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Processing of Signals From Fiber Bragg Gratings Using Unbalanced Interferometers

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Processing of signals from fiber Bragg gratings using unbalanced interferometers

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ABSTRACT

Fiber Bragg gratings (FBG) have become preferred sensory structures in fiber optic sensing system. High sensitivity, embedability, and multiplexing capabilities make FBGs superior to other sensor configurations. The main feature of FBGs is that they respond in the wavelength domain with the wavelength of the returned signal as the indicator of the measured parameter. The wavelength is then converted to optical intensity by a photodetector to detect corresponding changes in intensity. This wavelength-to-intensity conversion is a crucial part in any FBG-based sensing system. Among the various types of wavelength-to-intensity converters, unbalanced interferometers are especially attractive because of their small weight and volume, lack of moving parts, easy integration, and good stability.

In this paper we investigate the applicability of unbalanced interferometers to analyze signals reflected from Bragg gratings. Analytical and experimental data are presented.

Keywords: Fiber Bragg gratings, temperature sensors, fiber optics, interferometer

1. INTRODUCTION

Fiber Bragg gratings (FBGs) have found numerous applications in sensing and communication systems.[1] The principle of FBGs is based on a selective spectral reflectivity of a section of fiber that has a periodically varied refractive index. The period of these variations is affected by the environmental conditions the fiber is in and varies with changes in the environment. Thus, with changes in the environment, the spectra of the reflected signal changes. This property makes an FBG a superior sensing element.

Another distinguished feature of Bragg grating sensors is that these sensors are so called spectral sensors. This means that the response of Bragg gratings to changes in the environment occurs in the spectral domain. The position of the signal peak in the spectral domain is affected by the environment (temperature, pressure, etc.). To evaluate the performance of an FBG one should send a signal reflected from the grating to a spectrometer with a dispersive element like spectral prism or focal plane array detector. Sophisticated software then would correlate a position of the optical spot on the array detector with the wavelength of light that generated the spot. Such an arrangement suffers drawbacks because of the weight and size of constituent components. Another approach, more practical and suitable for aerospace applications, would involve a smaller and lighter device capable of converting the wavelength to intensity. One of such devices is an unbalanced interferometer.[2–4]

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2. UNBALANCED INTERFEROMETER

2.1 Interference in unbalanced interferometer

It has been previously shown that the intensity pattern resulting from the interference of two optical beams having identical intensities, I_0, and wavelengths, λ_0, has the following form:

$$I = 2I_0\left[1+\cos\left(\frac{2\pi}{\lambda_0}\Delta(nL)\right)\gamma\right], \tag{1}$$

where I_0 is the light intensity in each arms of the interferometer,

λ_0 is the central wavelength of the light,

$\Delta(nL)$ is the optical path difference or imbalance in the interferometer,

γ is the fringe visibility function.

The optical path difference, $\Delta(nL)$, is a function of the physical lengths of the interferometer arms and the refractive indices of the arm materials. Changes in the environment may affect both the refractive indices and the physical length of the arms, altering the optical path length. The optical path difference of the two arms is called imbalance. The interferometer is also sensitive to the wavelength of light that passes through it. In this case, if the imbalance of the interferometer is unchanged, it becomes a wavelength detector.

The fringe visibility function is

$$\gamma = \exp\left[-\left(\frac{\pi}{2\sqrt{\ln 2}}\frac{\Delta\lambda}{\lambda_0^2}\Delta(nL)\right)^2\right], \tag{2}$$

where $\Delta\lambda$ is the optical bandwidth.

Analysis of Eq. (1) show that continuous monotonic variations in the wavelength, λ_0, lead to quasi-periodic variations in the resultant intensity output of the interferometer.

