IEEE Photonics Journal
An IEEE Photonics Society Publication

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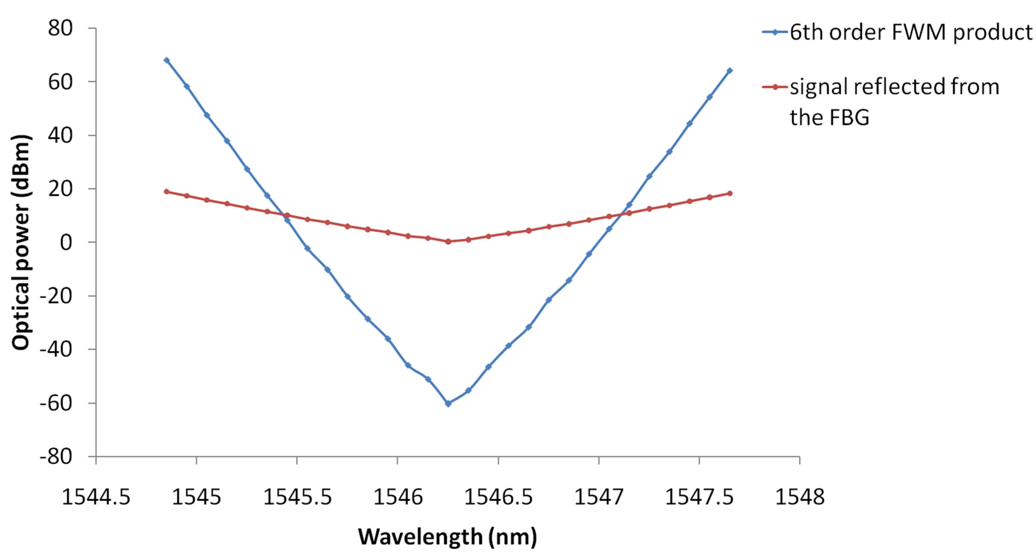
Volume 12, Number 1, February 2020

Chiranjit Ghosh, *Member, IEEE*
Vishnu Priye, *Senior Member, IEEE*



DOI: 10.1109/JPHOT.2019.2912266

Highly Sensitive FBG Strain Sensor With Enhanced Measurement Range Based On Higher Order FWM

Chiranjit Ghosh, ***Member, IEEE*****,**
and Vishnu Priye, ***Senior Member, IEEE***

Department of Electronics Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad, Dhanbad 826004, India

DOI:10.1109/JPHOT.2019.2912266

Manuscript received March 19, 2019; revised April 12, 2019; accepted April 16, 2019. Date of publication June 17, 2019; date of current version January 15, 2020. This work was supported by the Ministry of Electronics and Information Technology (Meity), Government of India under the Visvesvaraya Ph.D. scheme for Electronics and IT. Corresponding author: Chiranjit Ghosh (e-mail: chiranjit9119@gmail.com).

Abstract: To meet the simultaneous requirement of high sensitivity and high measurement range is an uphill task in the development of fiber Bragg grating (FBG) strain sensor. A unique scheme of highly sensitive FBG strain sensor is proposed based on nonlinear four wave mixing (FWM) with a high measuring range. In this paper, both the edges of FBG reflection spectrum are used without increasing the number of sources. The FWM products generated are tuned to the reflection edges of the FBG. The signals reflected from the edges of the FBG are then utilized in the subsequent FWM process to enhance the sensitivity of the system. The proposed scheme can provide a strain measurement range of 2310 $\mu\epsilon$ with strain sensitivity of 91.21 dBm/nm.

Index Terms: Fiber Bragg Grating, four wave mixing, strain sensor, edge filter.

