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Bending Radius Determination Using Modified Fibre Bragg Grating Structures

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ABSTRACT The development of novel fibre Bragg grating (FBG)-based bending measurement methods requires comprehensive experimental validation under controlled laboratory conditions. This preliminary stage is essential for verifying the proposed sensing principle, optimising the sensor configuration, and evaluating the interrogation technique prior to implementation in practical applications. Controlled laboratory experiments provide repeatable and well-defined loading conditions, enabling the influence of individual parameters, such as bending radius and temperature, to be investigated independently while minimising the effects of external disturbances. Such investigations facilitate a thorough assessment of sensor performance, including sensitivity, repeatability, and temperature cross-sensitivity, and provide the basis for optimising the sensing system. Consequently, laboratory validation constitutes a fundamental stage in the development of advanced FBG-based bending sensing techniques, significantly accelerating the translation of innovative sensing concepts into engineering and industrial applications. Accordingly, the development of robust and temperature-independent bending measurement methods remains an important area of research. The objective of this work is to present a novel optoelectronic method for determining the bending radius using modified periodic fibre structures. Based on a comprehensive analysis of existing fibre Bragg grating based bending sensing principles and sensor configurations, an original bending determination method employing a modified FBG structure was developed. The proposed experimental configuration comprises a superluminescent diode source, an optical circulator, two optical spectrum analysers, a uniform fibre Bragg grating, and a tilted fibre Bragg grating. Experimental investigations of the spectral response of the combined FBG-tilted FBG (TFBG) structure under various bending conditions and throughout the intended operating temperature range provide the basis for the development of a temperature-independent bending determination method. Prior to implementing the proposed sensing approach, the uniform FBG and TFBG are fabricated in accordance with the specified design parameters, and their spectral characteristics are characterised over the given temperature range. The experimental results are subsequently used to establish design guidelines for selecting the optimal FBG and TFBG parameters to achieve temperature-independent bending sensing.

KEYWORDS fibre Bragg grating (FBG), temperature-independent measurement, optical sensing, bending radius determination, sensor electronics.

I. INTRODUCTION

The development of fibre Bragg grating (FBG)-based bending sensing systems has advanced significantly over the past decades, driven by the growing demand for accurate, reliable, and real-time monitoring in industrial, biomedical, aerospace, civil engineering and other applications [1-6]. A wide variety of FBG-based bending sensing systems have been proposed, differing in sensor configuration, sensing principle, interrogation technique, and signal processing algorithms. These differences lead to substantial variations in their metrological and operational performance.

The performance of an FBG-based bending sensing system is commonly evaluated using several key parameters, including measurement accuracy, measurement range and temperature cross-sensitivity. In addition, practical considerations such as e.g. system complexity, cost, robustness, power consumption and suitability for real-time operation are important. Despite the considerable progress achieved to date, existing FBG-based bending sensing systems still face limitations related to these parameters. Consequently, there is a growing need to develop novel bending measurement methods and to design advanced sensing systems based on these methods. Such developments are expected to improve measurement performance, increase robustness and reliability, reduce implementation costs, and expand the applicability of FBG-based bending sensors in demanding engineering and industrial environments.

The development of novel bending measurement methods should be preceded by comprehensive laboratory investigations under controlled experimental conditions. This preliminary stage is essential because it enables the validation of the sensing principle, optimization of the sensor configuration, and evaluation of the interrogation method before deployment in practical applications. Laboratory experiments provide repeatable and well-defined loading conditions, allowing the influence of individual parameters, such as e. g. bending radius or temperature, to be investigated independently. Consequently, laboratory investigations constitute a fundamental stage in the development of new FBG-based bending measurement methods, accelerating the transfer of innovative sensing solutions to practical engineering and industrial applications. Therefore, the development of innovative bending measurement techniques remains an important area of research. The purpose of the work is presentation of the optoelectronic method for determining the bending radius using modified periodic fibre structures.

