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Temperature-insensitive strain sensor based on four-wave mixing using Raman fiber Bragg grating laser sensor with cooperative Rayleigh scattering

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Abstract A temperature-insensitive strain sensor based on Four-Wave Mixing (FWM) using two Raman fiber Bragg grating (FBG) lasers with cooperative Rayleigh scattering is proposed. Two FBG were used to form two linear cavities laser sensors based on Raman amplification combined with cooperative Rayleigh scattering. Due to the very low dispersion coefficient of the fiber, it is possible to obtain the FWM using the two lasers. This configuration allows the operation as a temperature-insensitive strain sensor where both sensors have the same sensitivity to temperature but only one of the FBG laser is sensitive to strain. The difference between the wavelengths of the signal sensor and the converted signal presents a strain coefficient sensitivity of 2 pm/με with insensitivity to temperature. The FWM efficiency is also dependent on the applied strain, but it is temperature independent, presenting a maximum sensibility of 0.01 dB/με.

1 Introduction

Fiber Bragg grating (FBG) sensors can be used as sensing head for measurement strain, temperature or others physical parameters [1]. The variation of these parameters induces changes of the central Bragg wavelength, which can also be converted in optical power variation through a linear filter [1].

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A number of fiber lasers or amplifiers architectures based on Raman effect can present some restrictions when high power is injected in the optical fiber due to the gain suppression created by the Rayleigh scattering growth. This Rayleigh scattering growth can be a problem for specific applications namely in optical communications but can be used as a distributed mirror to enhance the generation of Brillouin Stokes combs [2], multiwavelength generation [3] and distributed lasers [4].

However, a lossless fiber span where power losses are continuously compensated for with ultrahigh precision has been demonstrated [5]. This has been used to generate ultralong Raman fiber lasers with cavity lengths of up to 270 km [6], but can also be used to compensate Rayleigh scattering induced losses and increase the distances of remote sensing.

The Four-Wave Mixing (FWM) for wavelength conversion has advantages that include large spectral and dynamic range as well as providing strict bit rate and modulation format transparency. In optical sensing, this effect is underexplored. Only in 2007 was demonstrated a fiber ring laser sensor for strain-temperature discrimination [7]. The measurands used in this configuration were the wavelength variation of the FBG sensor and the FWM efficiency. Due to the different sensitivities it was possible to use a matrix method to characterize the sensing laser sensor for simultaneous measurement of strain and temperature.

In the present work, the authors demonstrate two possibilities for an interrogation system based on FWM effect obtained by two Raman fiber Bragg grating laser sensors with cooperative Rayleigh scattering. The first possibility is to use the power of the converted signal and the transfer function of the FWM efficiency, to obtain a temperature-independent strain sensor. The second possibility is to use the difference between the signal sensor wavelength and

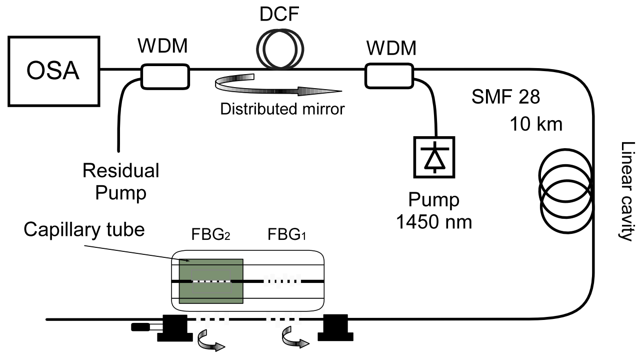

Fig. 1 Experimental setup using Bragg grating laser sensor

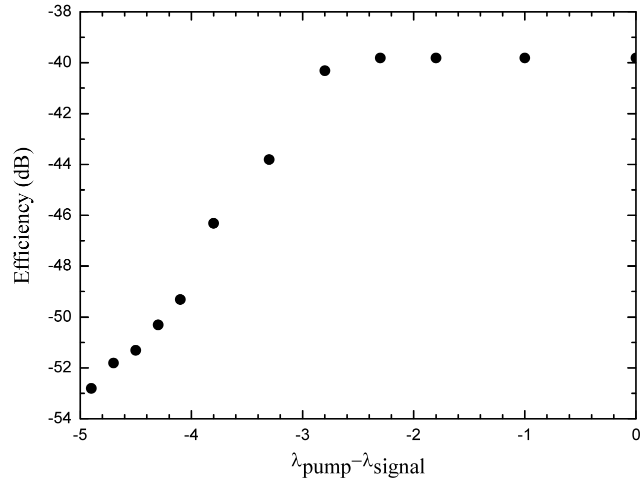

Fig. 2 FWM efficiency using this configuration

the converted signal wavelength to obtain a temperature-independent strain sensor.