2.2 Instrument function

The ability of an instrument to change the otherwise continuously constant spectrum of incident light is described by its instrument function. In the case of an unbalanced interferometer, its instrument function, as a function of wavelength, is described as follows:

$$I(\lambda) = 2\left[1+\cos\left(\frac{2\pi}{\lambda}\Delta(nL)\right)\right], \tag{3}$$

Figure 1 shows a plot of the computed instrument function of an unbalanced interferometer with an optical imbalance of 2.0 mm. Oscillations in the wavelength domain are clearly observed and the period of these oscillations, Λ_λ, is approximately:

$$\Lambda_\lambda \approx \frac{\lambda_0^2}{\Delta(nL)}, \tag{4}$$

2.3 Observation of the instrument function

To obtain an instrument function of an unbalanced interferometer, its input should be a time-domain Delta function, which in the spectral domain, corresponds to an infinitely broad spectrum. In practice we generate a quasi-transfer function by applying an input signal with a broad, but wavelength limited spectrum. Experimentally, the quasi-transfer function of the interferometer in the optical domain is obtained by sending broadband light through the interferometer and detecting the transmitted spectrum using a commercial optical spectrum analyzer. The source of the broadband light used in this experiment was a superluminescent light emitting diode with a nominal center wavelength of 1550 nm and optical bandwidth of 40 nm. Figure 2 depicts the quasi-transfer function of the unbalanced interferometer used in the experiment. This plot clearly displays quasi-periodic changes of the resultant light intensity in the spectral domain and monotonic variations in the instrument function between its neighboring maximum and minimum values.

When an unbalanced interferometer is used to measure wavelength, the interferometer's instrument function causes its resultant light intensity to vary depending on the spectral position of the wavelength relative to the instrument function. If the wavelength of the incident light varies between the neighboring maximum and minimum values of the instrument function, then the value of the resultant light intensity changes monotonically.

3. EXPERIMENT

3.1. Test setup

The test setup, as seen in Fig. 3, consists of a thermally stabilized super-luminescent diode (SLED) light source connected to a 90/10 coupler. The 10% output of the coupler is connected to a photodetector, PD, used to monitor the SLED stability throughout the experiment. The 90% output port of the coupler is connected to the first port of a 3-port fiber optic circulator. The second port of the circulator is connected to the FBG which is inside a box furnace. The reflected signal from the FBG propagates back through the circulator to an optical amplifier. The amplifier boosts the signal to a more easily detectable level. The amplified signal from the FBG is then multiplied by the instrument function of the unbalanced interferometer. The output of the interferometer is monitored using an optical spectrum analyzer (OSA). All equipment control and data acquisition is accomplished using LabVIEW. The arrangement permits recording and processing the quasi-instantaneous light spectra that reach the OSA as well as conducting a fast integration of the light intensities over a broad range of wavelengths. The integration of light intensities over a broad range of wavelengths is similar to a having a photodetector instead of the OSA.

The experiment consists of heating the furnace with the FBG from room temperature up to 500 °C and measuring the total power of the optical signal reflected by the FBG using the OSA. Because the optical signal, prior to reaching the OSA, has to pass through the unbalanced interferometer, its intensity is modulated by the interferometer's instrument function. Integrating the signals from the OSA during the heating process of the FBG provides information on changes in the total optical power and thus changes in the FBG's wavelength.

3.2 Fiber Bragg gratings

Conversion of wavelength to intensity assumes that the intensity of the optical signal reflected back from the FBG remains constant over a large range of temperatures. To assure the FBGs are stable, they to be specially treated. This treatment consists of annealing the gratings at 1000 °C for several hundred hours. This treatment leads to the dissipation of the original FBG and subsequent formation of secondary gratings in place of the original. It has been recently demonstrated that the secondary gratings exhibit high thermal stability, thus providing a stable intensity level to the interferometer.[5–7]

After evaluating the performance of the unbalanced interferometer, the FBG's response to changes in temperature was reevaluated by processing spectra of corresponding signals reflected by the grating. The setup for this was identical to the one described in Fig. 3 with the exception of the removal of the unbalanced interferometer from the setup. Figure 4 shows FBG spectra from this evaluation recorded at three different temperatures with a 100 °C interval. It can be seen in this figure that the peak power at the FBG reflected wavelengths was practically unchanged.

