)-(7), we obtain:

$$I_{ji}(X) = K_j \exp[-4(\ln 2)\frac{(B * X + C - \lambda_{Si})^2}{\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2}] \tag{8}$$

where equation (7) shows that $I_{ji}(X) \sim X$ curve is also a Gaussian with the FWHM expressed as $\sqrt{(\Delta\lambda_{An}^2 + \Delta\lambda_{Si}^2)}$ and the peak value as K_j. The peak value is reached when $\lambda_{Si} = B*X+C$. Hence, by finding the value of the tuning parameter corresponding to the peak of the $I_{ji}(X) \sim X$ curve, we obtain the sensor wavelength, λ_{Si}.

4.2 Lab prototype development

In this prototype development work, Echelle Diffractive Gratings (EDG) based demultiplexer is used. As the transmission wavelengths of the EDG demultiplexer can be linearly tuned with the chip temperature T, as shown in Figure 11, Equation (7) can be rewritten as:

$$I_{ji}(T) = K_j \exp[-4(\ln 2)\frac{(B * T + C - \lambda_{Si})^2}{\Delta\lambda_{Ej}^2 + \Delta\lambda_{Si}^2}] \tag{9}$$

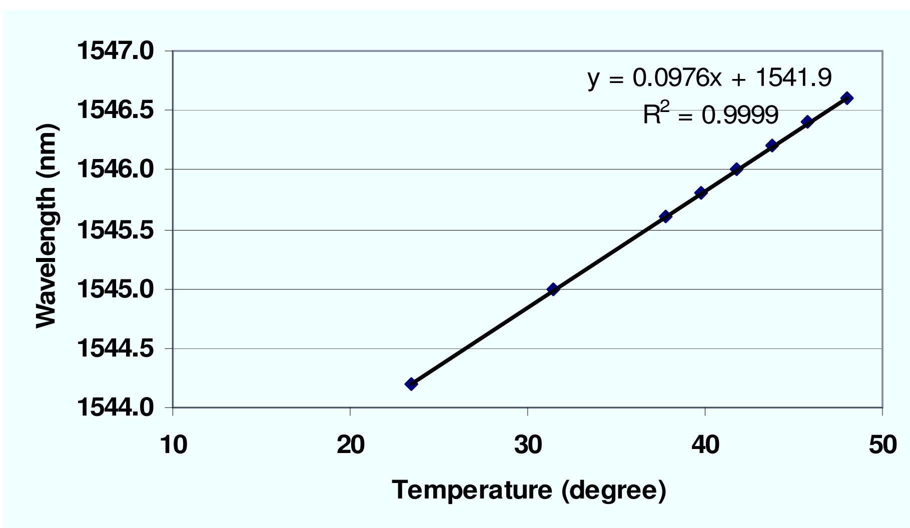
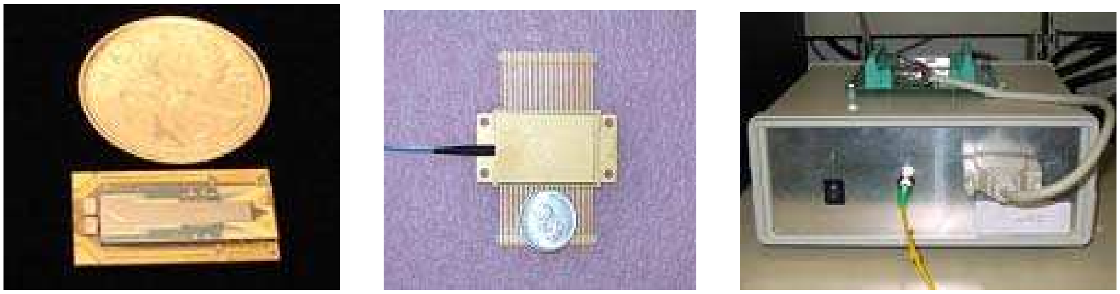


Figure 11 Example of the changes of the transmission wavelength of the EDG demultiplexer with the chip temperature

Hence, by finding the value of the chip temperature corresponding to the peak of the $I_{ji}(T)$ ~ T curve, the wavelength of the i^{th} sensor, λ_{Si}, can be determined.



