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SELECTED ISSUES CONCERNING FIBRE-OPTIC BENDING SENSORS

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***Abstract**. This paper presents a comprehensive review of bending sensors and their classifications. The main focus is on advancements in the design of optical fibre bending sensors based on fibre Bragg gratings (FBGs). Various measurement principles employed in optical fibre bending sensors are analysed, highlighting their respective advantages and limitations. Particular attention is given to sensors utilising long period gratings (LPGs), Tilted fibre Bragg gratings (TFBGs), and multicore (MCF) fibre structures, which demonstrate significant potential for the development of highly sensitive and compact bending sensing systems.*

Keywords: optical fibre, bending sensor, Fibre Bragg Grating, Long Period Grating, tilted Fibre Bragg Grating, multicore fibre sensor

WYBRANE ZAGADNIENIA DOTYCZĄCE ŚWIATŁOWODOWYCH CZUJNIKÓW ZGIĘCIA

***Streszczenie**. Niniejszy artykuł przedstawia kompleksowy przegląd czujników zgięcia (bending sensors) i ich klasyfikacji. Główny nacisk kładzie się na osiągnięcia w projektowaniu optycznych światłowodowych czujników zgięcia opartych na światłowodowych siatkach Bragga (FBG). Przeanalizowano różne zasady pomiaru stosowane w światłowodowych czujnikach zgięcia, podkreślając ich zalety i ograniczenia. Szczególną uwagę poświęcono czujnikom wykorzystującym siatki długookresowe (LPG), światłowodowe skośne siatki Bragga (TFBG) oraz wielordzeniowe struktury światłowodowe, które wykazują znaczny potencjał w zakresie rozwoju wysoce czułych i kompaktowych czujników zgięcia.*

Słowa kluczowe: światłowód, czujnik zgięcia, światłowodowa siatka Bragga, siatka długookresowa, światłowodowa skośna siatka Bragga, światłowodowy czujnik wielordzeniowy

Introduction

Bending measurement assesses the amount of deformation caused by applying an external force to an element and is currently used in many engineering applications, such as aerospace, robotics, and other industries. This includes continuous monitoring of buildings, bridge piles, aircraft, military ships and aerospace equipment. Various types of bending sensors are used to determine the magnitude and direction of bending. They can be classified: 1) by their operating principle (resistive, capacitive, piezoelectric, triboelectric, optical, magnetic and inductive bending sensors); 2) by the measured parameter (linear and angular displacement); 3) by the type of output signal (analogue, discrete and digital). Flexible bending sensor sensing mechanisms are presented in Fig. 1.

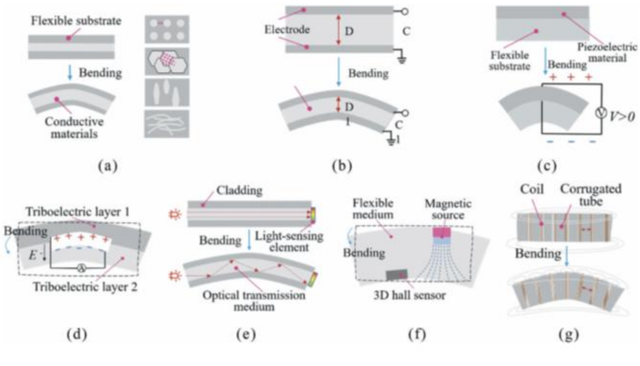

Fig. 1. Flexible bending sensor mechanism. (a) resistive bending sensors, (b) capacitive bending sensors, (c) piezoelectric bending sensors, (d) triboelectric bending sensors, (e) optical bending sensors, (f) magnetic bending sensors, (g) inductive bending sensors [13]

Optical bending sensors occupy a special place. They detect changes in light properties, such as intensity, polarisation, phase and frequency, which depend on the sensor's bending. Optical bending sensors can be classified: 1) by their operating principle (reflectometric and interferometric); 2) by the type of sensing element (sensors based on reflective coatings: measure the angle of reflection of the beam from the surface on which the curvature has occurred; fibre-optic sensors: radiation passes through an optical fibre, which is deformed under the influence of bending, leading to a change in the characteristics of the light (intensity, phase, polarisation).