3.3. Unbalanced interferometer

To keep the optical path difference of the interferometer constant, its construction takes advantage of the birefringent properties of a $LiNbO_3$ crystal. Detailed descriptions of devices that utilize these properties and their principle of operation are described elsewhere.[8,9] The imbalance, $\Delta(nL)$, in the $LiNbO_3$ crystals is generated by a difference in the transit time between the two orthogonally polarized components of light propagating through the crystal. These components have different refractive indices, n_o and n_e, and are referred to as ordinary and extraordinary beams. The difference in the transit time for these two components leads to the optical imbalance.

The unbalanced interferometer was made from a long Z-cut $LiNbO_3$ crystal that is approximately 20.05 mm long. This crystal splits the incident light into two orthogonally polarized components, which, after passing through the entire length of the crystal, accumulate the optical path difference.[10] The refractive indices, n_o and n_e, of the crystal follow the dispersion relationship for liquids and solids described by Sellmeier's dispersion formula.[11,12] For a wavelength around 1550 nm at room temperature, the indices are found to be approximately n_o~ 2.211 and n_e ~2.138.[13] Thus, over the length of the crystal, the accumulated optical path difference $L(n_o - n_e)$ is approximately 1.464 mm.

Figure 5 shows the impact of the unbalanced interferometer on the FBG spectrum as observed by the OSA. The spectra were taken under conditions similar to those used for generating Fig. 4. Differences in the FBG peak power at the three temperatures shown are due to the unbalanced interferometer.

4. RESULTS AND DISCUSSION

The results of this work have demonstrated that an unbalanced interferometer can change the peak power of an FBG's spectrum. When the FBG's reflected wavelength moves in the spectral domain according to an applied temperature, that change in wavelength can be converted into a corresponding change in the intensity. To track a temperature unambiguously, the interferometer should be constructed in such a way as to make the conversion monotonous. In other words, the period of the quasi-periodic instrument function and the range of thermal variations should match such that changes in the temperature applied to the FBG would always place the corresponding FBG reflected wavelength at either leading or trailing slopes of the instrument function. Figure 6 shows four FBG spectra obtained at different temperatures that place the corresponding FBG wavelengths on a leading slope of the instrument function of the interferometer. Those spectra integrated over a broad range of wavelengths are depicted in Fig. 7. This figure shows the increase in total power as a function of temperature over a range from ambient to about 130 °C.

As shown in previous work, the peak wavelength of an FBG is an accurate representation of temperature and, after annealing, its power output is very stable over a wide temperature range. Also, the power output of the interferometer followed the product of its instrument function and the FBGs input signal very precisely. However an accurate correlation between temperature and the interferometer's output was hampered by the instability of the interferometer. The interferometer was sensitive to the input light's polarization state which we did not have a good means of controlling in this work. With better control of the input polarization, the signal from interferometer would have most likely have been more stable. Alternately, using a depolarizer at the input to the interferometer should greatly reduce interferometer's sensitivity to polarization state. The interferometer used would, in practice, only allow for a relatively narrow temperature range for the sensor. Using an interferometer with a shorter path would allow for a much broader temperature range. Given the results from this experiment, we believe that an FBG in combination with an unbalanced interferometer could be used as a compact temperature measurement system with a wide dynamic range.

