FBG sensor for strain measurement with enhanced sensitivity by using degenerated FWM in highly nonlinear fibre

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A method for enhancing the sensitivity of a fibre Bragg grating (FBG) sensor by all-optical signal processing is demonstrated. Degenerated four-wave mixing (FWM) has been used to perform frequency chirp magnification, which can be used for magnifying the wavelength drift of the FBG sensor. Ultra-highly sensitive measurement of the static strain has been experimentally demonstrated with strain sensitivity of 5.40 pm/με. The sensitivity has been enhanced by a factor of five.

Introduction: Fibre Bragg grating (FBG) has been widely used in optical sensing owing to its attractive advantages of compactness, all-fibre structure, high sensitivity, simple fabrication and low cost [1, 2]. There have been a lot of industry applications using FBG for strain sensing. Usually, one can obtain a strain sensitivity of about 1 pm/με for an FBG sensor [3]. Such a sensitivity leads to a strain resolution of 20 με for a standard optical spectrum analyser (OSA) based interrogator with 0.02 nm wavelength resolution. A smaller strain beneath 20 με will be invisible to the OSA. For example, the Earth’s crustal deformation induced strain is at the scale of 10⁻⁶ [4]. Thus, the required wavelength resolution is about 1 fm which makes the interrogation very difficult (impossible for an OSA). To overcome this issue, one can either improve the interrogation resolution or increase the sensitivity of the sensor. To date, there have been several demonstrations of high-resolution interrogation, usually with rather complicated technology [5, 6]. However, increasing the sensitivity of the FBG is difficult.

By pre-processing the FBG’s fibre structure, one can obtain a strain sensitivity of 2.5 pm [7]. Pre-processing of the FBG is usually difficult. Thus, it would be quite attractive if the sensitivity could be enhanced by post-processing of the signal.

In this Letter, we demonstrate a post signal processing method for enhancing the sensitivity of an FBG-based strain sensor. The sensitivity enhancement is achieved by frequency chirp magnification based on degenerated four-wave mixing (FWM) in a highly nonlinear fibre. The strain induced wavelength drift of the FBG sensor has been magnified in a high-order FWM process. Ultra-highly sensitive measurement of the static strain has been experimentally demonstrated with a strain sensitivity of 5.4 pm/με, which has been magnified by a factor of five.

Principle: In a degenerated FWM process, the first-order idler wavelength will have a doubled frequency chirp compared with that of the pump wavelength [8, 9], which has been schematically illustrated in Fig. 1a. Consider the FWM with high-order idler components; the frequency chirp will be magnified with a linearly magnified compensation factor along with the increase of the idler order [9]. Therefore, considering a wavelength drift of δλs at the pump wavelength; one can obtain a magnified wavelength drift of δλfi at idler-2 as shown in Fig. 1a, which has been amplified by a factor of three. Then, in a high-order FWM process, the frequency drift δλfi at idler-n is (n+1)δλfi.

Fig. 1 Schematic illustration of frequency chirp and wavelength drift magnification based on high-order degenerated FWM
a Frequency chirp
b Wavelength drift

Based on such a mechanism indicated in Fig. 1, one can develop an FBG sensor with significantly enhanced sensitivity by post-processing of the signal. Considering the FBG resonant wavelength as the pump wavelength, the strain induced wavelength drift will be amplified and the strain sensitivity will thus be enhanced. The enhancement is merely realised by the post-processing of the signal, which makes this method a universal solution for a wide range of applications.

Experiments: Fig. 2 shows the experimental setup which consists of a fibre laser system based on a FBG and a FWM system based on highly nonlinear fibre (HNLF). The output port of the EDFA is connected to a circulator, which directs the light to the FBG. The reflected light from the FBG is redirected to a polarisation controller (PC) by the circulator and then launched into the OC, which has a splitting ratio of 30:70. The 70% port of the OC is connected to an isolator (ISO) and the ISO is connected with the input port of the EDFA. Thus, a fibre laser is constructed based on the FBG with the output lasing wavelength located at the FBG resonant wavelength of 1551.69 nm. The FBG laser and the tunable laser (TL) are combined and launched into the EDFA. The amplified pump at 1551.69 nm and signal at 1548.37 nm are then directed into the HNLF after a bandpass filter (BPF). The 500m HNLF used in this work has a nonlinear coefficient of 11 W⁻¹ km⁻¹.

Fig. 2 Experimental setup consists of FBG-based fibre laser system and FWM system
EDFA: erbium-doped fibre amplifier; CIR: circulator; PC: polarisation controller; ISO: isolator; TL: tunable laser; BPF: bandpass filter; HNLF: highly nonlinear fibre

By stretching the FBG, a certain amount of strain can be loaded onto the FBG. Therefore, the resonant wavelength of the FBG will be shifted. Consequently, the lasing wavelength of the fibre laser will drift along with the strain loading. In this work, the strain is loaded by driving the motors of a fusion splicer in manual mode with the two ends of the FBG fastened by the holders. The moving step of the motors is 1401 µm and the total length of the FBG plus the fibre between the two holders is 27.8 mm. It is found that the strain induced fibre laser wavelength drift is about 0.57 nm with 540 µε (15 µm stretching over 27.8 mm), which is in good agreement with the resonant wavelength drift for the FBG measured by ASE transmission. Therefore, we can find that the original strain sensitivity of the FBG is about 1.06 pm/µε.

Fig. 3 Measured optical spectra after degenerated FWM
δλs−δλfi are wavelength drifts for pump and idlers

The degenerated FWM in the HNLF generates high-order idler components as shown in Fig. 3. Four idlers have been generated by considering the fibre laser at 1551.69 nm as the pump with 27dBm EDFA output power. After the degenerated FWM process, the frequency chirp magnification leads to a magnified wavelength drift at the idlers.
Shown in Fig. 4 is the wavelength drift at different idler components. The wavelength drifts are 1.14, 1.72, 2.32 and 2.92 nm, respectively, for idler-1, idler-2, idler-3 and idler-4. Thus, five times chirp magnification at idler-4 has been achieved, which results in a wavelength drift of $5\delta\lambda_0$. The wavelength drifts are 1.14, 1.72, 2.32 and 2.92 nm, respectively, for idler-1, idler-2, idler-3 and idler-4. At idler-4, the wavelength sensitivity is measured to be 5.40 pm/$\mu$e, which is five times that of the original FBG. The curve in Fig. 4 is a linear curve, indicating a linearly increased magnification. Therefore, the magnification will not be saturated along with the generation of higher order idler components.

The proposed method is a post-processing technology, which can be applied to a wide range of fibre sensing applications because it does not affect the sensor head. The FWM in this work is realised in a 500m HNLF in a single-stage operation. Further improvement can be achieved by using a longer HNLF with higher pump power and multiple-stage operation to generate more idler components for obtaining a higher sensitivity.

Conclusion: We have demonstrated a method for enhancing the strain sensitivity of an FBG sensor. The enhancement is achieved by a degenerated FWM, which is one kind of all-optical signal processing technology. Ultra-highly sensitive strain measurement with a sensitivity of 5.40 pm/$\mu$e has been experimentally realised, which has been magnified by a factor of five. The proposed method is of particular significance to high-resolution FBG sensing applications.

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Fig. 4 Wavelength drift at different orders of idler components

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