Optical bending sensors are used where it is necessary to measure or control physical quantities, such as pressure, distance, movement or compression. The development of optical bending sensor technologies has expanded their areas of use in construction (for monitoring deformations and deflections of bridges, buildings and other structures), medicine (in endoscopes, catheters and other medical devices for position and bending control), in mechanical engineering (for monitoring bending and vibration in moving parts of mechanisms, especially those related to measurement), robotics (for monitoring the position and movements of manipulators), the automotive industry (for monitoring deformations of the body or other elements of the car in real time), automation and control (as part of control systems for feedback from mechanisms), quality control (for checking integrity and deformation of products) [13].

1. Fibre-optic bending sensors

Advances in technology in the telecommunications industry have led to numerous developments in fibre-optic sensors, which can be used to replace traditional piezoelectric solutions in a wide range of applications. The advantages of fibre-optic sensors over other existing measurement technologies include flexibility, low weight, increased sensitivity, high response speed, high repeatability, immunity to electromagnetic influences, form factor versatility, resistance to aggressive environments and the ability to withstand high temperatures [15]. Fibre optic sensors can be classified as: phase-modulated (Mach-Zehnder interferometer, Michelson interferometer, Fabry-Pérot interferometer (FPI), Sagnac interferometer), intensity modulated (transmissive sensors, reflective sensors, intrinsic sensors and ones based on bending), wavelength modulated fibre Bragg gratings (FBG sensors), scattering-based (Rayleigh, Brillouin or Raman types), polarisation-based (extrinsic birefringent component-based sensors, intrinsic Faraday rotation-based sensors, intrinsic polarisation maintaining Bragg grating-based sensors) [14]. Fibre optic sensors can also be classified as: point sensors (FBGs, Fabry-Pérot interferometer), long-gauge sensors (SOFO interferometric sensor) and distributed sensors (of the Rayleigh, Brillouin or Raman type) [5]. The review for optical fibre bending/curvature sensors including FBGs is given in [17].

Currently the main directions of optical fibre bending sensor technologies are based on interferometric methods, FBGs and LPGs [13].

One promising area of fibre-optic bending sensor development is the development of new sensor designs using FBGs, which are a periodic structure of refractive index modulation induced in the core of an optical fibre. Changes in strain and temperature affect the effective refractive index and grating period, causing a shift in the wavelength of the reflected signal (Fig. 2).

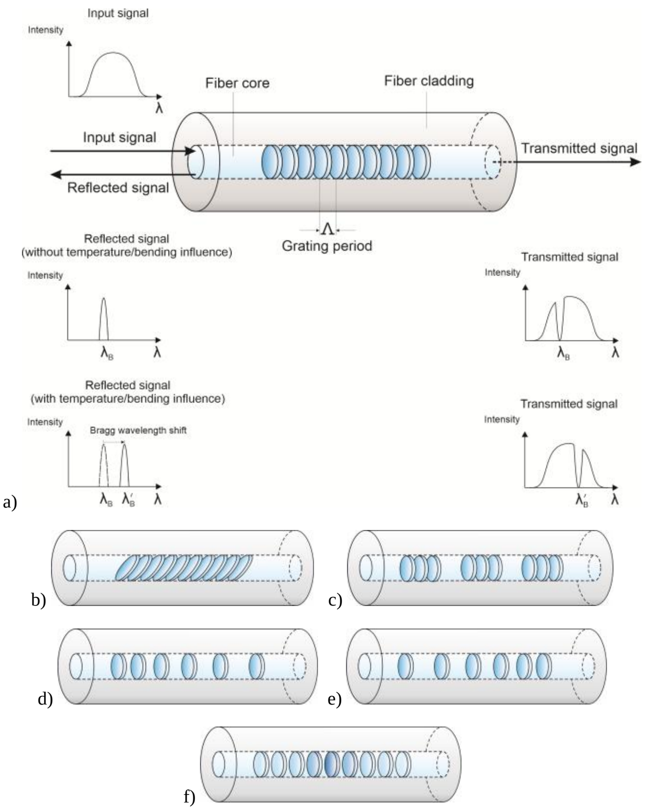

Fig. 2. Schematic of FBGs: a) uniform FBG, b) tilted FBG, c)superstructure FBG, d) positive chriped FBG, e) negative chriped FBG, f) apodised FBG

FBG sensors are compatible with optical communication systems and can scan at large distances from the processing unit without requiring power supply to the sensing element. Another advantage of these sensors is their suitability for use in challenging environments (e.g. electromagnetic fields, explosion-proof environments). The FBG Sensor Market size is valued at USD 0.83 billion in 2025, and is forecast to attain USD 1.26 billion by 2030 [6]. FBG application market expansion is connected with infrastructure monitoring (bridges, pipelines, buildings), industrial automation (machinery monitoring, robotics) and transportation (vehicle stability systems, railway infrastructure) [4].