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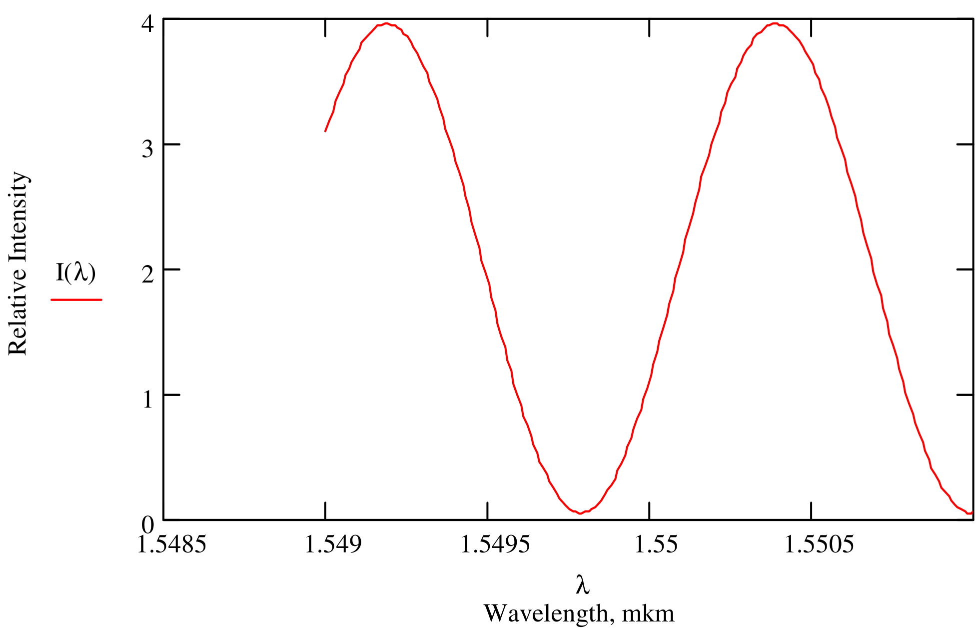

Fig. 1. Instrument function of an unbalanced interferometer with an optical imbalance of 2.0 mm.

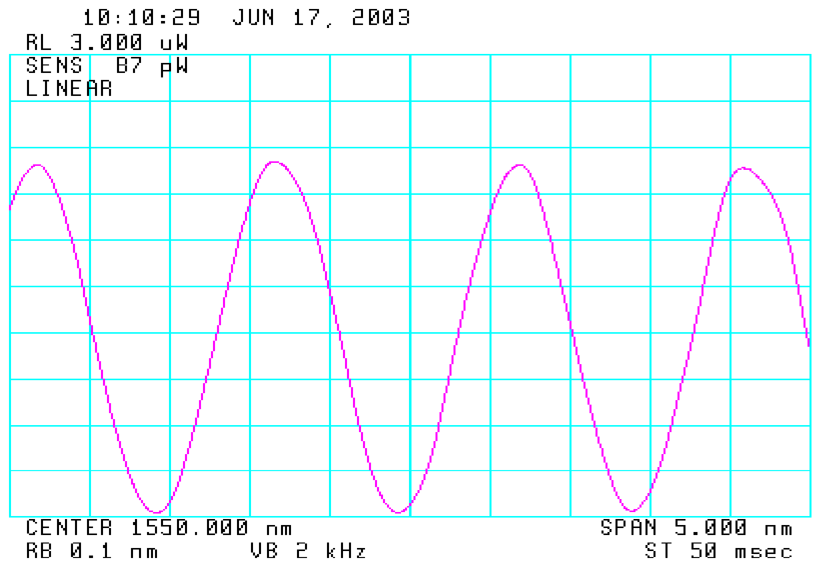

Fig. 2. Instrument function of an unbalanced interferometer observed on the screen of a spectrum analyzer.

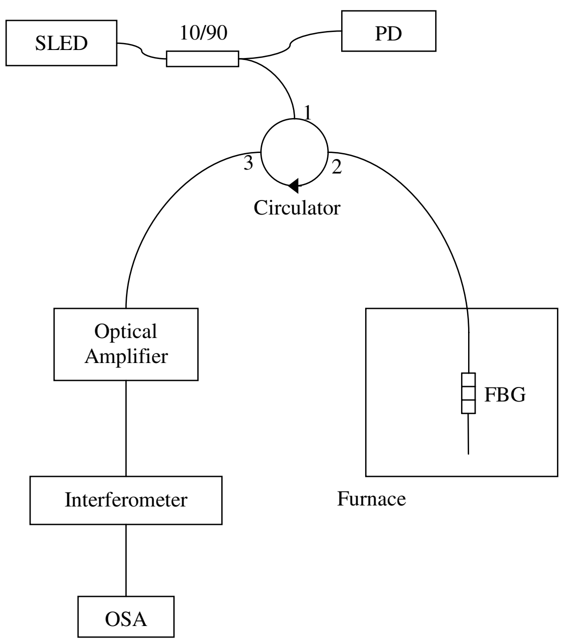

Fig. 3. Experimental setup to demonstrate the suitability of unbalanced interferometers for the wavelength-to-intensity conversion of signals generated by FBGs.