II. FBG-BASED METHODS FOR BENDING MEASUREMENT

The most common laboratory FBG-based method for bending measurement uses a light source, an optical circulator and detector (optical spectrum analyser (OSA), spectrometer or photodiode). For reflection-mode FBG sensors a three-port optical circulator is commonly employed as a passive, non-reciprocal optical component providing unidirectional routing of optical signals by directing the incident light from Port 1 to Port 2 and the reflected light from Port 2 to Port 3. This configuration enables the separation of the transmitted and reflected optical signals. The main advantage is direct observation of the reflected spectrum and straightforward identification of the Bragg peak and other specific peaks. Optical circulators are the preferred components in reflective FBG bending sensing systems because they maximise optical efficiency, improve signal-to-noise ratio, reduce back reflections, and facilitate long-distance and multiplexed sensing. FBG is the passive optical sensing element in the FBG bending sensing systems.

The schematic of optical circulator and the example of its application in FBG-based systems is given in Fig. 1.

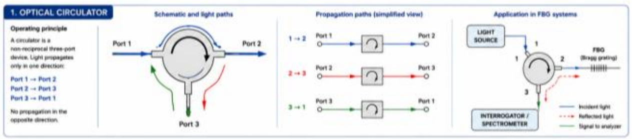


FIG. 1. Schematic of optical circulator and the example of its application in FBG-based systems.

An optical circulator is a single passive optical component while an optical interrogator is an optoelectronic measurement instrument that typically contains a light source, optical routing components (e.g., a circulator or coupler), photodetector or optical spectral analyser, and signal-processing electronics. An interrogation system is optical and electronic subsystem that supplies light to the FBG sensor, collects the reflected or transmitted optical signal, demodulates a measurable parameter (wavelength, intensity, phase, or frequency), converts that parameter into the into the corresponding measurand (bending/curvature). The techniques, trends, and applications of interrogation-based fibre-optic sensors are described in [7]. OSA measures the complete reflected spectrum of the FBG. Therefore, it can be used when the interrogation system needs to measure the specific wavelengths or analyse the complete reflection spectrum. Considering the advantages of OSA usage, including direct measurement of wavelength shift eliminating the need for additional wavelength demodulation techniques, high wavelength accuracy enabling highly accurate measurements of bending, strain, or temperature, full spectral information allowing detailed analysis of spectral shape, peak position, bandwidth, side lobes, and multiple resonances, it can be concluded that OSA is ideal for laboratory characterization. The drawbacks of OSAs are high cost, relatively long acquisition time and bulky design restricting their application in compact and real-time FBG sensing systems. In contrast to OSA the photodiode measures only the total optical power incident on it. Before the light reaches the photodiode, an optical filter converts wavelength changes into intensity changes. Photodiodes are much faster than OSAs.

Broadband interrogation using ASE (Amplified Spontaneous Emission) and SLD (Superluminescent Diode) sources combined with an optical spectrum analyser remains the predominant interrogation approach reported for FBG bending sensors [8]. ASE sources are preferred for high-power interrogation of multiplexed FBG arrays and laboratory systems, where optical power and spectral flatness are important. SLD sources are preferred for compact, low-power and cost-effective interrogation systems, making them attractive for portable and embedded bending sensing applications. Tunable-laser interrogators are used less frequently for higher-resolution measurements [9]. For most FBG-based bending sensing systems, commonly two approaches depending on the interrogation method are employed: the system measures wavelength shift (wavelength interrogation) or changes in the reflected optical power (intensity interrogation).

An analysis of existing FBG-based bending measurement methods was performed. Two of the analysed methods are described below.

A temperature-insensitive intensity-based bending sensor was proposed by [8] (Figs. 2-4). The operating principle of the proposed sensor is based on a superimposed TFBG–FBG structure. The tilted fibre Bragg grating (TFBG) couples the forward-propagating core mode to backward-propagating cladding modes, whose transmission characteristics are highly sensitive to fibre bending. A uniform FBG, inscribed at the end of the TFBG, reflects part of the incident light, which passes through the TFBG twice. Consequently, the reflected optical power is modulated by the bending-dependent transmission loss of the TFBG cladding-mode resonances. As the fibre curvature increases, the transmission loss of the cladding modes changes, leading to a corresponding variation in the reflected FBG power. In contrast, the Bragg resonance of the TFBG remains nearly unaffected by bending and therefore serves as a stable reference signal for compensating optical source power fluctuations. Furthermore, because the FBG and TFBG exhibit nearly identical temperature sensitivities, the sensor output is effectively insensitive to ambient temperature variations. In the quasi-linear operating range, the sensor exhibited a curvature sensitivity of approximately 0.6 dB·m^{-1}.

