High-speed fibre Bragg grating sensor interrogation using dispersion-compensation fibre

H.Y. Fu, H.L. Liu, X. Dong, H.Y. Tam, P.K.A. Wai and C. Lu

A novel high-speed fibre Bragg grating (FBG) sensor interrogator using dispersion-compensating fibre is proposed and demonstrated. The wavelength shift measurement of the FBG sensor is converted to time-domain measurement. The high-speed potential of this scheme was investigated experimentally, demonstrating an effective sampling speed of 2.44 megasamples per second.

Introduction: Fibre Bragg gratings (FBGs) have proved themselves as the ideal candidates for measuring strain and temperature in smart structures, civil engineering or other harsh environments. The advantages of the FBG sensor over conventional electrical sensors include small size, light weight, immunity to electromagnetic interference, low cost and other inherent advantages of fibre-optic sensors. FBG emerges as one of the most successful fibre-optic sensors owing to its wavelength-encoded nature which makes it insensitive to intensity fluctuation caused by losses in the connection fibre and connectors [1]. The key technology for an FBG sensor system is the interrogation of the shift of the Bragg wavelength reflected from an FBG. Various approaches to realise FBG interrogators have been developed, including those based on scanning filters, tunable lasers, interferometry, a discriminator using the power ratios of optical filters, a holographic grating based spectroscopic charge coupled device (CCD), long period gratings and chirped FBGs [2]. High-speed interrogation of FBG sensors in the order of megasamples per second is desirable in some applications where fast dynamic system response measurement is required. Most reported methods, however, interrogate FBGs at less than 1000 samples per second. Some schemes for high-speed interrogation were proposed recently, based on arrayed waveguide grating and short-pulse interferometry [3, 4]. In this Letter, we propose and demonstrate a novel FBG sensor interrogation system [5] using an electro-optic modulator (EOM) and a dispersion compensating module to convert wavelength to time measurement, and the system can interrogate FBGs at speed in the order of megasamples per second.

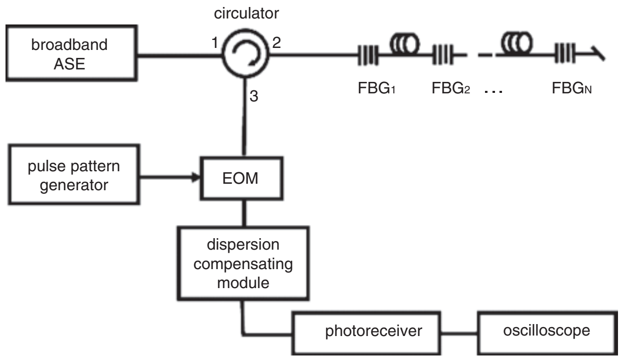

Fig. 1 *Experimental setup of proposed FBG interrogation system*

Experimental setup and operating principle: Fig. 1 shows the experimental setup of the proposed FBG interrogation system. An erbium-doped fibre amplified spontaneous emission (ASE) source launches light into port 1 of a three-port circulator and illuminates the FBG array via port 2 of the circulator. The light, the wavelength of which falls in the reflection spectrum of the FBG array, will be reflected back to the circulator. Light from port 3 of the circulator is launched to the EOM which is driven by a pulse pattern generator (PPG) that generates one bit '1' followed by a string of bit '0'. The pulsed signal is then fed to the dispersion compensation module. The spectrum within the pulse comprises the different wavelength components reflected by the FBG array and they take different times to propagate the dispersion compensation module. By measuring the time shift, Δt, we obtain the wavelength shift, $\Delta\lambda$ by the relationship

$$\Delta\lambda = \Delta t / D \quad (1)$$

where D is the total dispersion of the dispersion compensating module. Variations of Δt give the dynamic response of the FBGs. In absolute strain or temperature measurements, one of the FBGs in the array with either the shortest or longest wavelength can be used as a reference, and the time differences between it and the other FBGs are measured. The basic principle of the proposed interrogation technique is that instead of measuring wavelength shift using a wavelength meter, the dispersion fibre converts the wavelength difference to time difference which can be easily measured using a low-cost but high-speed photoreceiver and oscilloscope.

The broadband ASE source used in this experiment has high saturation output power of +27 dBm and operating wavelength from 1540 to 1565 nm. The EOM (JDSU, OC-192) is a 10 Gbit/s $LiNbO_3$ modulator driven by a pulse pattern generator (Anritsu, MP1763B). The dispersion-compensating module (OFS, WBDK: 170-C) is a 3.525 km-long wideband dispersion compensating fibre and has a total dispersion of −170 ps/nm at 1550 nm. The pulsed signal is detected by a 10 Gbit/s photoreceiver and measured with an oscilloscope.