2 Experimental results

Figure 1 presents the experimental setup for the Raman FBG laser sensor. A Raman pump laser at 1450 nm with a maximum power of 5 W and two wavelength division multiplexers (WDMs) (1450/1550 nm) are used. A one kilometer dispersion compensating fiber (DCF) with a dispersion coefficient of -132 ps/nm km is used to create the distributed mirror. Ten kilometers of SMF 28 are used to simulate a remote configuration. The sensing head consists in two fibers Bragg gratings with high reflectivity (>90%) separated by few centimeters. An Optical Spectrum Analyzer (OSA) was used to observe the optical spectrum. In this configuration we have two independent lasers. The gain for both lasers is a broadband Raman gain on the DCF with a maximum around 1550 nm generated by the 1450 nm pump laser with 600 mW. The two FBGs wavelengths are situated around this maximum and used as the narrowband mirrors for each laser [8]. The other mirror (distributed) for the lasers is generated by the Rayleigh scattering in the DCF. Thus, two Raman FBG linear laser cavities (at FBG_1 and FBG_2 wavelengths) are generated between the DCF and the FBGs. The bandwidths of the lasers are 0.1 nm and the signal-to-noise ratio (SNR) was larger than 55 dB.

The central Bragg wavelength of the FBG is shifted when strain or temperature are applied [1]. The FBG_2 is isolated to strain using the FBG inside of a capillary tube, but the FBG_1 is subjected to strain. Both FBGs have the same sensitivity to temperature and are assumed to be at the same temperature. This allows the measurement of strain with insensitivity to temperature, since the wavelength difference between pump and signal will only be affected by the strain.

Degenerate four-wave mixing is obtained in the DCF using the two lasers as pump and signal. The converted wave is used as the output of the measurement system. Four-wave mixing is a third order non-linearity in silica fibers, which is analogous to intermodulation distortion in electrical systems, so that in multichannel systems three optical frequencies mix to generate a fourth: $f_{\text{conv}} = f_{\text{pump1}} + f_{\text{pump2}} - f_{\text{signal}}$ where f_{pump1} and f_{pump2} are the pumping light frequencies, and f_{signal} is the frequency of the signal light. When the frequencies of the two pumping waves are identical, the more specific term "degenerated four-wave mixing" is used, and the equation for this case may be written: $f_{\text{conv}} = 2 f_{\text{pump}} - f_{\text{signal}}$.

A conventional experimental setup was used to characterize the FWM efficiency when the λ_{signal} is changed (see Fig. 2). A tunable laser was used to change λ_{signal} (with constant λ_{pump} and $P_{\text{pump}} = 600$ mW). The FWM efficiency is defined by the ratio between the optical power of the converted signal and the optical power of the signal. For a wavelength difference from 0 nm to 3 nm, the FWM efficiency is constant and after 3 nm there is a decrease of the FWM efficiency with the wavelength difference. Since the dispersion curve of the DCF is almost flat, the FWM efficiency will remain constant if the pump and signal experience equal wavelength shifts, being only dependent on the wavelength difference.

Using the experimental setup depicted in Fig. 1, for increasing applied strain in the signal sensor, the wavelength converted (λ_{conv}) and the wavelength signal (λ_{signal}) were equally shifted in opposite directions from the wavelength pump (λ_{pump}) which remained constant. The optical power of the converted signal sensors was observed to decrease and the optical power of the signal sensor remained constant (Fig. 3a). Varying the temperature of the sensing head, an equal shift on the wavelength of all peaks was observed. Therefore the optical power remained constant for all signals (Fig. 3b). This result is expected since the transfer function of the FWM depends on the wavelength spacing between the pump and signal sensors.