Classification of FBGs is given in Fig. 3. In FBG strain sensors both temperature and strain affect the spectrum of the reflected signal. The FBG central wavelength changes with strain, curvature, bending and also temperature making it difficult to measure only bending. To obtain accurate bend measurement data, it is necessary to compensate for the effect of temperature on the FBG. The compensation for FBG temperature cross-sensitivity could be done using a separate FBG sensor as a reference one or using FBGs on different cores which have the same temperature sensitivity but different bending sensitivities [21].

Sensitivity of FBGs to bending is also related with FBG position: increasing the sensor sensitivity can be achieved by a larger deviation from the neutral axis which results in a larger strain and a more significant wavelength shift. Thus, for bending sensing FBGs are formed on the fibre core of eccentric core fibre (ECF) (the magnitude and direction of bending in a single plane can be measured with high sensitivity) or multi-core fibre (multi-dimensional bending can be measured, bending vector can be determined using difference in wavelength shifts between the cores).

Choice of the sensor to be used is dependent on its parameters, e. g. FBGs are characterised by high precision for magnitude, fast response, can multiplex other parameters (temp/strain), small size, low cost and scattering-based sensors allow for measuring bending along the entire fibre. Thus, FBGs are more suitable for high-precision point measurements and scattering-based sensors are preferable for distributed sensing on long distances.

FBGs and LPGs differ in their primary principle: in FBG it is wavelength shift due to strain and temperature, in LPGs, bending can split transmission dips in the spectrum, and this splitting increases with curvature. As the operation principles of LPFG-based bending sensors are related to core-to-cladding mode coupling they are more sensitive to bending but also there is cross-sensitivity between bending and environmental factors such as temperature and surrounding refractive index changes of which cause a shift in the resonance wavelength, making it difficult to get accurate bending measurements. FBGs are less sensitive to such external conditions, but their bending response is weaker, though this can be enhanced by tilting the grating surfaces.

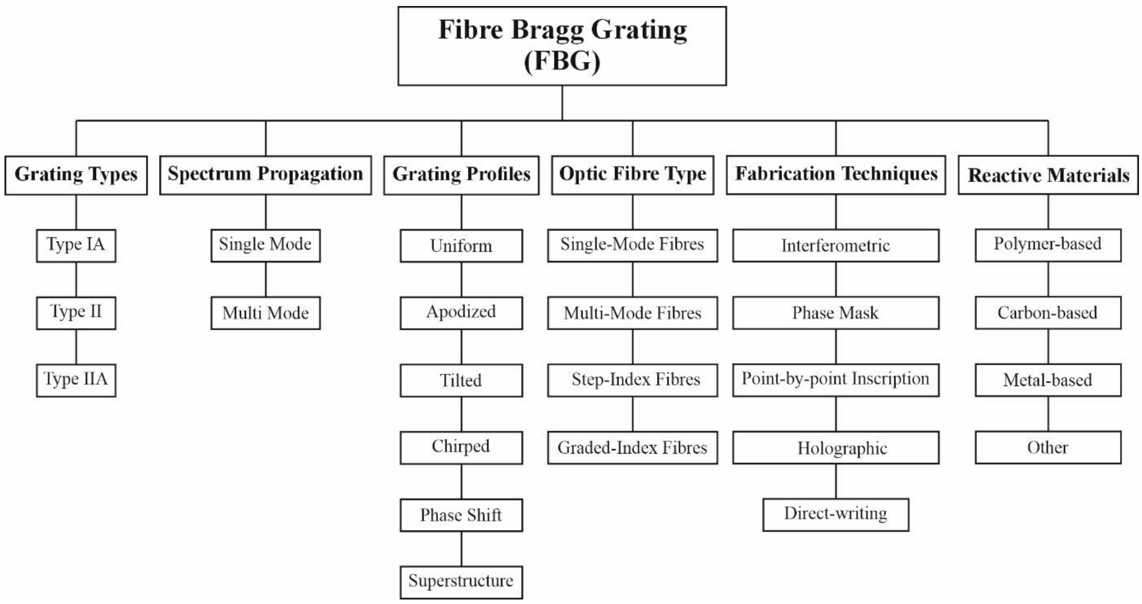

Fig. 3. FBG classification (adapted from [9], [22])

