Demultiplexing of Interferometrically Interrogated Fiber Bragg Grating Sensors: FFT vs MUSIC

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Abstract: We describe an interferometric technique for the demodulation of serial fiber Bragg grating sensor arrays, yielding absolute measurement of the individual grating mean wavelengths. We compare two methods for decoding the Bragg wavelengths of gratings.
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OCIS codes: (060.4230) Multiplexing; (070.2590) Fourier transforms; (070.6020) Signal processing; (060.2370) Fiber optics sensors.

1. INTRODUCTION

A variety of schemes for the multiplexing of fiber Bragg grating (FBG) sensors have been demonstrated [1-3]. The multiplexing capacity of FBGs is one of the most important advantages of these sensors as it provides the ability to monitor strain and temperature at multiple points along a single fiber path. This can be easily accomplished by wavelength division multiplexing multiple FBG sensors on a single optical fiber. Each grating has a different Bragg wavelength. The measured information is recovered from these devices by determining the wavelength shift in the Bragg resonance as the FBGs are strained. A variety of techniques have been proposed and demonstrated for the measurement of the Bragg wavelength of FBG sensors. These approaches have often used passive broadband illumination of the sensor and optical filtering techniques, such as interferometric elements, applied to the reflected signal. Interferometric interrogation is, by far, the most sensitive of all interrogation techniques, however interrogating multiplexed FBGs is not straightforward. FBG sensor arrays have been demultiplexed by passing the light reflected from the array through a scanning Michelson interferometer and processing the resulting interferogram to determine peak wavelengths. Davis and Kersey [4] reported 15 pm wavelength resolutions. Flavin et. al. [5], applying the Hilbert transform, reported 5 pm resolution. They also demonstrated an interferometric signal processing technique that provides absolute measurement of the grating's central wavelength with unlimited unambiguous range. Recently, a criterion to design wavelength insensitive interferometers with mirror symmetry, based on Mach-Zehnder add/drop filters has been proposed [6].

In this paper we demonstrate a related technique that can interrogate multiplexed gratings, separating out the signals from each grating using a signal post-processing software. As in ref. [5], the grating's central wavelength is measured by comparing the periodicity of the interferogram with that of a high coherence reference interferogram. The latter was obtained using a tuneable laser source. In this case the interferogram is obtained using a scanning Fabry-Pérot cavity. This device is simpler and, potentially, more stable than the conventional Mach-Zehnder or Michelson interferometers.

The interrogation technique employed calculates the analytic signal of both interferograms, assigning a phase value to every sampled point. We have experimentally compared two processing algorithms for the interrogation of fiber Bragg grating (FBG) sensors which yield absolute measurement of the Bragg wavelength: the Fast Fourier Transform (FFT) method and a novel interrogation technique based on parametric frequency estimation called MUSIC [7,8]. As was theoretically demonstrated in [9], we have determined that the accuracy and the resolution provided by MUSIC are better than that of the FFT method. Also, we discuss processing advantages and tradeoffs of both techniques. They can be useful for measuring a very large number of densely multiplexed wavelengths reflected by gratings illuminated by a broadband source or for interrogating interferometric sensors [8].

2. NETWORK CONFIGURATION

Figure 1 shows a schematic view of the interrogation system proposed. The gratings were illuminated by a Superluminiscent Diode Laser (SLD) via a 2x2 coupler. The reflected signal is led to a scanning Fabry-Pérot interferometer using a three-port circulator. In this work we chose to use a Fabry-Pérot interferometer instead of the more popular Mach-Zehnder for being it easier to implement, more stable and for allowing longer scanning ranges. A Michelson interferometer could have been used instead, but again the Fabry-Pérot is a simpler and more stable interferometer. The output interferogram was periodically sampled at the photodetector as the mirror was scanned through a length L.

When working with a non-monochromatic light such as that coming from an array of FBG sensors, the problem comes from the fact that the interferograms corresponding to the "individual Bragg wavelengths" overlap at the detector composing a more complex image. It is from this complex interferogram that we have to estimate the different Bragg wavelengths that have given rise to it.

One of the major problems in interferometric interrogation techniques has to do with achieving a uniform scanning. This is hard to accomplish in the real world, especially if a low-cost interrogation technique wants to be developed and, therefore, high-end translation stages are to be avoided. However, there is a way to come round that problem. As in references [3,4,10,11] we used a laser reference interferogram. In our approach we simultaneously acquired N samples of both signal and reference interferograms at a fixed sampling rate and we corrected scan non-uniformity entirely in software. Our software derived values of the scan group delay τ_k from the corresponding phase $\phi_L(\tau_k)$ of the reference interferogram's analytic signal by using $\tau_k = \phi_L(\tau_k)\lambda_L / 2\pi c$, where λ_L is the wavelength of the reference source. The interferograms are then resampled at uniform delay intervals by interpolation. This way the effects of a non-uniform scanning are significantly reduced.
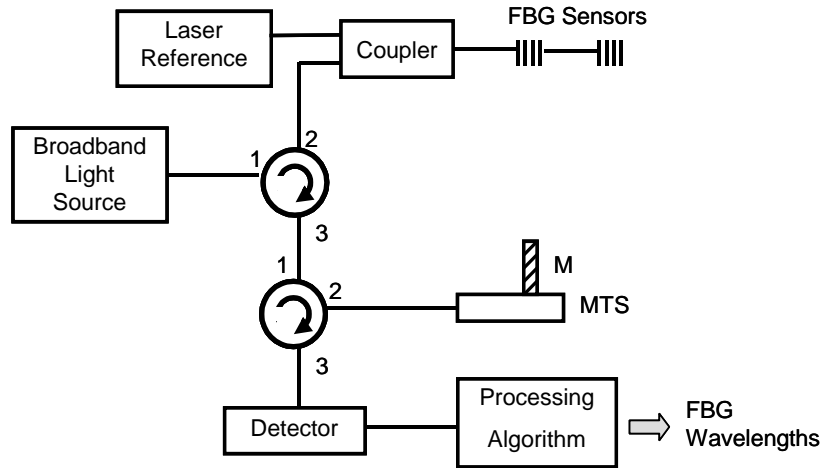

