VCSEL-powered and polarization-maintaining fiber-optic grating vector rotation sensor

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Abstract: A compact fiber-optic vector rotation sensor in which a short section of polarization-maintaining (PM) fiber stub containing a straight fiber Bragg grating (FBG) is spliced to another single mode fiber without any lateral offset is proposed and experimentally demonstrated. Due to the intrinsic birefringence of the PM fiber, two well-defined resonances (i.e. orthogonally polarized FBG core modes) with wavelength separation of 0.5 nm have been achieved in reflection, and they exhibit a high sensitivity to fiber rotation. Both the orientation and the angle of rotation can be determined unambiguously via simple power detection of the relative amplitudes of the orthogonal core reflections. Meanwhile, instead of using a broadband source (BBS), the sensor is powered by a commercial vertical cavity surface emitting laser (VCSEL) with the laser wavelength matched to the PM-FBG core modes, which enables the sensor to work at much higher power levels (~15 dB better than BBS). This improves the signal-to-noise ratio considerably (~50 dB), and makes a demodulation filter unnecessary. Vector rotation measurement with a sensitivity of 0.09 dB/deg has been achieved via cost-effective single detector real time power measurement, and the unwanted power fluctuations and temperature perturbations can be effectively referenced out.

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OCIS codes: (060.2370) Fiber optics sensors; (060.0060) Fiber optics and optical communications.

References and links

1. Introduction

Structural health monitoring is a critical issue in various engineering applications, especially for large civil structures. Among many parameters to be considered, torsion is one of the key measurements for monitoring structures [1]. For more than two decades, fiber-optic torsion sensors have attracted considerable interest for their unique properties. More recently, all fiber sensors have been demonstrated to achieve more compact and stable torsion measurements. In these sensors, the recovery of the torsion signal information is accomplished by the detection of the strain-induced polarimetric modulations of the transmission light. For example, by using a photonic crystal fiber (two large asymmetric holes adjacent to the core fiber), one can get the two separate interferometers (along x- and y-direction) and achieve the torsion information by fast Fourier transform [2–4]. Meanwhile, long-period fiber gratings (LPGs) based in-fiber grating torsion sensors have also been proposed, such as using a corrugated LPG configuration [5] or an ultra-LPG inscribed by CO$_2$ laser exposure [6]. However, the expensive cost of photonic crystal fiber and the strong strain-temperature cross sensitivity of LPGs limit such sensors for in field applications. Meanwhile, for all torsion sensors mentioned above, erbium amplified spontaneous emission broadband sources (BBSs) or tunable laser based swept wavelength systems are used to interrogate the system. In the former case the spectral power density is low and results in a small signal-to-noise ratio (SNR), while conventional tunable lasers do not suffer this limitation but tend to be quite expensive and are typically limited to 1 kHz sweep rates.

In this paper, we propose and experimentally demonstrate a compact fiber-optic vector torsion sensing configuration, in which a polarization-maintaining fiber Bragg grating (PM-FBG) fiber stub containing a normal straight FBG is spliced to another single-mode fiber without any lateral offset. The intrinsic birefringence of the PM fiber makes the grating reflect two well defined core resonances separated in wavelength [7–11]. These two core resonances correspond to orthogonal polarizations and show high sensitivity but inverse intensity response to fiber rotation. Both the orientation and the angle of rotation can be determined unambiguously via simple power detection of the relative amplitudes of the orthogonal core reflections. In order to achieve power detection of two reflections that are separated spectrally, a commercial vertical cavity surface emitting laser (VCSEL) was used to power the sensor, with 10 kHz continuous wavelength tuning over 2 nm just covering the two core resonances. This enables the sensor to return a much higher power level and better SNR at low cost and high repetition rate [12–14]. Finally, the rotation sensor has very low intrinsic sensitivity to temperature and axial strain variations (shift both resonances together but with no intensity variation), immune to intensity fluctuations from the light source and the optical path (normalized power output). The sensor is small in size (work in reflection), can be fabricated reproducibly as it is made up of a normal straight grating with no offset splicing. Finally the real time interrogation system require is very cost-effective as it requires only a power meter without narrow band spectral filter, making it a good candidate for in field torsion measurement.