1. Introduction

Fiber Bragg Grating (FBG) sensors have been widely used for strain measurements due to its main attractive features of high sensitivity, small size, low cost, immunity to electromagnetic interference and multiplexing ability [1], [2]. However detection of the small wavelength shift information due to strain with FBG sensors is a challenging issue. A proper selection of interrogation scheme is critical to FBG sensor to monitor the small change in strain. In addition to the requirement of high sensitivity and high measurement range, interrogation methods should have the merits of low cost and simple to use. In practical applications, simultaneous attainment of high sensitivity and high measurement range is essential for FBG sensor. High resolution interrogation is usually involved with rather complicated technology [3], [4]. By preprocessing the FBG structure [5], [6] sensitivity can be improved. However increased complexity and ineffectiveness are the main limitations of this technique. Thus a simple and cost effective post processing technique is more suitable to enhance the sensitivity. FBG interrogation technique presented so far have atleast one of the following issues; poor resolution or small measurement range. Optical spectrum analyzer (OSA) as a interrogator for FBG sensor has been used widely. However the bulkiness, low resolution, and high cost of OSA limits the application areas of FBG sensors [7].

In recent years FBG interrogation methods based on matched grating and edge filters [8]–[11] have been realized. In these techniques by detecting the optical power the wavelength shift information can be obtained. However, the above methods come at the expense of small measurement range. Moreover matched FBG interrogation scheme requires the need of many matching FBGs for multiple point measurements [10]. Its dynamic range is also limited by the bandwidths of the two matched gratings. Among the nonlinear processes four wave mixing (FWM) is one kind of important third order nonlinear process in optical fibers, which extend applications in sensors [12]. In the case of standard FWM effect, three optical signals propagate through the optical fiber in the same direction with frequencies, f_i, f_j, f_k and subsequently interact with each other generating a fourth signal with frequency f_{ijk}, where $f_{ijk} = f_i + f_j - f_k$, with i, j $\neq$ k [2]. The letters i, j, k represents three distinct channels in a multichannel structure. A new scheme of FBG strain sensor with enhanced sensitivity based on higher order FWM effect has been proposed recently [12]. However it showed a trade-off between measurement range and sensitivity achieved.

In this paper, a unique scheme of FBG strain sensor has been proposed to simultaneously achieve high measurement range (2310 $\mu\epsilon$) and high sensitivity(91.21 dBm/nm). In this work, the measurement range is increased by utilizing both the edges of the FBG reflection spectrum in such a way that the ending point of the effective range of one of the reflection edge of FBG is identical to the starting point of the effective range of the other reflection edge of the FBG. The proposed work eliminates the need of additional laser sources, with the FWM products being used as sources to interrogate the FBG. Further the signals reflected from the edges of the FBG are used in subsequent FWM process to enhance the sensitivity of the system.

2. Principle

When light from laser source is tuned to one of the edges of the reflection spectrum of the FBG, the power obtained through convolution between the output of a narrowband laser and the FBG reflection spectrum is given by [12]:

$$P_1 = P(\lambda_G, \lambda_L) = I_0 R_0 \int_{-\infty}^{\infty} \exp\left[-4\log_e 2\left(\frac{\lambda-\lambda_G}{\Delta\lambda_G}\right)^2\right]\exp\left[-4\log_e 2\left(\frac{\lambda-\lambda_L}{\Delta\lambda_L}\right)^2\right] d\lambda$$

$$= \frac{I_0 R_0 \exp\left[-4\log_e 2 \frac{(\lambda_G-\lambda_L)^2}{\Delta\lambda_G{}^2+\Delta\lambda_L{}^2}\right]}{\sqrt{\frac{4\log_e 2}{\pi}\left(\frac{1}{\Delta\lambda_G{}^2}+\frac{1}{\Delta\lambda_L{}^2}\right)}} \tag{1}$$

where λ_G and $\Delta\lambda_G$ are the central wavelength and FWHM of the FBG reflection spectrum respectively. λ_L and $\Delta\lambda_L$ are the central wavelength and FWHM of the laser source respectively. I_0 is the light intensity at central wavelength λ_L and R_0 is the peak reflectivity of FBG at central wavelength λ_G. The reflected signal from FBG (P_1) when combined with another signal P_2 of constant power and propagated through nonlinear fiber, the FWM products are generated. The power of the higher order FWM products increases much more compared with the signal reflected from the edge of the FBG and the lower order FWM products.

