Application of a Fiber Fourier Transform Spectrometer to the Detection of Wavelength-Encoded Signals from Bragg Grating Sensors

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Abstract—We describe an all-fiber Fourier transform spectrometer for decoding the wavelength shifts from a series of Bragg grating sensors. The system described uses an optical fiber Michelson interferometer with one arm wrapped on a piezoelectric driven stretcher capable of inducing a ~10 cm fiber length change. Passive polarization compensation is utilized which eliminates the possibility of random polarization fading in the interferometer causing apodization of the interferogram. This permits an all-fiber design without the need for specialty optical fiber or external polarization adjustments. A reference Nd:YAG laser is used to stabilize the interferometric scan in a phase-locked loop configuration by way of slow and fast feedback correction elements. A spectral resolution of <0.07 cm⁻¹ was obtained, which corresponds to a Bragg wavelength shift of ~0.015 nm in the 1.55 μm region. The simultaneous wavelength determination capacity of the device also permits it to be used in a variety of other applications for analysis of optical spectra.

I. INTRODUCTION

CONSIDERABLE research activity lately has been centered on the development of "smart structures," that is, structures that have the capability to provide real-time information on their health and integrity and possibly adapt to compensate for any anomalies. The first step in the development of this technology is to incorporate a level of structural sensing capability. This can be achieved, for example, through the use of strain measurements taken at multiple locations throughout the structure. Many issues need to be addressed in the implementation of this technology, such as the compatibility of the sensing systems with the fabrication processes, incorporation of a telemetry means for reading multiple strain gauges, and material-sensor interactions, such as would occur due to the corrosive nature of certain materials, for example.

Fiber Bragg grating (FBG) strain sensors appear to be ideally suited for these applications due to the many advantages they possess: they are immune to EMI, they can be easily embedded and protected from various environments by way of the optical fiber coating, they provide an absolute strain measurement which is inherently encoded in the wavelength returned by the device, and can be easily multiplexed [1]. The multiplexing capacity of FBG's is one of the most important advantages of these sensors as it provides the ability to monitor strain at multiple points along a single fiber path. This can easily be accomplished by wavelength division multiplexing multiple FBG sensors on a single optical fiber, where each grating is written with its Bragg resonance at a different optical wavelength. The demodulation of these devices is achieved by determining the wavelength shift in the Bragg resonance conditions as the FBG's are strained. A variety of techniques have been proposed and demonstrated for the measurement of the Bragg wavelength of FBG sensors. These approaches have generally utilized passive broadband illumination of the sensor and optical filtering techniques, such as edge filters [2], tunable filters [3] or interferometric elements [4] applied to the reflected signal. These filtering techniques can typically process only one return signal at a time, so true simultaneous measurement of all the reflected Bragg wavelengths from several wavelength division multiplexed sensors is difficult. Typically additional couplers and detectors are required, which have the disadvantage of possibly further attenuating the returned signals from the FBG sensors. We have examined a number of approaches, and in this paper we demonstrate the use of an all fiber Fourier transform spectrometer (FTS) for decoding the return wavelengths from a series of FBG elements.

Fourier transform spectroscopy is an efficient analytical spectroscopic tool which has been used in a wide variety of fields for the analysis of very weak or broad spectra, principally in the IR region. The technique has been used extensively in IR molecular spectroscopy [5] and astrophysics [6] for the analysis of spectra which typically contain multiple narrow bandwidth components. This type of optical signal is similar to the output returned from a FBG array. FTS would thus seem to be an ideal method to use for decoding the wavelength shifts in an array of FBG sensors. In a FBG sensor array, the returned optical signal typically comprises a series of weak narrowband components spread over a bandwidth of possibly tens of nanometers or more. This necessitates the use of a very efficient optical signal processing scheme to monitor the Bragg wavelengths of the return signals. The sensitivity of the FTS technique provides a means to detect, with high resolution, the shift in wavelength of a series of FBG sensor elements. Additionally, the inherently fiber coupled return signals from a FBG array would be directly compatible with a
fiber implementation of a FTS spectrometer, further enhancing the efficiency of the concept.