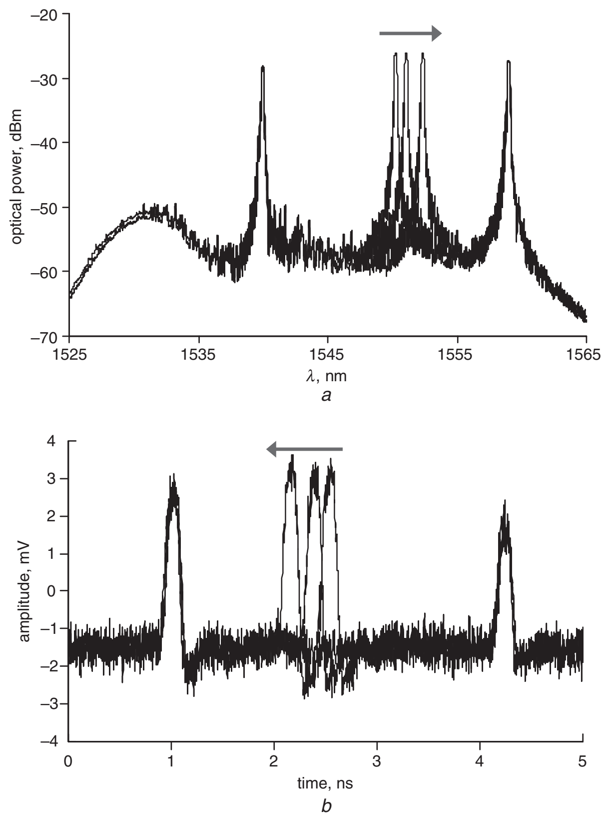

Fig. 2 *Measured optical spectrum and time-domain spectrum of three FBG sensing signals with FBG at 1550 nm under strain tuning*

a Measured optical spectrum
b Time-domain spectrum

Results and discussion: To demonstrate the high-speed capability of the FBG sensor interrogation system, we deploy three FBGs, the wavelengths of which are 1540.63, 1549.98 and 1558.92 nm. All three FBGs have reflectivities higher than 90%. The data length of the PPG is set to 64 bits with the first bit '1' followed by 63 bits of '0'. Therefore, the interrogation system is modulated by a signal with a pulse width of 0.1 ns and a repetition frequency of 156.25 MHz. Fig. 2*a* shows the superposition of three measured optical spectra of the FBGs and their corresponding measured waveform (after averaging of 64 periods) shown in Fig. 2*b* with the FBG at 1549.98 nm stretched at three different strains. One end of the FBG with Bragg wavelength at 1549.98 nm, is glued to a translation stage so that strain can be applied on it by moving the stage. As shown in the Figure, when strain was applied to the FBG, its central wavelength shifted to longer wavelength and the corresponding pulse in time-domain shifted accordingly. In the dispersion-compensating module, the longer wavelength takes a shorter time to propagate in the fibre. The wavelength spacing between adjacent FBGs is about 10 nm, which is equal to 1.7 ns spacing between the pulses in time-domain. In most applications, the typical operation wavelength range for an FBG sensor is about 2 nm, which corresponds to 0.34 ns. With a time period of 6.4 ns, the number of FBG sensors can be handled is 18. However, more FBG sensors can be interrogated by increasing the time period to extend the wavelength range. If we take one of the FBGs as a reference, we can determine the wavelength shift of the other two FBGs. The referenced FBG can also serve as a temperature compensator, since in most applications temperature fluctuation is inevitable.

Fig. 3 shows the measured time shift against wavelength shift of one of the FBGs. The Bragg wavelength of the FBG was varied by 5 nm, and the measured linearity is very good with an R-square value of 0.9992. The coefficient of time shift against wavelength shift is 0.168 ps/pm, which corresponds to a response rate of 0.202 ps/$\mu\varepsilon$, as the wavelength-strain sensitivity of the FBG is 1.2 pm/$\mu\varepsilon$. The measurement results agree well with the theoretical prediction given by (1). The highest time-base resolution of the oscilloscope (Agilent, 86100A) used in our experiment is 2 ps/div. and thus the wavelength shift resolution that can be achieved is $\sim$12 pm in our case. Higher resolution could be achieved using a longer length of the fibre or fibres with larger dispersion parameter. However, this may introduce higher loss as well as larger signal pulse broadening that make accurate peak measurement difficult. Curve-fitting techniques could be employed to improve the accuracy of detecting the peak of broadened pulses. This part of the work is ongoing and will be reported at a future data.

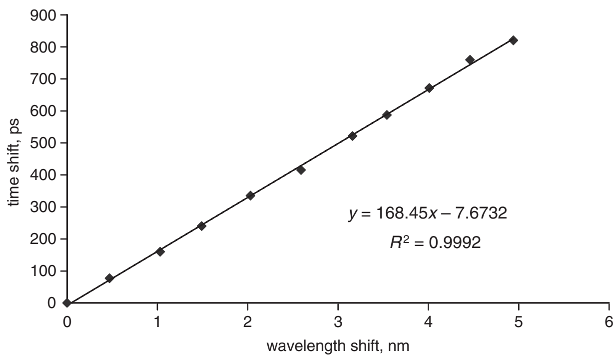

Fig. 3 *Time shift against wavelength shift*

The proposed FBG sensing interrogator has no moving parts and can demodulate FBGs at very high speed. As a result of the rapid progress of optical communications, high-speed devices such as modulators and photodetectors are becoming inexpensive and readily available. In our experiment, a 10 Gbit/s modulator was used to generate 0.1 ns pulses with a time period of 6.4 ns and according to (1) covers a wavelength range of about 37.65 nm. There is a trade-off between the interrogation speed and the measurable wavelength range, more scanning time is needed to increase the measurable wavelength range for a given total dispersion D. The measured waveform shown in Fig. 2 was obtained after an averaging of 64 signals, giving an effective sampling speed of 2.44 megasamples per second.

Conclusion: A novel high-speed FBG sensing interrogation system has been proposed and demonstrated experimentally with an effective sampling speed of 2.44 megasamples per second. We have analysed the multiplexing capability, sensitivity, accuracy and response speed of the proposed interrogator.

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