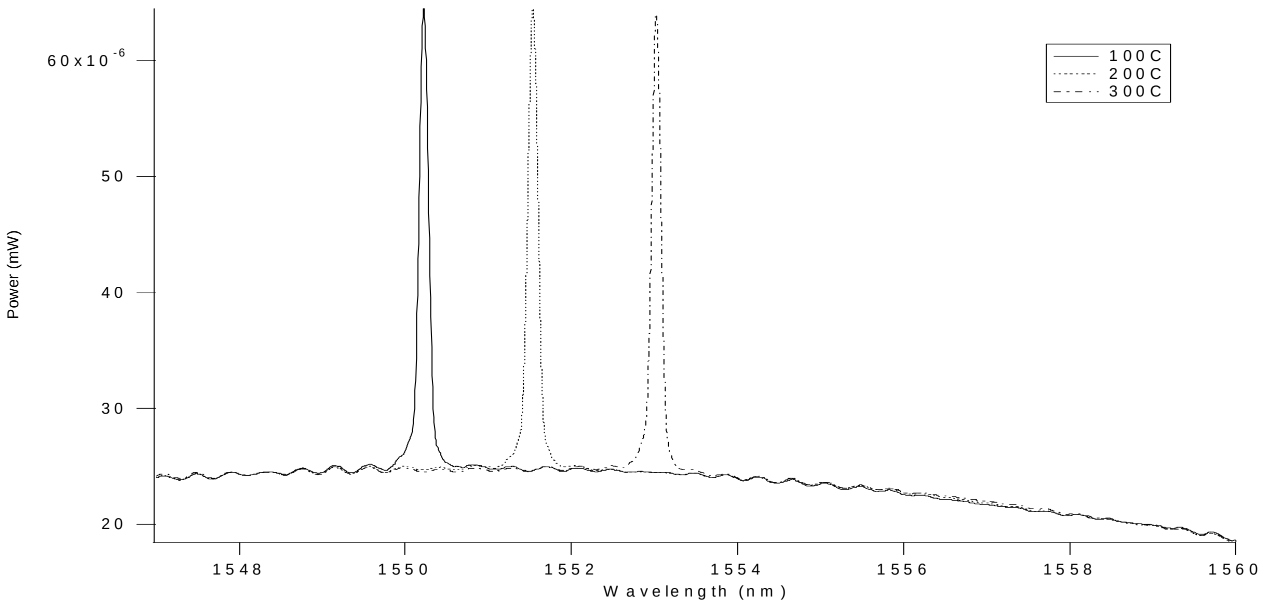

Fig. 4. FBG spectra recorded by a spectrum analyzer at three different temperatures with 100 °C intervals.