A basic Fourier transform spectrometer consists of a Michelson interferometer illuminated with light from the source of interest, in which the length of one arm is linearly changed, creating an interferogram at the output of the interferometer. The Fourier transform is then computed from the interferogram to obtain an accurate representation of the source spectra. At the interferometer output the difference in phase $\Delta \phi$ between the two arms at a given optical frequency $n$ is given by

$$\Delta \phi = \frac{2\pi (2n\Delta L)}{c} = 2\pi \nu x$$

where $x = (2n\Delta L)$ is the optical path difference (OPD) between the two arms and $\nu = \nu/c$ is the wavenumber of the incident light. The intensity at the output is then given by

$$S = \frac{I_0}{2} \eta R[1 + K \cos(2\pi \nu x)]$$

(2)

where $I_0$ is the source intensity into the Michelson, $\eta$ represents any optical power losses from the coupler, $R$ is the mirror reflectivity and $K(\nu)$ is the visibility of the interferometer and is a function of the input power, the coupling ratio and the polarization properties of the interferometer. If the mirror in one arm of the Michelson moves with a velocity of $V_m$, fringes will then be created at the output at a frequency of

$$f = \frac{2V_m\nu}{c} = 2V_m \nu.$$  

Equation (2) can be expanded further to include continuous or multiple-wavelength sources resulting in an equation for the output intensity of the interferometer for a given OPD ($x$) of

$$S(x) = \int_{-\infty}^{\infty} \frac{I_0(\nu)}{2} \eta R[1 + K(\nu) \cos(2\pi \nu x)] d\nu.$$  

(4)

This equation defines the interferogram obtained as the OPD of the interferometer is scanned. We can define a function $F(\nu)$ which is dependent on the input spectrum and the monochromatic visibility

$$F(\nu) = I_0(\nu)K(\nu).$$

(5)

and then rewrite (4) as

$$S(x) = \frac{\eta R}{2} \int_{-\infty}^{\infty} F(\nu) \frac{d\nu}{K(\nu)} + \frac{\eta R}{2} \int_{-\infty}^{\infty} F(\nu) \cos(2\pi \nu x) d\nu.$$  

(6)

In this expression the first term is the source integrated power while the second term describes the form of the interferogram and is related to the cosine Fourier transform of the source spectra [5]. A general Fourier transform pair can be expressed as

$$G(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(\nu) \exp(2\pi i\nu x) d\nu$$

$$F(\nu) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} G(x) \exp(-2\pi i\nu x) dx.$$  

(7)

Because the spectrum in our equations is real, the complex exponential seen in (7) can be replaced by a cosine. The similarities between (6) and the Fourier transform pair can then be seen and the other half of the Fourier transform pair for (6) can be written as

$$F(\nu) + \frac{2}{\eta R} \int_{-\infty}^{\infty} S(x) \cos(2\pi \nu x) dx.$$  

(8)

If the monochromatic visibility is known, this equation gives the intensity obtained from the interferometer for a given wavenumber, i.e., the source spectra [5], [6]. Consequently, (6) shows that by recording the intensity obtained as the length of one arm of the interferometer is scanned, $S(x)$, and then taking the Fourier transform the source spectra, $I_0(\nu)$, can be obtained. Additionally, (5) and (6) demonstrate the importance in maintaining a constant visibility throughout the acquisition of the interferogram to obtain a reliable source spectral profile.

With a bulk optic Michelson interferometer the change in OPD is achieved with one mirror mounted on a precision motorized stage, requiring precise mirror movements throughout the change in length of the one Michelson arm. However, these methods require precise mechanical movements that are generally not suited for portable systems. Furthermore, additional light losses can occur in these bulk optic systems which further degrade a potentially very efficient spectroscopic system. In an effort to maximize the efficiency and improve the robustness of Fourier transform spectroscopy several schemes have been developed [7]-[9] which use optical fiber in the arms of a Michelson or Mach–Zehnder interferometer based design. However, these techniques still utilize bulk optic components to some degree in the way of mirrors or splitters.