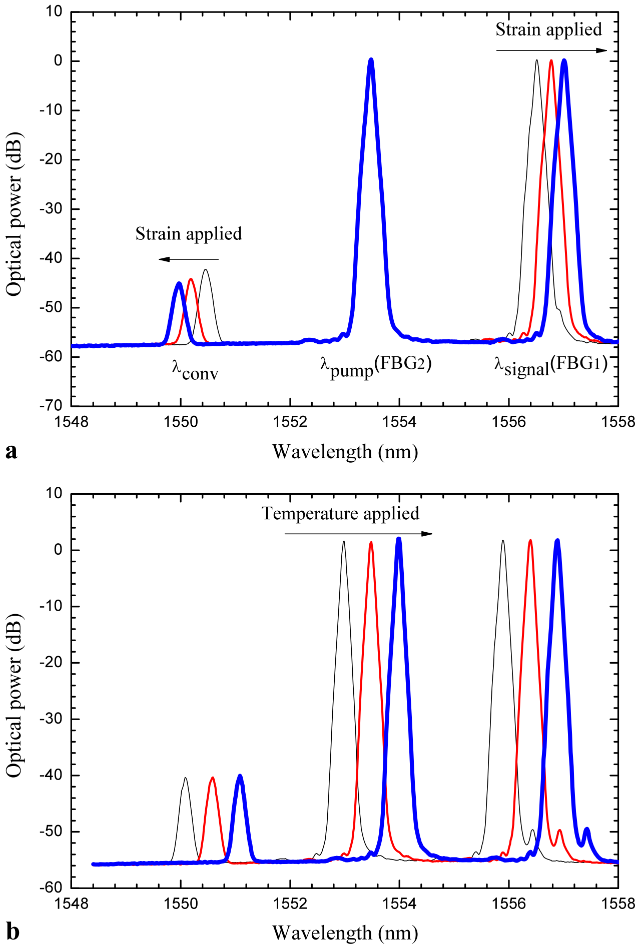

Fig. 3 Transfer function of the FWM when (**a**) strain and (**b**) temperature are applied

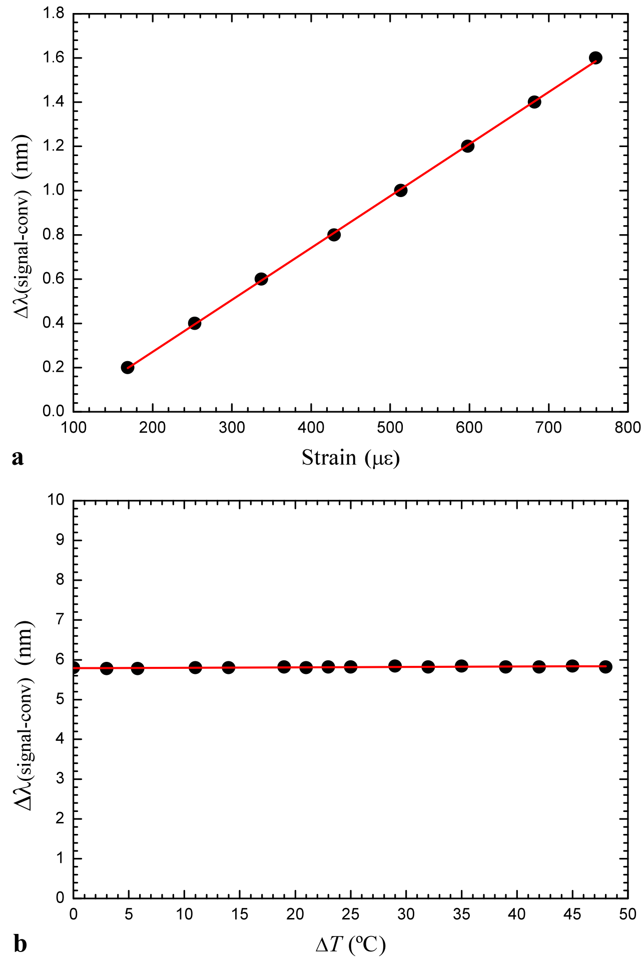

Fig. 4 The wavelength spacing between the signal and the converted ($\Delta\lambda_{(\text{signal-conv})}$) when the strain (**a**) and temperature (**b**) are applied

Figure 4a presents the relationship between the difference of the signal sensor and the converted signal ($\Delta\lambda_{(\text{signal-conv})}$) when the sensing head is subjected to strain. The coefficient sensitivity is 2.35 ± 0.15 pm/ με and that correspond to twice the value of the standard FBG response. This result is expected due to the opposite response of signal sensor and converted signal. Figure 4b shows the relationship between the difference of the signal sensor and the converted signal $\Delta\lambda_{(\text{signal-conv})}$ when temperature is applied. The sensing head response is maintained constant when the temperature was changed. This result is expected when the two Raman Bragg grating sensor have the same sensitivity to temperature.