The power of the FWM product can be expressed as [12]:

$$P_{q1} = \bar{\eta}_{q1}\left[\frac{I_0 R_0 \exp\left[-4\log_e 2 \frac{\Delta\lambda^2}{\Delta\lambda_G{}^2+\Delta\lambda_L{}^2}\right]}{\sqrt{\frac{4\log_e 2}{\pi}\left(\frac{1}{\Delta\lambda_G{}^2}+\frac{1}{\Delta\lambda_L{}^2}\right)}}\right]^{q+1} P_2{}^q \tag{2}$$

$$P_{q2} = \bar{\eta}_{q2}\left[\frac{I_0 R_0 \exp\left[-4\log_e 2 \frac{\Delta\lambda^2}{\Delta\lambda_G{}^2+\Delta\lambda_L{}^2}\right]}{\sqrt{\frac{4\log_e 2}{\pi}\left(\frac{1}{\Delta\lambda_G{}^2}+\frac{1}{\Delta\lambda_L{}^2}\right)}}\right]^{q} P_2{}^{q+1} \tag{3}$$

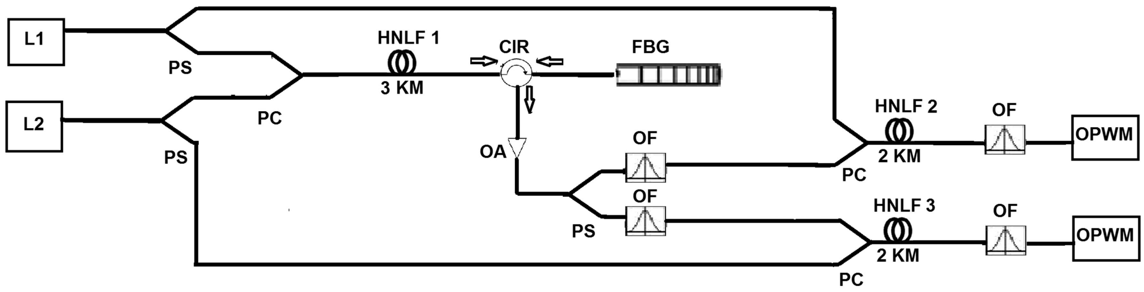


Fig. 1. Schematic diagram of the proposed strain sensor. L: laser. PC: Power Combiner. OA: Optical amplifier. PS: Power splitter. CIR: Circulator. OF: Optical filter. OPWM: Optical power meter.

where P_2 is the power received directly from the laser source, q is the order of mixing product and $\Delta\lambda = \lambda_G - \lambda_L$ is the change in wavelength due to strain.

Comparing eqn (1) and (2), it is observed that the power of qth order FWM product (P_{q1}) increases (q + 1) times with respect to the signal power(P_1) reflected from the edge of the FBG. The power of the higher order FWM products with the application of strain can be obtained from eqn (2) and (3). In this work the FWM products generated initially due to combination of the laser sources are used as sources to interrogate the FBG. The signals reflected from the edges of the FBG reflection spectrum are then combined with the corresponding laser sources to form the FWM products for augmenting the sensitivity.

3. Proposed Setup Configuration

The configuration of the proposed setup of the high strain resolution FBG sensor system is shown in Fig. 1. The light from the laser 1(L1) and laser 2(L2) of wavelength 1544.2 nm and 1548.3 nm respectively with power 12 dBm are combined and launched into the highly nonlinear fiber (HNLF1). The HNLF1 has nonlinear coefficient of 20.4 W^{-1}/km and zero dispersion wavelength of 1550 nm. The intense interaction between the signals from the laser sources generate higher order FWM products in HNLF1. The output of the HNLF1 is routed to the apodized chirped FBG. The FBG used has a chirp parameter of 3.2 nm and length 10 mm. The first order FWM products generated at 1540.1 nm and 1552.4 are located at the two edges of FBG reflection spectrum. After filtering, these first order FWM products are combined with the corresponding laser sources (i.e, FWM product at 1540.1 nm is combined with L1 and FWM product at 1552.4 nm is combined with L2) and launched into respective HNLF 2 and HNLF 3 to further produce higher order FWM products. The power of the corresponding sixth order FWM products are measured. The HNLF 2 and HNLF 3 employed has same nonlinear coefficient as that of HNLF 1 and are used for enhancing the sensitivity.