In bulk optical systems polarization behavior is not a major concern, however, with a fiber implementation of the FTS fiber birefringence can lead to problems, more specifically, visibility fading can occur due to random polarization fluctuations in the light in the two arms of the interferometer. Typical interferometers constructed using conventional low-birefringence fiber suffer from "polarization-induced fading" of the output interference signal, where temperature and other environmental perturbations can cause random fluctuations in the polarization of the interfering beams at the output of the interferometer. This results in random variations in the output fringe visibility and periodic fading of the interferometric detected signal. In a Fourier transform spectrometer, this random visibility fading causes apodization of the output interferogram which will be interpreted as structure when the Fourier transform is taken. It is therefore very important to prevent this visibility fading from inducing errors in the interferogram. Several techniques have been developed to overcome this problem in interferometric sensor systems, including adjustment of the polarization in one arm of the interferometer by way of manual or automatic polarization controllers [10], input polarization control schemes [11], and several "polarization diversity" approaches [12]-[14]. To circumvent this problem in a fiber FTS system, Page-Jones et al. [8] used specialty polarization maintaining fiber, Hi-Bi elliptical core (Andrew E-core), but their system still required...
adjustment of the polarization entering the interferometer to ensure that the light was coupled into the correct mode of the fiber. The FFTS we present here is an all-optical fiber design using commercial low birefringence Corning single-mode fiber with a nominally path balanced Michelson interferometer. We achieve completely passive polarization compensation by the use of orthoconjugate mirrors (Faraday rotator mirrors), which eliminate undesirable apodization of the interferogram.

II. EXPERIMENTAL SYSTEM

The fiber FTS system developed and the grating sensor array is shown in Fig. 1. The FBG elements are illuminated using a broadband source (erbium doped fiber, EDF, source), and the reflected narrowband components from the gratings are directed into the fiber Fourier transform spectrometer, which is based on a scanning Michelson interferometer. This interferometer comprises a coupler and two fiber arms of ~200 m each, which are path balanced to ~2 cm. The balancing technique used to achieve this path match is based on a cutback method in which the phase modulation response of the interferometer to a known frequency modulated laser input is monitored as the interferometer is incrementally balanced. The fiber in one arm is wound around a fiber stretcher formed by two segmented halves of a ~5-cm-diameter cylinder which are held apart by two piezoelectric stack positioners. These piezoelectric elements are driven from a HV supply, and can induce a change in fiber length, ΔL, of ~10 cm. This allows the physical length of one arm to be stretched by ~10 cm, and the interferometer optical path difference (OPD) to be changed by up to 30 cm (i.e., 2nΔL). The interferometer is configured such that the increased path length scans the interferometer through its zero OPD position. When the interferometer OPD is scanned linearly over a range ±D, an interferogram is generated at the output symmetrically around zero OPD. The width of this interferogram depends on the coherence length, Lc, the light input to the Michelson, and the Fourier transform of the interferogram taken on an electrical spectrum analyzer gives the optical spectrum of the light transposed into the audio frequency range. With the typical bandwidth of light reflected from a 1.55 μm FBG of ~0.1-0.2 nm, the effective coherence length is ~1-0.5 cm. Consequently, a minimum scan of >2 cm in interferometer OPD is required to fully resolve the interferogram. With this excursion in OPD, the resolution of the FBG “line” will be limited by an effective “instrumental bandwidth” comparable to that of the FBG. The instrument-limited resolution of the spectrometer is given in wavenumber by Δν = (1/2D) cm⁻¹, when D is given in centimeters; this leads to an optical frequency shift, Δν, of ~5 GHz at 1.55 μm for a 2 cm scan. However, we can improve the resolution by using a longer scan excursion, D, of up to 10 cm (i.e., D ≳ Lc) to give Δν = ~1 GHz and a wavelength resolution, Δλ, of ~0.012 nm. The spectrometers resolution is then limited in our case by the acquisition time of the electrical spectrum analyzer used to take the fast Fourier transform of the interferogram (i.e., the spectrum analyzer acquired the data for the specific frequencies of interest before the OPD scan was complete).

To provide a highly linear scan in OPD, a 1.319 μm single frequency Nd:YAG reference optical signal is also coupled into the Michelson as shown in Fig. 1. The reference 1.3 μm and FBG 1.55 μm optical signals are separated at the output using a WDM coupler and electronic filtering. The coherence length of the Nd:YAG laser is much longer than the largest OPD induced in the Michelson by the PZ stretchers, and thus interference fringes are produced over the entire scan in OPD. The rate at which the fringes in the 1.319 μm light (f0) are produced is compared to a reference oscillator (fr), and an error signal is produced which is fed back to correct the ramp slope being fed to the piezoelectric stacks, and directly to an additional piezoelectric cylinder located in the other arm of the Michelson. This second PZ cylinder allows for rapid feedback of the scan rate to overcome any momentary glitches which can occur in the uniformity of the
scan. The feedback configuration forms a phase locked loop where \( f_0 = f_r \) and the OPD of the interferometer increases linearly with time as the fiber is stretched. With the large change in OPD induced by the \( \pi/2 \) stretcher a large degree of birefringence modulation in the fiber can occur which leads to polarization fading of the interferogram. This effect leads to a random apodization of the signal which would be interpreted by the FFT analyzer as spectra structure on the input light. To overcome this we used Faraday rotator mirrors as the reflectors in the Michelson. These devices consist of a 45° Faraday rotator followed by a plane mirror and effectively compensate for any birefringence in the retraced optical path of the interferometer arms [15]. The use of Faraday rotator mirrors has previously been shown to greatly reduce polarization fading in a Michelson interferometer [16]. Although these devices were optimized at 1.55 \( \mu \)m light they also performed adequately for the Nd:YAG reference laser maintaining a visibility >85% at 1.319 \( \mu \)m.