(a) EDG chip *(b) interrogator without controller* *(c) interrogator with controller*

Figure 12: Pictures of the EDG based interrogator.

The EDG demultiplexer (Figure 12(a)) and the detector arrays can be monolithically integrated on an InP chip, as shown in Figure 12(b). Based on this chip, we have developed a compact and light-weight interrogator prototype with our industrial partners (Metro Photonics, O/E Land and IgnisPhotonyx). Figure 12(c) shows the pictures of this device. It includes a monolithically integrated EDG demultiplexer and waveguide PIN detector arrays on an InP chip, a thermoelectric cooler (TEC), a RTD sensor, a heat dissipater and the electronic controller. The TEC was integrated with the chip for the purpose of adjusting the temperature of the chip while the RTD sensor was integrated into the chip for the monitoring of the temperature change in the chip. The whole packaged device without the controller, shown in Figure 12(b)) weighs less than 60 g and is smaller than 45 mm x 30 mm x 15 mm.

This miniaturized interrogator has been used to monitor the wavelength of five distributed fibre Bragg gratings. Figure 13 gives an example of the signals collected by the interrogator. The results show a Gaussian relationship between the signal intensity and the EDG chip temperature, thus confirming equation (9). The measured wavelength values are listed in Table 3.

Table 3 Comparison between the Bragg wavelengths of the FBG sensors measured by the miniaturized interrogator prototype and those supplied by the manufacturer in the static mode

Sensors	Sensor wavelength (nm)	Sensor wavelength supplied by the manufacturer (nm)
1	1543.486	1543.52
2	1544.267	1544.30
3	1545.048	1545.06
4	1545.911	1545.90
5	1546.658	1546.66

It is noted that the measurement resolution of the interrogator is better than 1pm as the reading resolution of the EDG chip temperature is better than 0.01°C. For comparison purpose, we also quote the grating wavelengths supplied by the manufacturer. It is observed that the measured wavelengths are in good agreement with those provided by the manufacturer. The small variations between the data measured and those provided by the manufacturer can be attributed to the differences in measurement environments such as the impact of temperature and strain on the grating. It is well known that Bragg wavelength shifts with temperature at a rate of ~ 13 pm/°C and strain at a rate of ~ 1.2 pm/με for Bragg wavelength of 1550 nm [19].

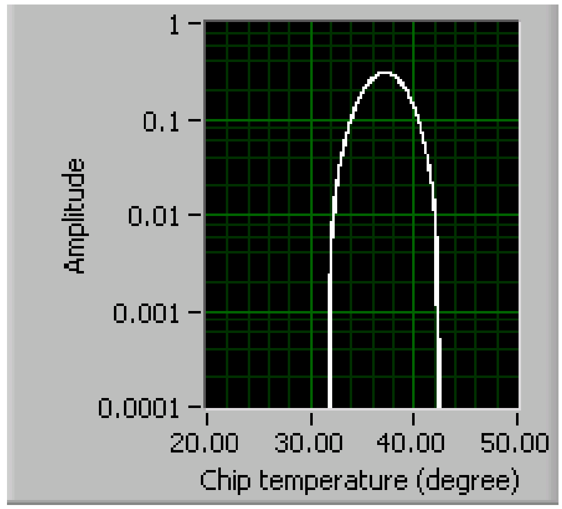


Figure 13 Example of the changes of sensor signal with the EDG chip temperature

The interrogator has also been used to directly monitor the sensing parameter, such as temperature. Figure 14 presents an example of the experimental results of a FBG temperature sensor interrogated by the miniaturized interrogator illustrated in Figure 12. As shown, by monitoring the EDG temperature corresponding to the maximum optical power in a dedicated channel, the FBG temperature sensor can be precisely interrogated.