4. Results and Discussion

The FBG is designed in such a way that the ending point of the effective range of one of the reflection edge of FBG is identical to the starting point of the effective range of the other reflection edge of the FBG. The FWM products generated in HNLF 1 is shown in Fig. 2. The first order FWM signals at 1540.1 nm and 1552.4 nm denoted as F1 and F2 are used as sources tuned to the FBG reflection edges. The signals F1 and F2 are filtered and combined with the laser sources L1 and L2 respectively.

In the proposed scheme, initially the central wavelength of the chirped FBG is at 1544.85 nm as shown in Fig. 3(a).The signal F1 is located at the highest level of the linear zone of the FBG reflection edge (left) whereas F2 signal is not in the linear zone of the other FBG reflection edge (right). On increasing strain on the FBG, the signal F1 shifts downward resulting in decreased power. The reflection spectra of the FBG at central wavelength 1546.25 nm is shown in Fig. 3(b).

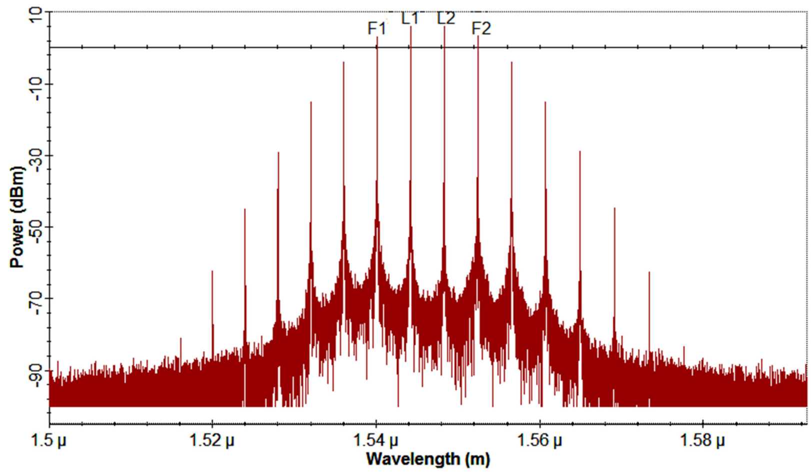


Fig. 2. Optical spectra after propagating through HNLF 1. F1, F2: First order FWM signal at 1540.1nm and 1552.4 nm respectively. L1, L2: laser 1 and laser 2 respectively.

