Fiber Bragg grating interrogation using a wavelength modulated 1651 nm tunable distributed feedback laser and a fiber ring resonator for wearable biomedical sensors

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ABSTRACT

This paper demonstrates the interrogation of a fiber Bragg grating with a flat-topped reflection spectrum centred on 1649.55 nm using only a single mode tunable 1651.93 nm semiconductor laser and a fiber ring resonator. The Bragg shift is accurately measured with the fiber-optic ring resonator that has a free spectral range (FSR) of 0.1008 GHz and a broadband photo-detector. Laser wavelength modulation and harmonic detection are used to transform the gentle edges of the flat-topped FBG spectrum into prominent leading and trailing peaks, either of which can be used to accurately measure spectral shifts of the FBG reflection spectrum with a resolution of 0.9 pm. A Raspberry Pi-based low-cost embedded processor is used to measure the temperature-induced spectral shifts over the range 30˚C – 80˚C. The shift was linear with a temperature sensitivity of 12.8 pm/˚C. This technique does not use an optical spectrum analyzer at any stage of its design or operation. The laser does not need to be pre-characterized either. This technique can be readily extended to all types of tunable diode lasers and is ideally suited for compact field instruments.

Keywords: Fiber Bragg gratings, wavelength modulation spectroscopy, strain sensing, stroke rehabilitation

1. INTRODUCTION

A wide variety of fiber Bragg grating (FBG) sensor interrogation techniques with varying degrees of complexity are currently in use for physical sensing [1-11] and chemical sensing [12-13]. The early generation of FBG sensors used a broadband light source and an optical spectrum analyzer (OSA) that recorded the spectral distribution of the reflected or transmitted light. The OSA however, is often prohibitively expensive, bulky and not rugged enough for field-deployment. FBGs have also been interrogated with tunable semiconductor lasers whose wavelength vary linearly with current [1-4], although in almost every case an OSA is required to first characterize the wavelength tuning behaviour of the laser. A vertical cavity surface emitting laser (VCSEL) based interrogation system has also been demonstrated [3], in which the VCSEL's wavelength tuning is deduced from the laser's pre-characterized current-wavelength relationship. Gagliardi *et al.* [5] have applied the frequency modulation spectroscopy (FMS) technique to a tunable laser diode to perform beat frequency detection using a 5 GHz photo-detector and phase sensitive detection. This is a high-sensitivity approach, but expensive and complex. A broadband source and a second FBG to detect the edge of the sensing FBG has also been used [6]. An FBG interrogation system with 1 pm wavelength resolution has been demonstrated using a standard telecommunication DWDM transmission module with a wavelength locker [7]. A π-phase shifted grating (π-PSFBG) and a fiber Fabry-Perot interferometer (FFPI) and a dual Pound-Drever-Hall feedback loop for laser frequency locking has also be used [8, 9] for non-swept laser interrogation technique. The very high strain resolution justifies the complexity of the system that comprises a phase modulator, an intensity modulator and two lock-in amplifiers (LIAs). Vibration sensing has been demonstrated [10] using two FBGs written 4 mm apart on single mode fiber to form a Fabry-Perot interferometer (FPI). The sensor is interrogated by a DFB laser by converting wavelength to time. The current-wavelength relationship must first be characterized with an OSA. A reduced graphene oxide-coated FBG [11] interrogated by a commercial FBG interrogator has exhibited enhanced strain and temperature sensitivity. FBG-based [12] and long-period grating-based [13] sensors functionalized with graphene and palladium have been used for high-sensitivity gas detection. These systems use an OSA to interrogate the structure, although the spectral coverage required to recover the FBG transmission spectrum (1.5 nm) and the spectral shift (10 nm) is achievable with laser diodes. This paper demonstrates an alternative interrogation method based on the tunable diode laser spectroscopy (TDLS) technique [14] that is ideal for such applications because it is compact, robust, offers high resolution and because the spectral shifts involved are well within the scan range of tunable diode lasers. The FBG reflection spectrum is viewed as a single rotational-vibrational gas absorption line, and the spectral shift is equivalent to pressure-induced shifts of the absorption