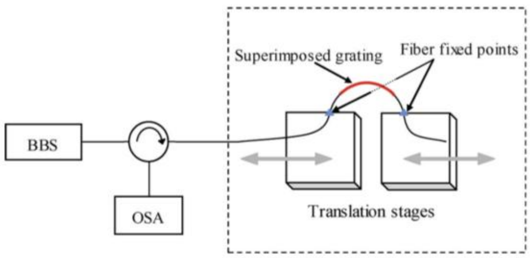


FIG. 2. Schematic diagram of the experimental setup for bending measurement [8].

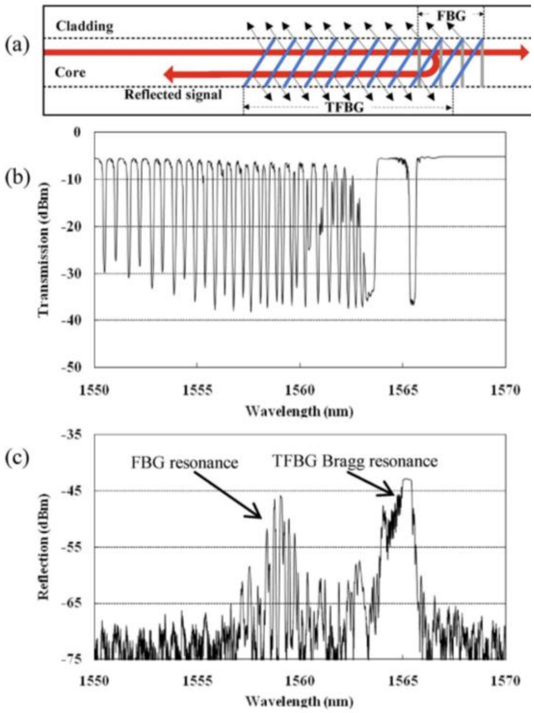


FIG. 3. Schematic diagram of the superimposed fibre Bragg grating (a), transmission spectrum of the TFBG (b), reflection spectrum of the superimposed grating (c) [8].

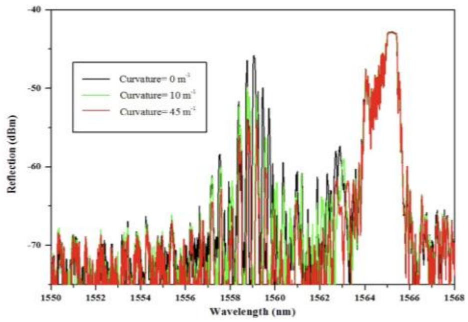


FIG. 4. The reflection spectra of the superimposed grating for various curvature [8].

The authors in [10] proposed a compact fibre-optic three-dimensional (3D) shape sensor based on two serially connected tilted fibre Bragg gratings (TFBGs) with mutually orthogonal grating planes (Figs. 5-6). The sensor simultaneously measures bending and axial strain using a single-ended interrogation configuration based on Fresnel reflection from the cleaved fibre end. The bending magnitude and direction are determined from the differential intensity response of selected cladding-mode resonances, whereas axial strain is obtained from the Bragg wavelength shift. Owing to the orthogonal orientation of the two TFBGs, the sensor enables determination of the bend magnitude and orientation (with a ±180° ambiguity). Experimental results demonstrated bending sensitivities ranging from -0.33 to +0.21 $dB\cdot m^{-1}$, depending on the bending direction, and an axial strain sensitivity of 1.06 $pm\cdot\mu\varepsilon^{-1}$. The sensor was interrogated using a tunable laser source and a high-resolution optical spectrum analyser, allowing accurate spectral intensity and wavelength measurements.

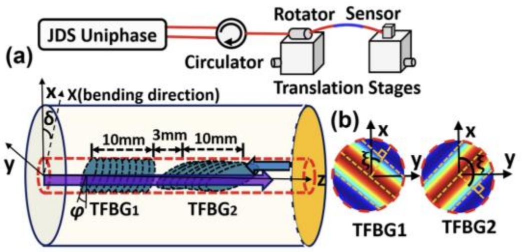


FIG. 5. Schematic diagrams of experimental setup for bending and strain measurements (a) and the pair of orthogonal TFBGs (b) [10].