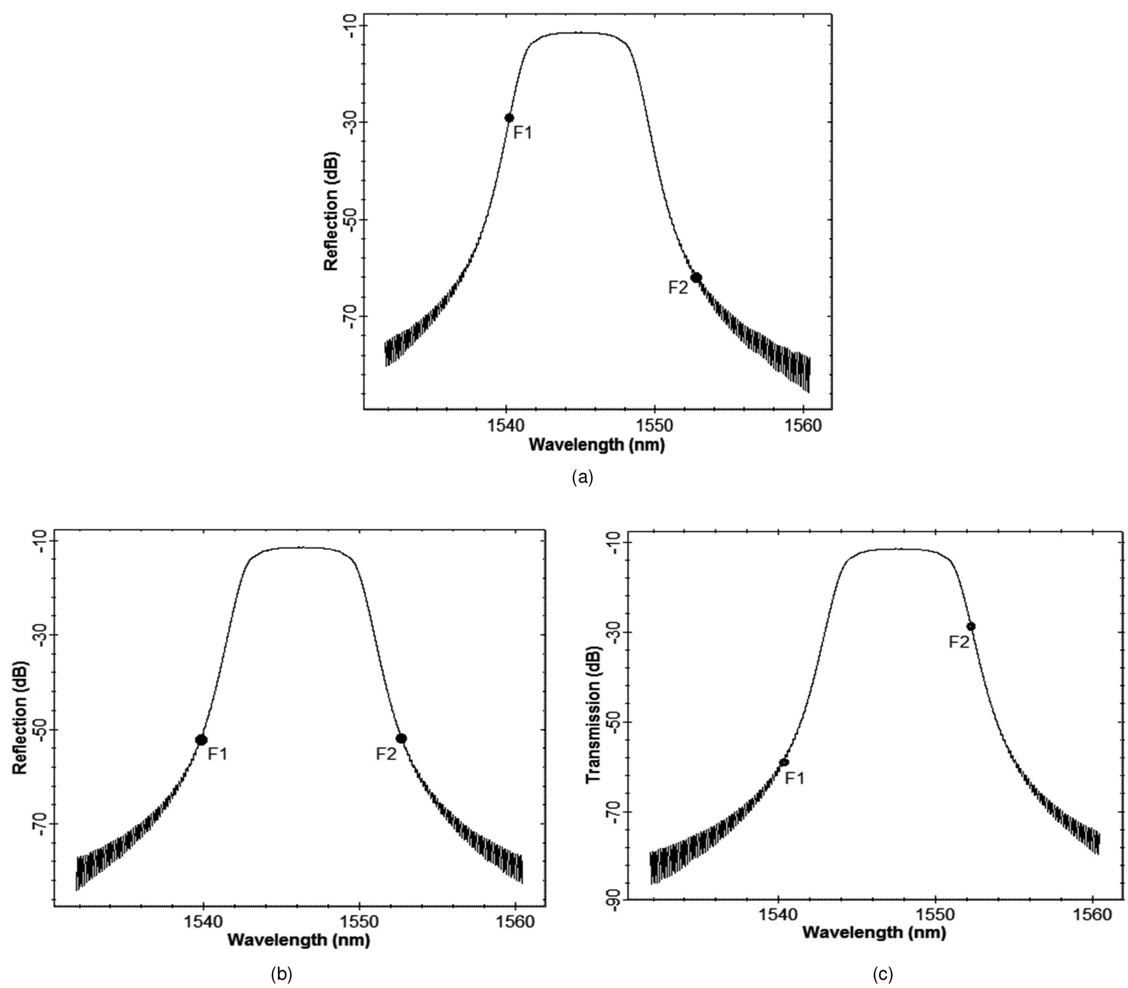


Fig. 3. Reflection spectrum of the chirped FBG of center wavelength of (a) 1544.85 nm (b) 1546.25 nm (c) 1547.65 nm. F1, F2: First order FWM signal at 1540.1 nm and 1552.4 nm respectively.

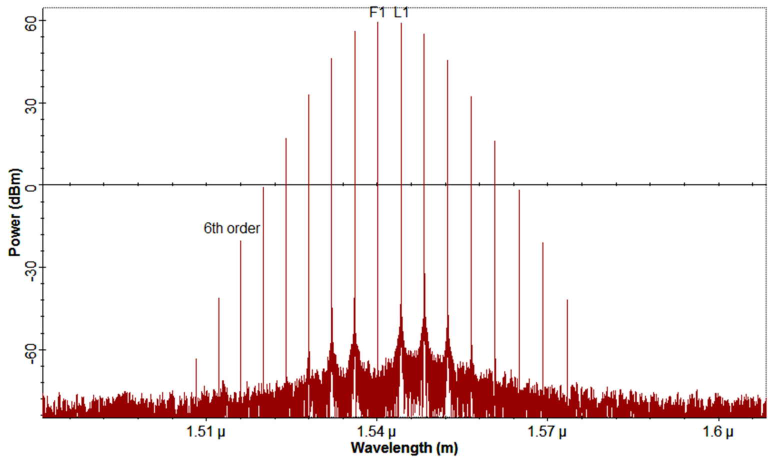


Fig. 4. Optical spectra after propagating through the HNLF 2 when the centre wavelength of the FBG is 1545.75 nm.