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lines. The only difference is that the FBG spectrum is 4 to 5 times wider than a typical gas absorption line. The FBG is interrogated with a single mode tunable laser diode whose line width is much narrower than the FBG reflection spectrum, and the spectral shift of the FBG reflection spectrum is measured with a stable and accurately pre-characterized low-FSR fiber ring resonator. A reference gas line close to the FBG reflection spectrum serves as an absolute wavelength marker. Frequency shifts can be accurately measured because these lasers have precisely defined and stable emission wavelengths, and have line widths (2-5 MHz) that are much smaller than the FBG bandwidth (0.24 nm at 1649.55 nm = 26.44 GHz). The wavelength jitter is negligible compared to the FBG bandwidth when driven by a PID-stabilized current controller. The stability of the resonator peaks ensures accurate and high-resolution measurement of spectral shifts. All modulation techniques used in TDLS [14] to increase signal-to-noise ratio can be applied without any modification. The system does not use an OSA at any stage of its design or operation.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement shown in Fig. 1(a) uses a fiber-coupled, tunable 1651.93 nm single mode laser (Toptica Photonics). The FBG (Technica SA) centred on 1649.55 nm has a flat-topped bandwidth of 0.24 nm. A temperature controller (Thorlabs, TED 200C) and a current controller (Thorlabs, LDC 220C) are used to drive the laser. The light transmitted through the FBG and the fiber ring resonator [14] is detected with InGaAs photo-detectors (Thorlabs, PDA10D-EC) and digitized with a 12-bit analog-digital converter. An Octave program that runs on a Raspberry Pi processor controls data acquisition and processing. The laser's wavelength is initially temperature-tuned close to the FBG resonance and a periodic current ramp is then applied to repeatedly scan the wavelength across it. The FBG's reflected spectrum consists of a single peak (black trace) as shown in the Fig. 1(b). The R4 absorption line of methane (broken red trace) is used as the absolute wavelength marker. The output of the fiber resonator is shown in Fig. 1(c). Finally, the wavelength-referenced FBG reflected spectrum is shown in Fig. 1(d). The resonator's FSR was accurately characterized to be 0.2095 GHz (1.9 pm at 1649.55 nm). A second resonator with an FSR of 0.1008 GHz was built to improve the resolution to 0.9 pm. The truncated outputs of the two resonators shown in Figs 1(e) and 1(f) clarify that the congested resonator trace in Fig. 1(c) is actually a usable interference pattern. The low FSR achievable with fiber-based resonators brings the resolution at par with that of commercial interrogators.