Figure 5a presents the FWM efficiency response when the strain is applied in the sensing head. The sensitivity of the FWM efficiency with varying applied strain was obtained between 0.01 dB/με and 0.004 dB/με. Figure 5b shows the FWM efficiency results of the sensing head when the temperature is applied and the FWM efficiency is constant for varying applied temperature.

3 Conclusion

A temperature-insensitive strain sensor based on linear Raman FBG laser sensor with cooperative Rayleigh scattering was demonstrated. When the strain is applied in the sensing head, it is observed an increase of the difference between the signal sensor and the converted signal sensor wavelengths and also an optical power variation of the FWM efficiency.

It was also demonstrated that the optical power of the converted signal and the difference between the signal sensor and the converted signal sensor wavelengths are constant for temperature changes.

Considering an almost flat dispersion of the DCF, the transfer function of the FWM depends only in the separation between the pump and signal sensor wavelengths and therefore the temperature insensitivity is guaranteed. This configuration allows interrogating Raman FBG lasers sensors for remote sensing through the optical power variation.

In conclusion, it is possible to obtain a strain sensitivity of 2 pm/με when the signal and pump wavelengths separation are used or a sensitivity of up to ≈0.01 dB/με using

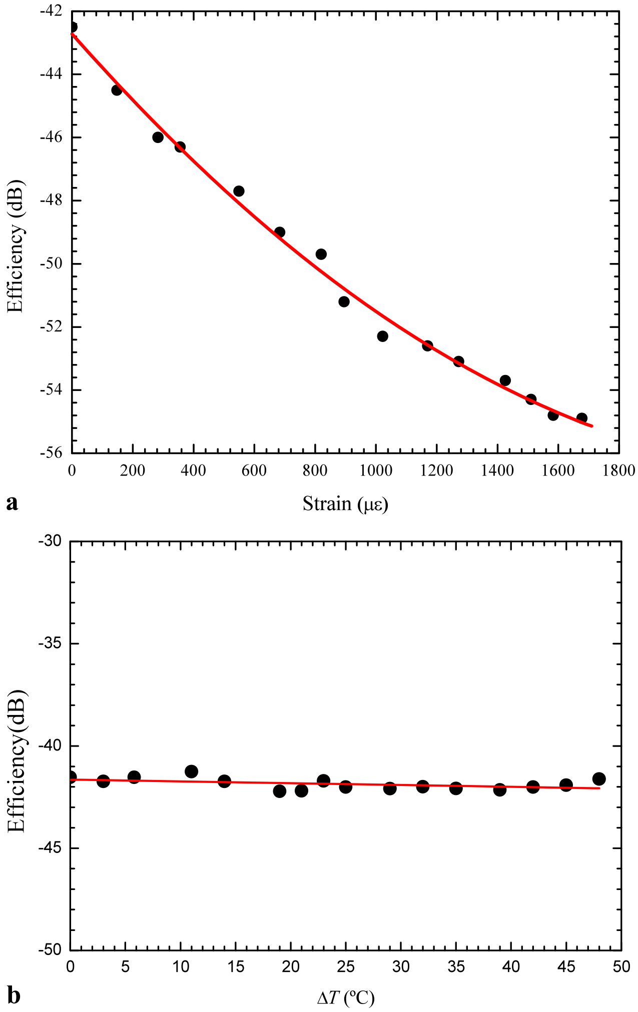

Fig. 5 FWM efficiency for applied (**a**) strain and (**b**) temperature on the sensor

the ratio between the optical power of the converted signal and the optical power of the signal (FWM efficiency). Depending on the interrogation system, it is possible to obtain a low cost remote system based on WDM to separate the signal sensor and the converted signal. In this case, both optical power signals can be read by photodetectors. This work demonstrated an interrogation system to eliminate the cross-sensitivity of the temperature to the strain sensor. However, this configuration can be used to interrogate other physical parameters with insensitivity to temperature, including pressure, curvature, torsion and displacement.

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