Fig.1. Block-diagram of the proposed interrogation scheme for grating interrogation. M, mirror; MTS, motorized translation stage.

If we consider the intensities of a FBG sensor and the reference laser at the output of the interferometer represented as functions of the delay τ between the interferometer arms we obtain:

$$I_j(\tau) = A_j(\tau)\cos(\phi_j(\tau)) = A_j(\tau)\cos(\omega_j\tau + \varepsilon_j) \tag{1}$$

where the subscripts j = L, B refer to the laser reference and the reflection from the Bragg grating, respectively, ω_j and ε_j are the frequency and initial phase terms and $A_j(\tau)$ are slowly varying functions of τ. The laser reference wavelength was 1560 nm.

The phase functions may, therefore, be written as:

$$\phi_L(\tau) = \omega_L\tau + \varepsilon_L \tag{2}$$

$$\phi_B(\tau) = \left(\frac{\omega_B}{\omega_L}\right)\{\phi_L(\tau) - \varepsilon_L\} + \varepsilon_B \tag{3}$$

From equation (3), the ratio of the optical frequencies ω_B/ω_L is equal to the slope of the graph of $\phi_B(\tau)$ against $\phi_L(\tau)$, which we define as $\eta_{BL} = \Delta\phi_B/\Delta\phi_L = \omega_B/\omega_L$. The ratio of the grating centre wavelength to reference wavelength is just the inverse of this: $\lambda_B/\lambda_L = \omega_L/\omega_B$, hence $\lambda_B = \lambda_L/\eta_{BL}$. So, in order to recover $\phi_B(\tau)$ and $\phi_L(\tau)$, and therefore the Bragg wavelength, a frequency estimation process of a short interval of each interferogram is required. We applied to them the FFT

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algorithm (which is the common practice) or other algorithms specifically designed to accomplish this task. In particular, in [7-9], a parametric frequency estimation algorithm known as MUSIC has been explored. With the sensors interferograms' frequency, ωj, obtained with the FFT or MUSIC algorithms, we will have the sensors' Bragg wavelength. The MUSIC algorithm estimates the pseudospectrum from a signal or a correlation matrix using Schmidt's eigenspace analysis method. The algorithm performs eigenspace analysis of the signal's correlation matrix in order to estimate the signal's frequency content. This algorithm is particularly suitable for signals that are the sum of sinusoids with additive white Gaussian noise. It is better suited than FFT for obtaining the frequencies of multiple sinusoids in noise since it has a much higher resolution. The new algorithm performs slightly better than the FFT as will be shown in the next section. However one small drawback of this parametric algorithm is that it assumes a known number of tones in the measured signal. Therefore the number of sensors to be interrogated should be known in advance. However this is not a big practical limitation in real-world applications since the number of sensors that have been installed is known. Another problem of this algorithm is its processing time, which is higher than the FFT algorithm.
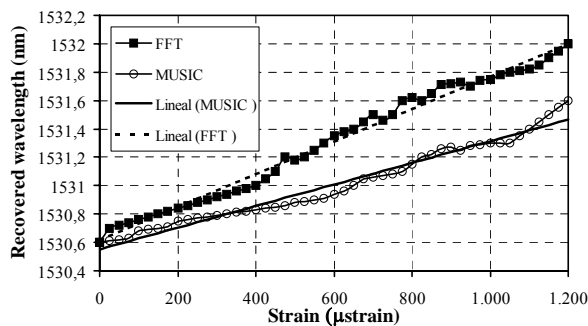
3. RESULTS

Fig. 2. Results of the variation of the Bragg wavelength with strain using the FFT and MUSIC methods.

A setup like the one shown in Fig. 1 was used for the experimental demonstration of the proposed interrogation system. The broadband light source was a superluminiscent diode (SLD-761-DIL-SM-PD from Fiberon Inc.). The scanning Low-Finesse Fabry-Pérot cavity was formed by placing the tip of a fiber right in front of a mirror attached to a motorized translation stage.