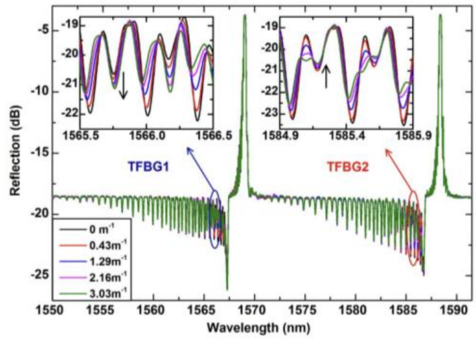


FIG. 6. Transmission spectra of the dual orthogonal TFBGs for various curvatures [10].

III. PROPOSED BENDING RADIUS DETERMINATION METHOD

Based on a comprehensive analysis of existing FBG-based bending sensing methods and sensor designs, an original bending determination method employing modified FBG structures was proposed. The experimental setup used for bending radius determination is given in Fig. 7.

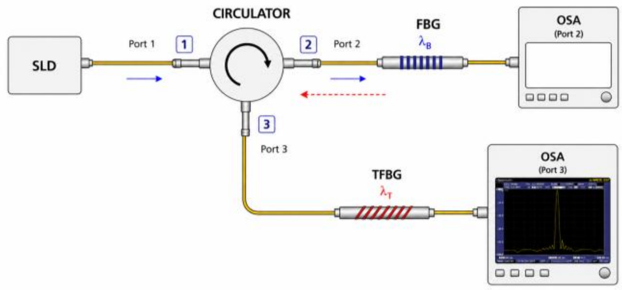
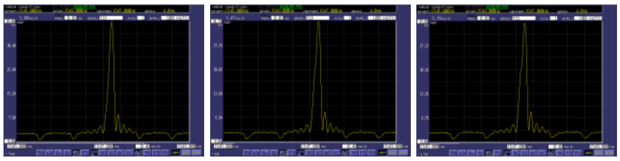
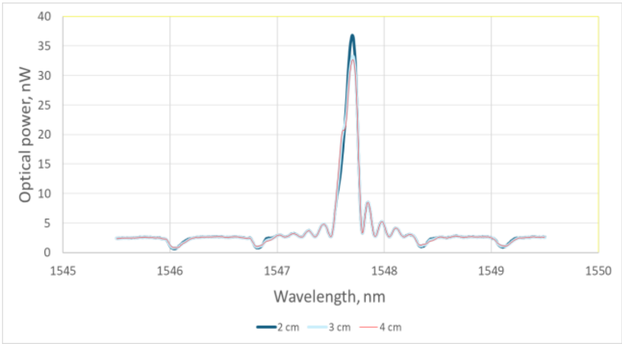


FIG. 7. Schematic diagram of the experimental setup for bending radius determination.

The experimental setup consists of a SLD source, an optical circulator, a climatic chamber (in which the uniform FBG and TFBG are mounted in the fibre bending control system) and two OSAs. The uniform FBG is connected to Port 2 of the optical circulator. Light emitted by the SLD source enters Port 1 and is directed through Port 2 to the uniform FBG. The transmitted spectrum is recorded by the first OSA. The light reflected by the FBG, containing the Bragg wavelength component, is routed from Port 2 to Port 3 and subsequently launched into the TFBG. The spectrum transmitted through the TFBG is recorded by the second OSA. The resulting spectrum contains the FBG Bragg reflection peak, whose spectral profile is modified by fibre bending due to the interaction with the TFBG, as shown in Fig. 8 for different bending radii.



a) b) c)



d)

FIG. 8. Resulting spectra for different radii: 2 cm (a, d), 3 cm (b, d), 4 cm (c, d) for the investigated FBG based structures.

Fig. 8d demonstrates that the resulting spectra vary with the bending radius. The most pronounced changes are observed in the modified Bragg peak, whose spectral characteristics exhibit a strong dependence on the applied bending. Both the intensity and the spectral shape of the modified Bragg peak exhibit variations with bending radius, providing additional spectral features that can be exploited for bending-radius sensing (Fig. 9). Quantitative analysis of the characteristic spectral parameters as a function of bending radius enables the development of a robust optical sensing method for bending radius measurement.