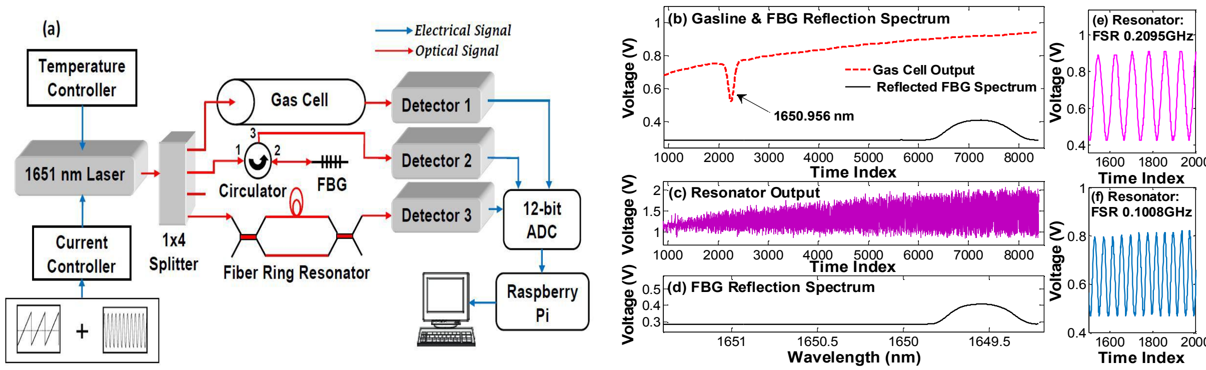

Figure 1. (a) Experimental set-up used for the interrogation of the FBG, (b) Time-indexed reflection spectrum of the 1649.55 nm FBG (black) and the R4 rotational-vibrational line of methane (broken red) used as a wavelength marker; (c) Output of the fiber resonator (magenta) with FSR of 0.2095 GHz; (d) Wavelength-referenced unperturbed FBG reflection spectrum; (e) Output of the resonator with FSR = 0.2095 GHz; (f) Output of the resonator with FSR = 0.1008 GHz

3. RESULTS AND DISCUSSION

High-resolution interrogation of a flat-topped FBG is complicated by the fact that it lacks a sharp feature whose spectral traversal can be easily tracked. The laser's injection current is therefore modulated with a 3mA, 10 kHz sine wave to produce wavelength modulation (WM) that interacts with the FBG spectrum to give rise to signals at harmonics ($1f$, $2f$ etc) of the modulation frequency (f_m) [14]. For low modulation amplitude these are well approximated by the derivatives of the FBG spectrum. The WM therefore produces one sharp (n^{th} derivative) feature each for the leading and trailing FBG edge for n^{th} harmonic detection. The key point is that in order to measure the Bragg shift, it is no longer necessary to scan the laser across the entire FBG spectrum but only across either of the derivative peaks. The FBG reflection spectrum is shown in Fig. 2(a). The flat-topped nature is not apparent here because the intensity of the laser increases significantly across the scan range. The resultant pronounced FBG spectrum peak may seem to be useful but that is not so because the peak quickly moves out of the laser's wavelength range when the FBG is strained or heated and therefore cannot be used to measure the Bragg shift. Figures 2(c) and 2(d) show respectively, the X-, the Y- and the magnitude components of the LIA output of the 1*f* and 2*f* signals. The WM transforms the gentle FBG pass band edges into pronounced leading and trailing peaks, either of which can be tracked to measure spectral shifts with high resolution. Temperature tests of the FBG were carried out from 30-80˚C. Figures 2(e) to 2(h) shows the FBG reflection spectrum and the corresponding harmonic components as the temperature is increased. Note that for temperatures higher than 51˚C, the FBG spectrum moves out of the laser's tunable range and can therefore not be fully recovered unless either the current ramp is increased or the laser wavelength is temperature-tuned further. However, the WM approach allows the first edge to be tracked. It is not necessary to recover the entire FBG spectrum to measure the spectral shift.