2. Vector rotation sensing system

As shown in the Fig. 1, the torsion sensor configuration we propose here is based on a FBG (6 mm) inscribed in a PM fiber stub (12 mm). The grating is fabricated with a uniform phase mask using a pulsed KrF excimer laser. The PMF stub was spliced back to a 1 m long piece
of single-mode fiber (SMF) using a commercial fusion splicer. Rotation is applied on the upstream side of the SMF-PMF splicing point (indicated by red crossing lines in Fig. 1).

The operation principle of the proposed sensor can be explained by the difference in the behavior of the E-field vector between the linear-polarized input light (controlled by the upstream polarizer and PC) and the principal axis orientation of the downstream PMF, to which the above two parts are connected by a standard SMF (exposed to twist around its longitudinal axe). In detail, when linearly polarized (LP) light is excited and launched into SMF, the input LP E-field spatial orientation is maintained throughout the entire SMF section, regardless of SMF twist around its longitudinal axis. This is because the moderate axial twisting of fully circularly symmetric fiber (i.e. SMF) does not influence or break the circular geometry or material symmetry of the fiber’s core to the extent that could effectively turn the spatial E-field’s orientation [15,16]. Thus, twisting of the SMF does not change the spatial orientation of the E-field. However, the downstream PM-FBG assembly, which freely rotates together with the SMF, acts as a polarization sensitive mirror (i.e. polarization analyzer). Therefore, rotation/twist of SMF thus causes rotation of PM-FBG’s principal axis orientation relative to the input LP E-field orientation, while the standard SMF only performs a low-loss interconnection and does not rotate the E-field vector. This allows for a simple and straightforward measure of torsion.

Instead of using a BBS as light source, a high-speed continuous wavelength tunable VCSEL is utilized to launch light into the sensing fiber through a 3 dB coupler. The sensor reflection is measured by a power meter connected to an oscilloscope (or a data acquisition card). As the VCSEL wavelength is swept, the spectral positions of the two reflected peaks corresponding to the two eigenpolarizations of the PM-FBG occur at two different times and their separate amplitudes can be measured.

3. VCSEL characteristics

The tuning characteristics of VCSEL are determined by the modulation of its driving current. Figure 2 gives a detailed observation on the effect of the driving current (corresponding to current amplitude (a) and repetition rate (b)) on the VCSEL’s tuning spectra (a continuous VCSEL tuning recorded at the optical spectrum analyzer (OSA) using “maximum hold” mode). The VCSEL wavelength tuning range increases with the amplitude rise of the driving current (2.5–8.0 mA) and decreases with the increase of the tuning speed (1–100 KHz), as shown in Figs. 2(a) and 2(b), respectively. Combining the two methods, the laser wavelength of VCSEL can be flexibly tuned over 2 nm. The slight peak power variations (especially for the repetition rate tuning in Fig. 2(b)) are due to the temperature dominated refractive index modulation in VCSEL’s resonator. When the VCSEL tunes with a very high speed, the input scanning current drops before the cavity temperature rises to its “steady-state” value for which the power is maximum. This narrows the tuning range. Figure 2(a) shows a better approach for wavelength tuning by modulating the amplitude of bias current. A smooth wavelength tuning without the unwanted power fluctuations is achieved. Meanwhile, the
potential slight power fluctuation (versus wavelength) should not matter since we use the normalized intensity ratio of the two PM-FBG core modes for rotation measurement. The VCSEL tuning

![Fig. 2](image1.png)

Fig. 2. Spectral tuning characteristics of VCSEL versus driving currents with different (a) amplitude (with fixed repetition rate of 10 kHz) and (b) repetition rate (with fixed bias current of 4.5 mA).

![Fig. 3](image2.png)

Fig. 3. Spectral tuning characteristics of VCSEL versus driving signals: (a) saw-tooth, (b) triangle and (c) sine wave.

bandwidth can be further broadened up to 3–4 nm if we decrease the repetition rate of driving current to 1 Hz or even lower (depending on the interrogation response time needed). This enables the PM-FBG sensor to have more free spectral room to tolerate environmental temperature changes (up to tens of degrees Celsius).

The spectral tuning characteristics of VCSEL are also influenced by its driving signal. As shown in Fig. 3, three types of driving current signals (with fixed 10 kHz and 2.5 mA), including (a) saw-tooth wave, (b) triangle wave and (c) sine wave are studied for comparison. Obviously, the saw-tooth wave driving signal provides a much smooth spectral tuning over the whole bandwidth together with a stable maximum power level, as shown in Fig. 3(a).