Several experiments were carried out with this setup. The first one tested the performance of the technique for strain measurement using a FBG. The grating had a nominal Bragg resonant wavelength of 1531 nm. The collimated reflected Bragg beam and the laser beam were directed to the PC-based detecting electronics. The grating was subjected to strains in the range 0-1200 µstrain. Fig. 2 shows the experimental results for the variation of the Bragg wavelength with strain.

This same experiment was processed with both the FFT and MUSIC algorithms, and it was found that the second one performed slightly better than the other. Thus, the average accuracy error when using the new algorithm is around 0.6 nm whereas with the FFT this value increases up to 1 nm. However, in both cases the accuracy of the system is around 1% of the measured grating wavelength. In an interrogation unit the most important thing is the exact and accurate determination of the wavelength variation, more than the precise value of the wavelength. From Fig. 2, the resolution of the system was 100 pm using the FFT, whereas with MUSIC the resolution was around 40 pm, which corresponds to the minimum wavelength variation detected. When comparing the linearity of the system, it was also found a slightly better behaviour with the adapted MUSIC algorithm.
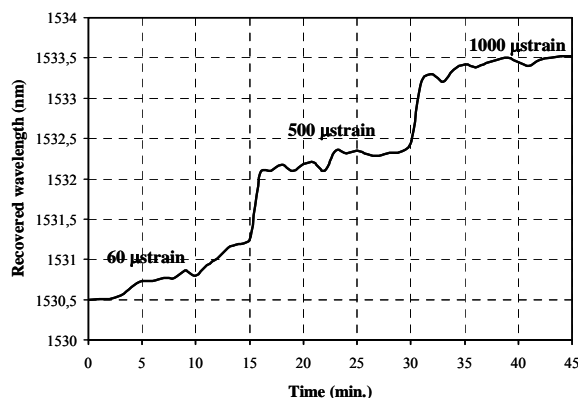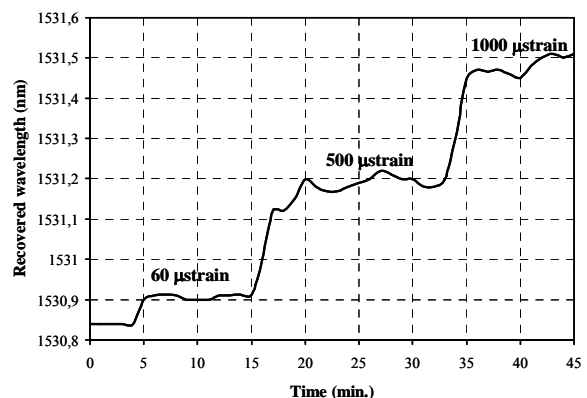

Fig. 3. (a) Results of the stability experiment in three zones when strains of 60 µstrain, 500 µstrain and 1000 µstrain are applied using the FFT method.

Fig. 3. (b) Results of the stability experiment in three zones when strains of 60 µstrain, 500 µstrain and 1000 µstrain are applied using the MUSIC method.

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Figure 3 shows the result of a stability experiment. During it, the grating with Bragg resonant wavelength of 1531 nm was increasingly stretched in three 15min steps from 60 μstrain, to 500 μstrain and finally to 1000 μstrain. Periodic measurements of the same grating configuration over 45 minutes yielded 0.52 nm maximum error in wavelength determination in case of using the MUSIC method, whereas with the FFT this value increased in 2 nm. The maximum wavelength fluctuations using the FFT are up to 3 nm, whereas with MUSIC this value is below 1 nm. The temporal stability of the graphs shown in Fig.3 is not very good due to the fact that we wanted to develop a low-cost interferometric technique. This result reveals that we need to work harder on the correction algorithm.

Finally there was also an experiment to test the capacity of recovering the wavelengths from two multiplexed FBGs (Bragg wavelengths of 1524 and 1534 nm respectively). The demultiplexing is achieved by bandpass filtering the frequency spectrum of the recovered interferogram. First, a frequency estimation to determine the central band of the bandpass filter was carried out, and then the filtering was performed. After that, the FFT and MUSIC methods were applied and compared. The wavelengths were calculated using an interferogram of 2^{16} points. Using the FFT, the gratings wavelengths obtained were 1524.9 and 1533.74 nm, whereas with MUSIC the recovered grating wavelengths were 1524.15 and 1534.13 nm. So, the Bragg wavelength obtained with MUSIC differed ≤0.15 nm from the actual grating wavelength, whereas the FFT method provided ≤0.9 nm error in wavelength determination.

4. CONCLUSIONS

A novel algorithm for the recovering of the Bragg wavelengths of FBG sensors has been compared with the FFT. This new frequency estimation technique called MUSIC has been validated by a reported previous theoretical investigation. The measurements of Bragg wavelength have potentially high accuracy, due to the use of a tuneable laser as frequency reference, and high resolution, due to high-precision measurement of interferogram periodicity. The accuracy and the resolution provided by MUSIC are better than that of the FFT method. In general, the performance of the MUSIC algorithm in this issue is better than the FFT method.

We can conclude that if we use the high accuracy method called MUSIC it is possible to multiplex a large number of gratings using a single broadband source and a single receiving interferometer.

ACKNOWLEDGEMENTS

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