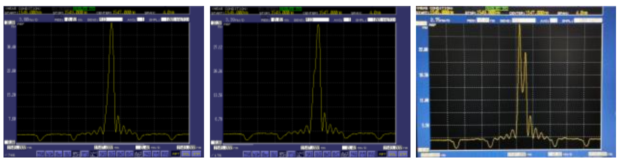


FIG. 9. Evolution of the modified Bragg peak shape in the resulting spectra with bending radius.

Experimental investigations of the spectral response of the combined FBG–TFBG structure under different bending conditions and over the intended operating temperature range enable the development of a temperature-independent bending measurement method. Prior to implementing the proposed method, the uniform FBG and TFBG are fabricated according to the required specifications, and their spectral characteristics are characterised over the intended operating temperature range. Based on the experimental results, guidelines for selecting appropriate FBG and TFBG parameters for temperature-independent bending sensing are established.

IV. CONCLUSION

The development of original FBG-based bending measurement methods and their experimental validation under controlled laboratory conditions remain essential steps toward the realization of high-performance sensing systems for practical engineering applications. Future research should focus on optimising and validating the proposed method to ensure its reliable operation under real operating conditions.

AUTHOR CONTRIBUTIONS

L.H. – conceptualization, methodology, investigation, writing-original draft preparation, writing-review and editing, visualization; J.K. – investigation, writing-review and editing.

COMPETING INTERESTS

The authors declare no conflicts of interest.

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Визначення радіуса вигину з використанням модифікованих волоконних брегґівських ґраток

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АНОТАЦІЯ Розробка нових методів вимірювання вигину на основі волоконних брегґівських ґраток (ВБҐ) вимагає комплексної експериментальної перевірки в контрольованих лабораторних умовах. Цей попередній етап є важливим для перевірки запропонованого принципу вимірювання, оптимізації конфігурації сенсора та оцінки методу опитування перед його впровадженням у практичні застосування. Контрольовані лабораторні експерименти забезпечують повторювані та чітко визначені умови навантаження, що дозволяє незалежно досліджувати вплив окремих параметрів, таких як радіус вигину та температура, мінімізуючи вплив зовнішніх збурень. Такі дослідження сприяють ретельній оцінці продуктивності сенсора, включаючи чутливість, повторюваність та перехресну чутливість до температури, та забезпечують основу для оптимізації системи вимірювання. Отже, лабораторна перевірка є фундаментальним етапом у розробці передових методів вимірювання вигину на основі ВБҐ, значно прискорюючи впровадження інноваційних концепцій вимірювання в інженерні та промислові застосування. Відповідно, розробка надійних та температурно-незалежних методів вимірювання вигину залишається важливою галуззю досліджень. Метою цієї роботи є представлення нового оптоелектронного методу визначення радіуса вигину з використанням модифікованих періодичних волоконних структур. На основі комплексного аналізу існуючих принципів та конфігурацій сенсорів вигину на основі волоконних брегґівських ґраток було розроблено оригінальний метод визначення вигину з використанням модифікованої структури ВБҐ. Запропонована експериментальна конфігурація містить джерело на основі суперлюмінесцентного діода, оптичний циркулятор, два оптичні аналізатори спектру, однорідну волоконну брегґівську ґратку та похилу волоконну брегґівську ґратку. Експериментальні дослідження спектральної характеристики комбінованої структури ВБҐ - похила ВБҐ (ПВБҐ) за різних умов вигину та в усьому передбачуваному діапазоні робочих температур забезпечують основу для розробки температурно-незалежного методу вимірювання вигину. Перед впровадженням запропонованого підходу до вимірювання однорідні ВБҐ та ПВБҐ виготовляються відповідно до заданих конструктивних параметрів, а їхні спектральні характеристики характеризуються в заданому діапазоні температур. Експериментальні результати згодом використовуються для встановлення рекомендацій щодо проектування та вибору оптимальних параметрів ВБҐ та ПВБҐ для досягнення температурно-незалежного визначення вигину.

КЛЮЧОВІ СЛОВА волоконна брегґівська ґратка (ВБҐ), температурно-незалежне вимірювання, оптична сенсорика, визначення радіуса вигину, сенсорна електроніка.