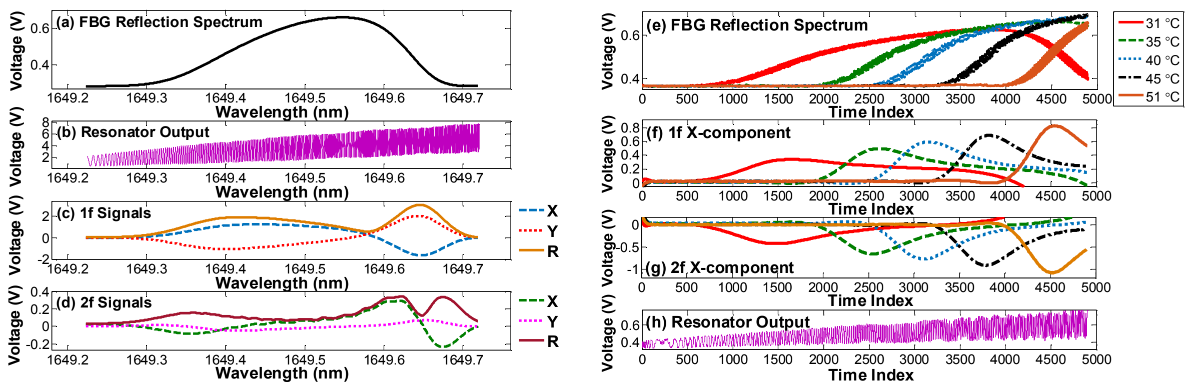

Figure 2. (a) FBG reflection spectrum, (b) resonator trace, (c) LIA in-phase (X) and quadrature-phase (Y) and the magnitude $R=\sqrt{X^2+Y^2}$ component of the 1*f* signal, (d) the corresponding 2*f* signal components, (e) FBG reflection spectra at increasing temperatures, (f) the 1*f* X component, and (g) the 2*f* X component, (h) the resonator trace. Note that the trailing edge of the FBG resonance can be tracked although the FBG resonance itself moves out of the scan range.

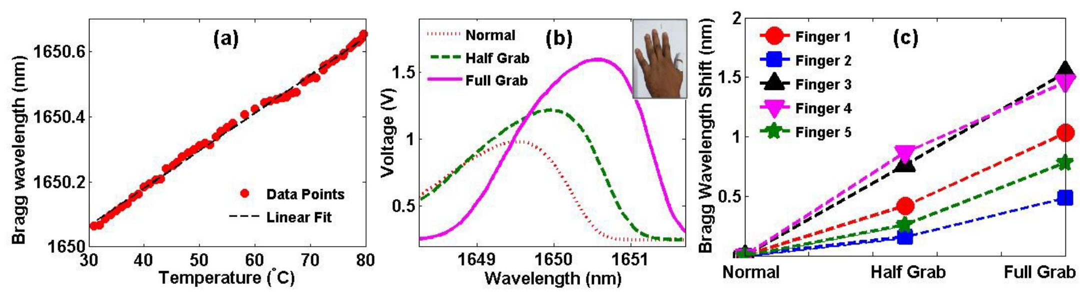

Figure 3. Temperature and strain response of the 1649.55 nm FBG showing (a) linear Bragg wavelength shift as it is heated from 30- 80℃, (b) shift of the reflected spectrum with the FBG attached to the thumb that is flexed, (c) the Bragg wavelength shift with the FBG attached to the five fingers of the left hand of a subject in half-grab and full-grab positions

Fig. 3(a) shows the spectral shift obtained using the 2*f* signal peak as the FBG was heated from 30˚C to 80˚C. The shift was found to be linear with a temperature sensitivity of 12.8 pm/˚C. Fig. 3(b) shows strain response of the FBG attached to the left thumb of a subject. The Bragg wavelength shift with respect to the unperturbed Bragg wavelength is 0.02% and 0.06% for the half-grab and full-grab positions respectively. Fig. 3(c) shows the percentage shifts going from half-grab to full-grab positions for the five fingers. The percentage shift is 147%, 207%, 103%, 69%, and 200% respectively. We intend to use this interrogation system for quantitative stroke rehabilitation studies by designing virtual-reality-based biomedical engineering applications [15] for diagnostic sensor gloves where the focus is on quantifying the rehabilitation process rather than on high strain resolution.

4. CONCLUSIONS

The important design factors for the FBG sensor are the dynamic range, accuracy, resolution and power requirement. Fiber-coupled VCSELs are ideal because they are widely tunable (tens of nm) and require low power. The laser's wavelength jitter, which must be lower than the minimum spectral shift that is to be detected, is not an issue because these thermoelectrically cooled lasers have very low jitter and their line widths (2-5 MHz) are much smaller than the spectral shifts of interest. The resolution is ultimately decided by the resonator's stability and by its FSR, which is much larger than other spectral widths involved, assuming that the laser's wavelength jitter is minimized to well below the resonator's FSR. This interrogation scheme is ideal for field applications of FBGs and wearable biomedical sensor applications [15]. The Raspberry Pi processor acquires and processes all data, thereby making the system low-cost and power efficient. The technique can be seamlessly integrated into existing sensor systems.

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