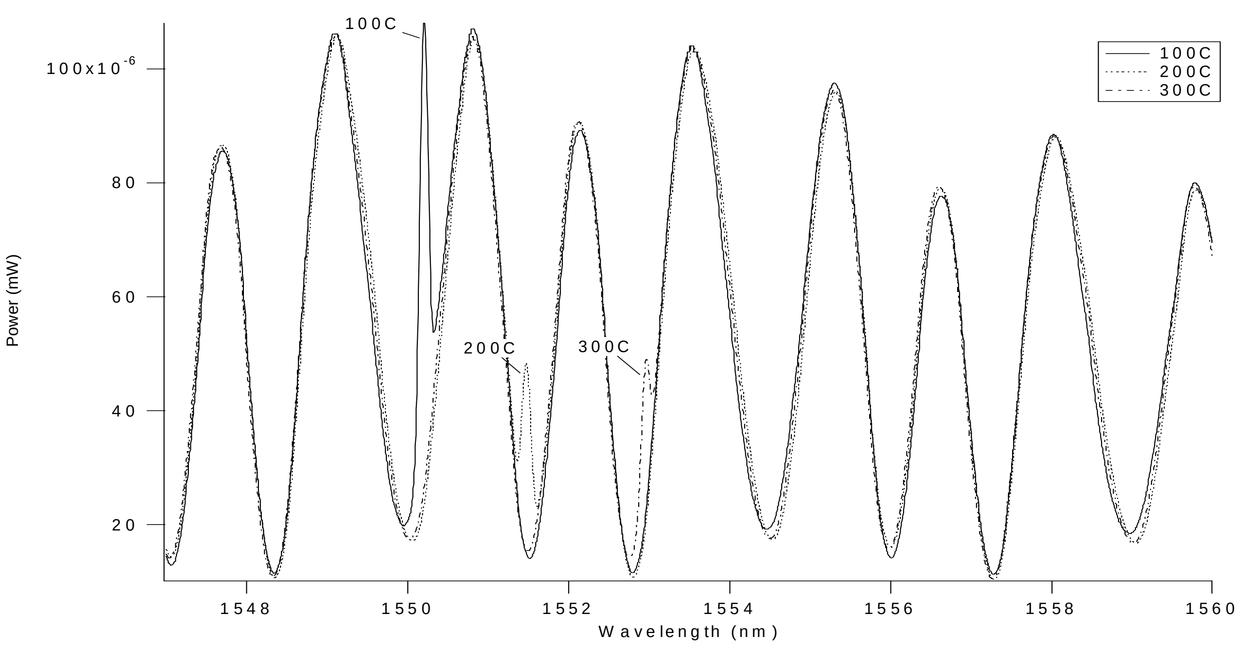

Fig. 5. Impact of an unbalanced interferometer on FBG spectra recorded by a spectrum analyzer at three different temperatures with the 100 °C interval in Fig. 4.

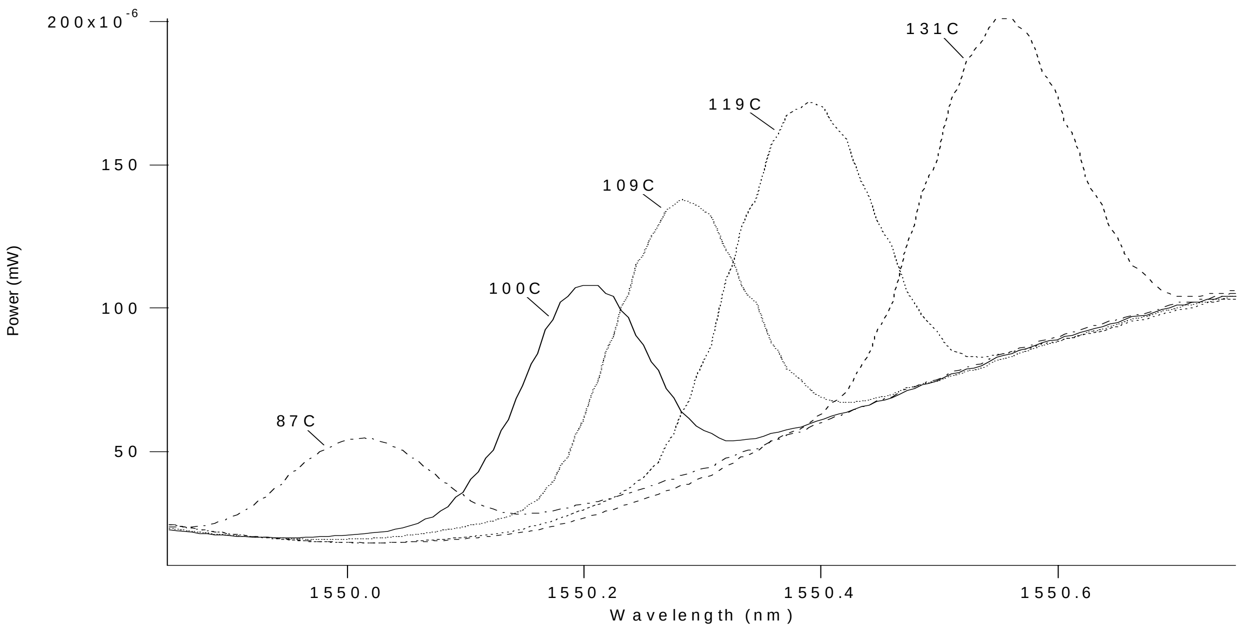

Fig. 6. FBG spectra obtained at five different temperatures that place the corresponding FBG wavelengths at a leading edge of the instrument function of the interferometer.