![Fig. 4](image3.png)

Fig. 4. PM-FBG reflections powered by BBS (black line) and VCSEL (red line), respectively. The dashed blue line shows the VCSEL tuning spectra recorded by the OSA “maximum hold” mode.
The special advantages of VCSEL we explore here are that the high-speed (10 kHz) continuous wavelength tuning (over a maximum range of 2 nm) of laser output perfectly covers the two PM-FBG core modes, as shown in Fig. 4. The VCSEL used here is a commercial product from RayCan with a nominal wavelength of 1547.45 nm, threshold current of 2 mA and typical output power of 0.5 mW. The driving signal is a saw-tooth wave with a frequency of 10 kHz and amplitude of 2.5 mA (bias current 4.5 mA). With this light source, the reflected power of the PM-FBG core modes are at a much higher power level with 15 dB improvement over using a BBS and an optical SNR of 48.5 dB is achieved.

4. Experimental results and discussions

Initial alignment of the system shown in Fig. 1 is performed simply by measuring the power reflected when the fiber is kept straight and the input polarization rotated by the polarization controller. For illustration, we show in Fig. 5 measurements of the system obtained with an OSA and BBS for various angles of the rotator. We define the twist angle to be 45° when both reflected resonances have the same peak intensity. Clearly, the spectral response of each orthogonal-polarimetric PM-FBG core modes occurs at angles of 0° and 90° respectively.

For the torsion sensor characterization, we set the initial polarization state at 0° and then twist the sensor probe by using the fiber rotator. Figures 6(a) and 6(b) present the reflection spectral response (again recorded by OSA for illustrative purposes) and the individual peak powers of the two orthogonal resonances of the PM-FBG. A symmetrical polarization dependent spectral and power response has been experimentally achieved, in which both polarization modes present a sinusoidal response over −90° to 90° rotation modulation but with π/2 phase delay relative to each other.
Figure 7 shows actual response of the VCSEL-driven system using the normalized intensity ratio $I_N = (P_x - P_y) / (P_x + P_y)$ of the orthogonal-polarimetric modes extracted from the real time oscilloscope data. The top part of Fig. 7 also shows the first order derivative of the normalized intensity plots and the corresponding fit lines. By using both normalized intensity and the first derivative data (set the origination of x- or y-polar as zero twist degree, as shown in Fig. 5), the rotation direction and the sensitivity are identified unambiguously (hence the name “vector rotation sensor”), with the green shaded regions corresponding to counter clockwise twist (minus value) and the gray regions to clockwise (plus value). The average sensitivity of the torsion is 0.09 dB/deg.

Finally, apart from the temperature sensitivity associated with the spectral shift of the FBG there might be a temperature-dependent polarization rotation in the SMF section of the twisted fiber, but based on the results shown in Ref. 15 this effect should be negligible (i.e. less than 1 degree of rotation) for temperature variations of a few tens of degrees Celsius, and twist angles up to 90 degrees.

5. Conclusion

A compact VCSEL-based PM-FBG fiber-optic polarimetric torsion sensor is proposed and experimentally demonstrated. The high-speed continuous wavelength tunable VCSEL and single photodetector coupled to a real-time data acquisition system enable the high SNR measurement of a closely spaced pair of reflections that correspond orthogonal modes of the PM fiber. We have shown that both the twist angle and direction of the rotation over a range of −90 to + 90 degrees can be accurately detected by comparing the normalized reflected powers of the two modes. This interrogation system effectively eliminates the potential light source power fluctuations while maintaining very low intrinsic sensitivity to temperature and axial strain as long as the two reflected peaks remain within the VCSEL spectral window. Compact size, low cost, good reproducibility, high sensitivity and SNR make the proposed PM-FBG sensor a good candidate for in-field torsion measurement.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (No. 61205080, No. 61235005), Guangdong Natural Science Foundation of China (No. S2011010001631, No. S2012010008385), Doctoral Program of Higher Education of China (No. 20114401120006), Pearl River Scholar for Distinguished Young Scientist (No. 2011J2200014). J. Albert is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Research Chairs Program.