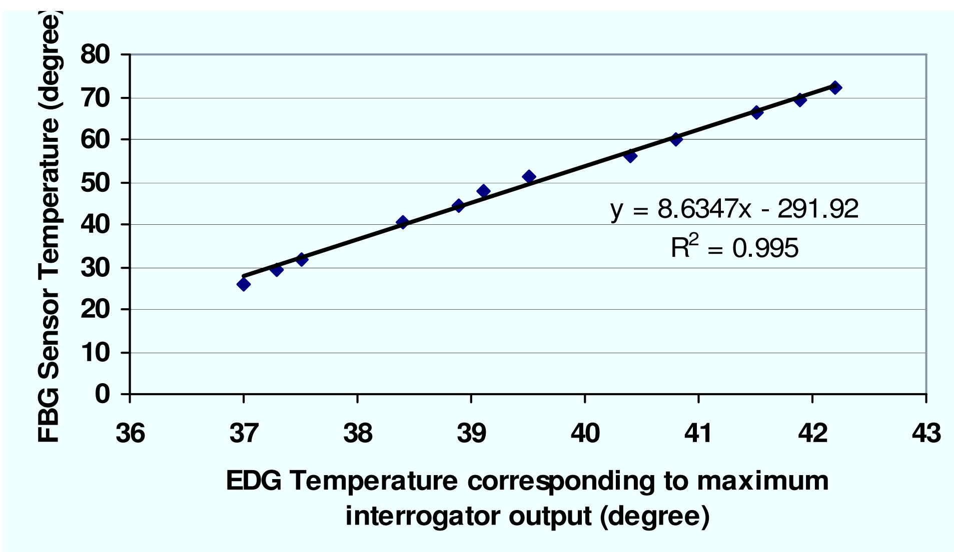


Figure 14 Interrogation result of a FBG temperature sensor using the miniaturized interrogator prototype

The accuracy of this interrogator has been found to be ±10 pm. Figure 15 shows the repeatability of three FBG sensors being measured over three days, the vertical axis is the chip temperature, which has a linear relationship with the wavelength (as the example shown in Figure 10)

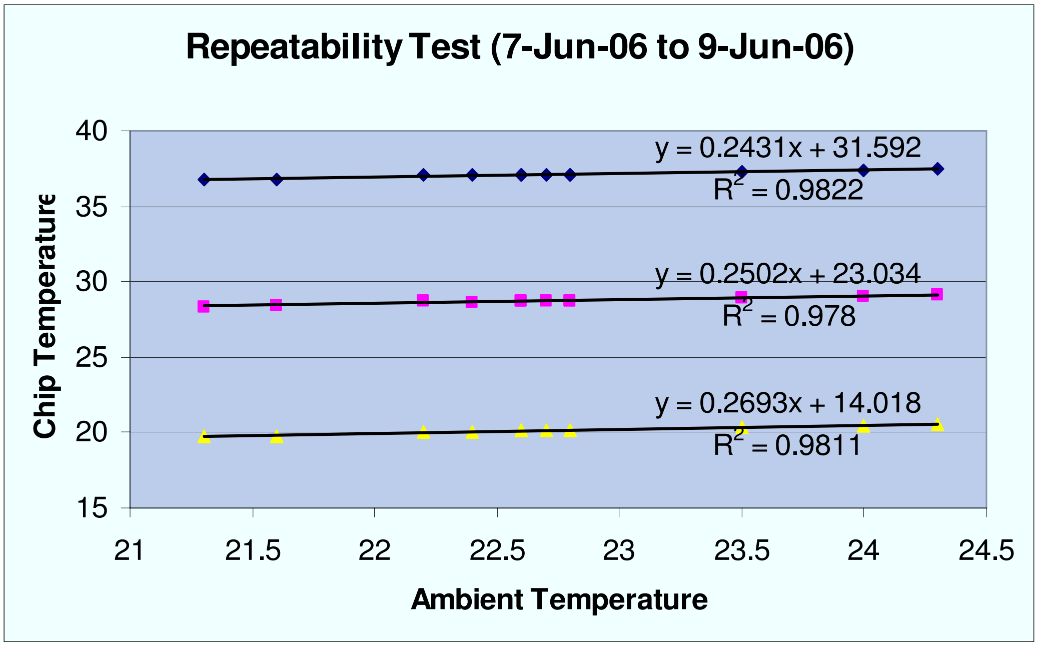


Figure 15 Repeatability of the EDG interrogator

5. Milestones achieved

The milestones listed in the statement of work appended to DND/NRC MOU Annex number DND/NRC/IAR/2005-11, for year 1 have been fully achieved. These are listed below:

- Sensing system requirements and technology assessment
- Delivery of a lab-based demodulation system conceptualization, design and prototype

5.1 Lab prototype

Figure 16 shows the lab prototype developed according to the plan. The performance of this prototype is shown in Table 4. It has met most of the performance specifications, except the response time. This will be addressed in the fieldable prototype. The dimension and the electric connection of the prototype will also be addressed in the year II of this project.

Figure 16 Picture of the lab prototype

Table 4 Main current and projected performance of the lab prototype

Parameters	Target	Current
Resolution	< ± 1 pm	< ± 1 pm
Accuracy	< ± 10 pm	< ±10 pm
Response time	<1 s	~ 1 minute
Number of sensors can be monitored	4	4
Monitoring range of each sensor	3.2 nm	3.2 nm
Dimension	Palm size	$250x250x110cm^3$

5.2 List of Publications

Gaozhi Xiao, Fengguo Sun, Zhiyi Zhang, Zhenguo Lu and Jiaren Liu, “A Miniaturized Optical Fiber Bragg Grating Sensor Interrogator Based on Echelle Diffractive Gratings”, Microwave and Optical Technology Letters, 49, 668-671 (2007)

F. G. Sun, G. Z. Xiao, Z. Y. Zhang and Z. G. Lu, “Modeling of Arrayed Gratings for Wavelength Interrogation Application”, Optics Communications, 271, 105-108 (2007)

Gaozhi Xiao, Fengguo Sun, Zhiyi Zhang, Zhenguo Lu, Jiaren Liu, Nezih Mrad, and Fang Wu; “A Monolithically Integrated Micro Wavelength Interrogator for Fiber Bragg Grating Sensor Applications”, Proceedings of the 18th International Conference on Optical Fiber Sensors Topical Meeting, TuE20, 23-27 October 2006, Cancun, Mexico.

G. Z. Xiao and N. Mrad, “Micro Fiber Optic Sensor Interrogation System for Aerospace Applications”, Caneus 2006 Conference on Micro and Nano Technologies for Aerospace Applications, Toulouse, France, 11028, August 27 to September 1 2006.

Gaozhi Xiao, N. Mrad, Fengguo Sun, Zhiyi Zhang and Jiaren Liu “Micro Fiber Optic Sensor Systems for Potential Aerospace Applications”, invited talk presented to Caneus 2006 Conference

on Micro and Nano Technologies for Aerospace Applications, Toulouse, France, S-10, August 27 to September 1 2006.

6. Plan for year II

The main plan for year II of this project is to develop a fieldable sensor interrogator prototype. We are expecting to meet the majority of the targeted specifications shown in Table 1, including optical, mechanical, electrical and data management specifications. For the environmental specifications, we are considering them in the design but not for testing and verifications.

7. Conclusions

In conclusion, we have fully achieved the milestones outlined in the project agreement. The sensing system requirements and technology assessment are presented in this report. A lab-based demodulation system has been conceptualized, designed and prototyped.

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The increasing requirements for efficient and cost effective aircraft fleets management necessitate the integration of on-line health monitoring capability. Such capability must be reliable, robust and must easily respond to the physical and environmental constraints imposed by the aircraft environment. Highly multiplexed fibre optic Bragg grating sensors are assessed to meet this challenging environment. In an effort to develop a suitable small size, rugged, reliable data acquisition (demodulation) system to interrogate these highly multiplexed fibre optic sensors, a research and developmental activity is initiated. This report documents the progress made towards such development. Preliminary results, demonstrated the suitability of the use of an Arrayed Waveguide Grating (AWG) based demodulation system for monitoring five serially multiplexed gratings. The currently experienced limitation of this miniature demodulation system resides in its inability to perform high speed (>1 min) dynamic measurements.

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