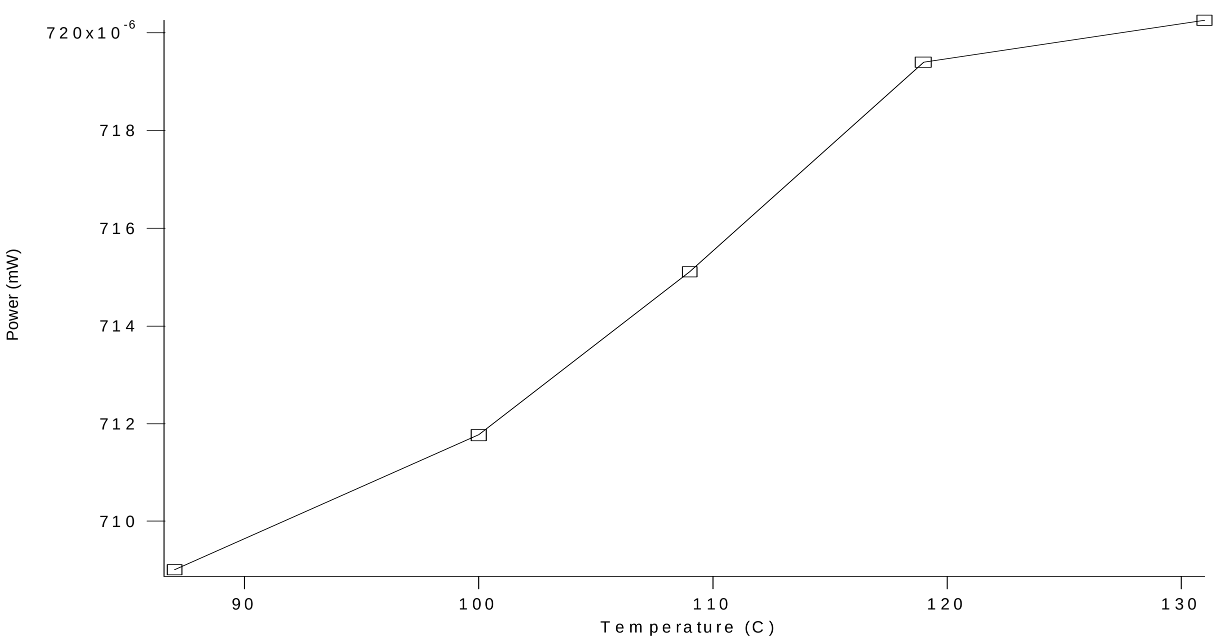

Fig. 7. Results of integration of the FBG spectra over a broad range of wavelengths, obtained at the five temperatures in Fig. 6.

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13. ABSTRACT ***(Maximum 200 words)***

Fiber Bragg gratings (FBG) have become preferred sensory structures in fiber optic sensing system. High sensitivity, embedability, and multiplexing capabilities make FBGs superior to other sensor configurations. The main feature of FBGs is that they respond in the wavelength domain with the wavelength of the returned signal as the indicator of the measured parameter. The wavelength is then converted to optical intensity by a photodetector to detect corresponding changes in intensity. This wavelength-to-intensity conversion is a crucial part in any FBG-based sensing system. Among the various types of wavelength-to-intensity converters, unbalanced interferometers are especially attractive because of their small weight and volume, lack of moving parts, easy integration, and good stability. In this paper we investigate the applicability of unbalanced interferometers to analyze signals reflected from Bragg gratings. Analytical and experimental data are presented.

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