In the experimental system the reference oscillator frequency \( (f_r) \) was set at 626.8 Hz and the FBG signals in the 1.55 \( \mu \)m range were then detected separately as shown and fed to a HP 3562 FFT spectrum analyzer. In bulk optic systems (3) can simply be applied to determine the relationship between the optical wavelength and frequencies generated by the Fourier transform. However in the case of an all fiber implementation the velocity of the mirror \( (V_m) \) must be rewritten as

\[
V_m = \frac{n \Delta L}{\Delta T}
\]

where \( \Delta L \) represents the physical fiber length change. Then, to determine the corresponding frequencies generated by the interference signals at 1.55 \( \mu \)m, we can use (3) and (9) and the ratio of the indexes of refraction for the fiber, \( n(1.55 \mu m)/n_r(1.3 \mu m) = 0.99952 \), to produce the following equation:

\[
f = f_r \frac{n}{n_r} \frac{V}{V_r} = 8.2661 \times 10^{-4} \nu.
\]

It was necessary to include the index of refraction of the fiber for the two wavelengths of interest, 1.3194 and 1.550 \( \mu \)m, into the equation to compensate for fiber dispersion and the resultant dependence of the OPD on wavelength. Consequently, the FFT spectrum analyzer was set to record the spectrum in a frequency range around 530 Hz with a resolution as high as 6 mHz.

### III. RESULTS

Fig. 2 shows the interferogram recorded with 1 FBG element \( (\lambda_B = 1.5482 \mu m) \). In order to observe the “fringes” within the interferogram envelope, the interferometer output was heterodyne down to <0.5 Hz. The interferogram form indicates a highly symmetric envelope and secondary lobes on either side of the central peak. We believe that the secondary lobes are caused by irregularities in the shape of the reflected FBG signal, particularly narrowband features seen on the profile. Fig. 3(a) shows the Fourier transform of this interferogram centered at about 533.7 Hz. In Fig. 3(b) an optical spectrum analyzer (OSA) plot is shown for the same FBG returned signal. The Fourier transform is plotted in frequency, by simply evaluating (10) over the frequency range the plot can be transposed into wavelength. On the short wavelength
Davis and Kersey: The Detection of Wavelength-Encoded Signals

Fig. 4. Spectra taken for one FBG with strain levels of 0, 100, and 1000 \( \mu \)strain.

Fig. 5. (a) Spectrum produced by the series of 3 FBG elements at 1.539 \( \mu \)m, 1.548 \( \mu \)m, and 1.551 \( \mu \)m for zero strain on all gratings. (b) Optical spectrum analyzer plot of same grating array.

Fig. 6. Spectrum of erbium doped fiber source passed through two FBG's. (a) Spectra showing the full erbium source emissions. (b) Narrow view of wavelength regions reflected out by the FBG sensors.
with this series of FBG elements. In this plot the frequencies obtained from the FFT have been converted to wavelengths and the three unstrained FBG returned signals can be seen at 1.539, 1.548, and 1.551 µm. In the accompanying OSA plot of Fig. 5(b) excellent correlation can be seen for all FBG returned signals when compared to the Fourier transform plot. Again profile detail in the 1.539 nm grating is clearly evident in the FFT output, but in the OSA output only broadening of the profile is seen. With the ~0.015 nm resolution of this device we were able to interrogate FBG strain sensors in the 1.55 µm with a strain resolution of ~12 µstrain.