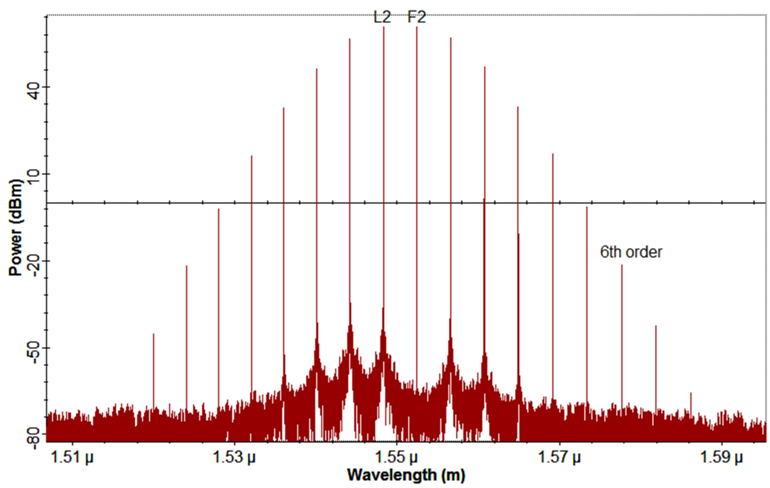


Fig. 5. Optical spectra after propagating through the HNLF 3 when the centre wavelength of the FBG is 1546.75 nm.

At this point, the signal F1 has reached the endpoint of the linear zone of FBG reflection edge while F2 signal is at the starting point of the linear zone of the other FBG reflection edge. In this case the power level of both F1 and F2 signals are same. On further application of strain, the signal F1 is dislodged from the linear zone whereas power of signal F2 increases and reaches the highest point of the linear zone at FBG central wavelength of 1547.65 nm as depicted in Fig. 3(c). Due to the interaction between signals F1 and L1 the sixth order FWM product is obtained at 1515.5 nm. Similarly the combination of the two signals F2 and L2 generates the sixth order FWM product at 1577 nm. The sixth order FWM product is utilized to cover the maximum range of measurement with high sensitivity. The power of the FWM products at 1515.5 nm and 1577 nm are measured with optical power meter. The power of the signal at 1515.5 nm decreases as power of the signal F1 decreases while the power of the signal at 1577 nm increases with the increase of F2 signal power.

The FWM products generated in the HNLF 2 and HNLF 3 due to the interaction of the signals between L1 and F1 and between L2 and F2 are depicted in Fig. 4 and 5 respectively.

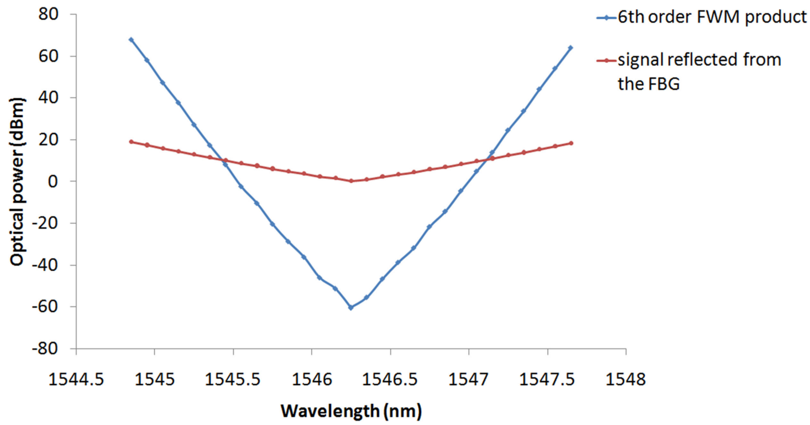


Fig. 6. Variation of optical power with wavelength shift for sixth order FWM product.

Furthermore it is observed from the Fig. 6 that the power of the sixth order FWM product changes much more rapidly compared to the reflected signal power from the FBG. The power of the signal reflected from the left edge of the FBG(F1) and the corresponding sixth order FWM product is measured in the wavelength range 1544.85 nm–1546.25 nm, whereas the power of the signal reflected from the right edge of the FBG (F2) and the corresponding sixth order FWM product is measured in the wavelength range 1546.25 nm–1547.65 nm. Thus a total wavelength shift of 2.8 nm (1544.85 nm–1547.65 nm) is obtained which indicates that a strain of 2310 $\mu\epsilon$ can be measured (the strain sensitivity of the FBG is 1.212 pm/$\mu\epsilon$).

Strain sensitivity of the signal reflected from the edges of FBG is found to be 13.18 dBm/nm whereas strain sensitivity of the sixth order FWM product is observed to be 91.21 dBm/nm. It is observed that the change in power of the sixth order FWM product is enhanced by a factor of seven compared to the signal reflected from the FBG.