IV. DISCUSSION

Although we described above the use of a FFTS to determine the wavelength shifts from an array of FBG sensors, it can also be used in a variety of applications to determine the optical spectrum of a reflecting or radiating body, the structure on optical sources (particularly fiber coupled devices), and for use in chemical sensing. The FFTS has the advantage of being all fiber and therefore a compact device and will not suffer from apodization of the interferogram due to the use of the Faraday rotator mirrors in the Michelson interferometer. To demonstrate another use of the FFTS we passed the broadband ASE signal from the erbium doped fiber through two fiber Bragg gratings and then into the FFTS. The interferogram obtained in this case consisted of a very short burst of fringes over ~2 mm change in the OPD of the Michelson interferometer, due to the short coherence length of the light produced by the broadband ASE spectrum of a Er doped fiber. After the fast Fourier transform was taken, the plots in Fig. 6 were obtained. In Fig. 6(a) the broadband spectrum of the source can be clearly seen with two narrowband components missing, corresponding to the transmissive "notches" associated with the two FBG's in line between the Er fiber and the FFTS. This demonstrates the capability of the device to resolve narrowband features in wide wavelength optical spectra. Fig. 6(b) gives a more detailed view of the wavelength region where the two Bragg gratings were located. This figure further illustrates how the device might be used as, for example, a remote gas absorption sensor. Broadband source light directed through a gas cell would experience attenuation of certain wavelengths in its spectra due to atomic or molecular absorption, producing a spectra similar to that shown in Fig. 6(b). This could then indicate the presence of certain atomic or molecular species and give data on the amount of the substance present.

The resolution of the FFTS demonstrated here permits its use where conventional optical spectrum analyzers, due to their bandwidth limitation of typically 0.1 to 0.05 nm, do not provide sufficient spectral information. A case where this might be true is the spectral splitting of fiber Bragg gratings, or the examination of side-lobe features on gratings. A further example of an application requiring high resolution would be an idea introduced by Huang et al. [17] where the distortion of a grating reflection profile can be analyzed to determine any strain gradients present across the FBG sensor itself. This utility was demonstrated with the experimental setup used to create FBG spectral splitting shown in Fig. 7. Two Peltier elements were placed under different halves of a Bragg grating as indicated. One element was cooled while the other was heated, causing the Bragg wavelength of each half to shift in opposite directions. Two separate FFTS scans were taken, before and after use of the Peltier elements and the results are indicated in Fig. 8. In the top graph a uniform temperature of 25°C was present across the grating giving a single reflected profile peak of width ~0.25 nm. When a temperature difference of 88°C was induced on the grating the lower plot indicates the results obtained. Here a split profile with a ~0.9 nm difference in wavelength between the two resultant spectral peaks was observed. In addition, a certain degree of small profile structure can be seen.

The system described here uses a Nd:YAG reference laser to provide a linear scan in OPD and an electrical spectrum analyzer. Several modifications of this prototype system could be envisioned which would reduce the cost of the FFTS. In one such modification the feedback loop is not required and instead a record of the rate of the reference fringe production could be kept throughout the length of the scan. The interferogram would then be normalized to this fringe rate to effectively linearize the scan. Alternatively, the reference fringes could be used to trigger a sampling circuit similar to that demonstrated by Takada et al. [9] which would normalize for nonlinear
Fig. 8. FBG returned signal before (ΔT = 0°C) and after spectral splitting
(ΔT = 88°C).

scans. If the data is then fed into a computer a fast Fourier transform could be taken, eliminating the need for a separate electrical spectrum analyzer. Additionally, alternative low cost light sources could be used in place of the Nd:YAG laser, provided they produced light with a coherence length longer than the maximum OPD in the Michelson interferometer.

V. SUMMARY

We have described the use of an all-fiber implementation of a Fourier transform spectrometer for decoding the wavelength shifts from an array of Bragg grating sensors. The system exhibits a significantly higher resolution than previously reported FTTS systems, and overcomes polarization problems by using passive polarization compensation. The system described has a spectral resolution of 0.07 cm⁻¹, which corresponds to a Bragg wavelength shift of ~0.015 nm in the 1.55 μm region. Due to the simultaneous wavelength determination capability of the device, it can also be used in a variety of other applications for analysis of optical spectra particularly fiber coupled sources and wavelength encoded optical sensing techniques. No bulk optical components or specialty fibers are required for this system, providing the potential for a low cost, robust and compact Fourier transform spectrometer.

ACKNOWLEDGMENT

The authors would like to thank J. Dexter of Code 5671, NRL, for loan of the fiber stretcher used in this work.

REFERENCES


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