5. Conclusion

A simple and unique interrogation scheme is proposed that can simultaneously achieve high sensitivity of 91.21 dBm/nm and wider range of strain measurement of 2310 $\mu\epsilon$ based on higher order FWM effects. In this work both the edges of the FBG reflection spectrum is used with FWM products serving as sources to interrogate the FBG. The signals reflected from the edges of the FBG are utilized in the succeeding FWM process for enhancing the sensitivity. The results show that the measurement range of strain attainable with this configuration is doubled to that using single reflection edge of the FBG while maintaining high sensitivity. The proposed scheme can also be used to design multiplexed FBG sensors where the FWM products can be used as sources to interrogate each FBG. In the FBG interrogation methods based on matched grating and edge filter, an increase in measurement range is accompanied with decrease in slope which in turn decreases the sensitivity and vice versa. The proposed sensing system eliminates this trade-off between high sensitivity and high measuring range and should be useful in strain sensing application requiring a high resolution as well as higher measuring range.

References

[1] C. Ghosh and V. Priye, "Dispersion compensation in a 24 $\times$ 20 Gbps DWDM system by cascaded chirped FBGs," *Optik*, vol. 164, pp. 335–344, Jul. 2018.
[2] C. Ghosh and V. Priye, "Augmentation of sensitivity of FBG strain sensor for biomedical operation," *Appl. Opt.*, vol. 57, no. 24, pp. 6906–6910, Aug. 2018.

[3] Q. Liu, T. Tokunaga, and Z. He, "Sub-nano resolution fiber-optic static strain sensor using a sideband interrogation technique," *Opt. Lett.*, vol. 37, no. 3, pp. 434–436, 2012.
[4] N. Kuse, A. Ozawa, and Y. Kobayashi, "Static FBG strain sensor with high resolution and large dynamic range by dual-comb spectroscopy," *Opt. Exp.*, vol. 21, no. 9, pp. 11141–11149, 2013.
[5] A. Cusano, D. Paladino, and A. Iadicicco, "Microstructured fiber Bragg gratings," *IEEE J. Lightw. Technol.*, vol. 27, no. 11, pp. 1663–1697, Jun. 2009.
[6] F. Gu, H. Yu, W. Fang, and L. Tong, "Nanoimprinted polymer micro/nanofiber bragg gratings for high-sensitivity strain sensing," *IEEE Photon. Technol. Lett.*, vol. 25, no. 1, pp. 22–24, Jan. 2013.
[7] M. Maheshwari, S.C. Tjin, Y. Yang, and A. Asundi, "Wavelength-shifted chirped FBGs for temperature compensated strain measurement," *Sens. Actuators A.*, vol. 265, pp. 231–235, Oct. 2017.
[8] J. Chen, F. Shi, X. Lei, and B. Peng, "A wide-range demodulation method for FBG sensor," *Microw. Opt. Technol. Lett.*, vol. 58, no. 10, pp. 2416–2419, Oct. 2016.
[9] H. Zou, D. Liang, and J. Zeng, "Dynamic strain measurement using two wavelength-matched fiber Bragg grating sensors interrogated by a cascaded long-period fiber grating," *Opt. Lasers Eng.*, vol. 50, no. 2, pp. 199–203, Feb. 2012.
[10] Y. Xiong, N. Ren, M. Wu, H. Liang, J. Han, and W. Yang, "Sensitivity-enhanced FBG demodulation system with multi-sideband filtering method," *Opt. Commun.*, vol. 382, pp. 246–252, Jan. 2017.
[11] U. Tiwari, K. Thyagarajan, M. R. Shenoy, and S. C. Jain, "EDF-based edge-filter interrogation scheme for FBG sensors," *IEEE Sensors J.* vol. 13, no. 4, pp. 1315–1319, Apr. 2013.
[12] C. Ghosh and V. Priye, "Ultrahigh-resolution interrogation of a fiber Bragg grating sensor based on higher order four-wave mixing," *Appl. Opt.*,vol. 57, no. 31, pp. 9388–9391, Nov. 2018.