Tilted FBGs are FBGs in which the grating surfaces are intentionally angled relatively to the optical fibre's axis. TFBGs operate by coupling core modes to cladding modes and radiation modes, with bending causing a spectral shift due to the tilt angle. This angle also allows TFBGs to be used for bend sensing. LPGs, conversely, rely on coupling core modes to higher-order cladding modes, with bending altering the phase matching condition between these modes to create a wavelength shift. TFBGs can measure a single bend axis with high accuracy and lower complexity than LPGs, while LPGs require more complex structures to measure bending in different directions. TFBGs also use a reference core mode that can be used to compensate for environmental changes (surrounding refractive index). Generally TFBGs are more stable due to lower cross-sensitivity and the presence of a core mode reference. One of the promising direction is development of the temperature-insensitive bending measurement methods using TFBGs [7]. This requires the analysis of the influence of bending optical fibres with TFBGs on their spectral parameters (spectral shifts in TFBGs, changes in the shape of spectral characteristics in TFBG optical fibres) [8].

2. Bending sensors based on multicore fibres

Another direction is the development of bending sensors based on multicore fibres (MCFs). In particular, we can consider the following bending sensors based on MCFs: MCF-based FBG, MCF-based tilted FBG and MCF-based LPG sensors [25]. In MCF the cores are arranged off-centre in the fibre unlike the normal SMFs (Single-Mode Fibre) in which the core is located at the fibre centre (strain neutral axis). Off-centre cores are sensitive to bending because fibre bending creates tangential strain: fibre bending causes differential response in different cores. MCFs allow for measuring both the magnitude and direction of bending [1].

MCF-based FBG bending sensor works by using FBGs inscribed in multiple cores of the MCF to detect changes in wavelength caused by bending. When the fibre bends, the FBGs in different cores experience different strains and their centre wavelengths shift in opposite directions. Application of such bending sensors is based on monitoring the magnitude of these opposite wavelength shifts or by measuring the intensity changes due to the loss of light in specific cores. Some MCF-FBG designs allow for simultaneous measuring temperature and curvature by using a central core FBG as a temperature reference. Curvature sensitivity magnitudes for an MCF-based FBG bending sensor depend on the sensor design. For example, in order to obtain high-sensitivity of bending sensor the sensor design based on FBGs fabricated on the symmetric distribution cores of seven-core fibre (SCF) where a 45-degree reflective cone frustum (RCF) was proposed by Shitai Yang et al. [21].

MCF-based tilted FBG (TFBG) bending sensors are more complex in fabrication due to the need for tilted gratings but have higher sensitivity comparing to MCF-based FBG sensors due to the tilted grating configuration and may be used to measure bending direction, while a standard MCF-based FBG sensor can be less sensitive to bending direction unless specific arrangements are used. As mentioned above, MCF-based LPG sensors are more sensitive to external medium changes, e.g. temperature comparing to MCF-based FBG sensors. An example of the directional curvature sensor using LPG design is described in [15]. Three different LPGs were inscribed in a seven core optical fibre: a single LPG in the external cores and an array of three LPGs in the central core.

3. Recent research on optical fibre bending/curvature sensors

Measurement methods, sensing structure, measurement principles and performance of optical fibre bending sensors have been analysed in detail in [17]. Optical fibre bending sensors differ by their construction, sensitivity and accuracy. Practical application of optical fibre bending sensors can be limited by low sensitivity, non-linear response over a wide range, insufficient directional sensing capabilities and surrounding (i.e. temperature) cross-sensitivity temperature. Therefore recent research directions focus on development of new designs of optical fibre bending sensors to achieve high curvature sensitivity and low temperature crosstalk. On the other hand, usage of new technologies should not only simplify sensor fabrication, but also not increase it. Comparative analysis of recent developed fibre optic bending/curvature sensor designs was conducted and included sensing structure, curvature/bending and temperature sensitivity, curvature range, vector property and dual-parameter sensing. The examples of different fibre optic structures proposed for bending sensing and investigated in the last 5 years are given in Fig. 4.

The sensor shown in Fig. 4a is composed of a short segment of asymmetric MCF that is fusion spliced to a standard single-mode fibre (SMF). Curvature sensitivity equals 506.72 ± 5.50 pm/° [1]. The next sensor (Fig. 4b) is fabricated by inscribing short-length FBGs into a section of strongly coupled MCF (SCMCF), which is spliced to a conventional SMF. Curvature sensitivity equals 15.9 dB/m^{-1} [12]. A vector bending sensor based on the multimode–dual-core–multimode fibre (MMF-DCF-MMF) cascaded FBG structure has been proposed to achieve simultaneous measurement of bending magnitude and direction with enhanced sensitivity (Fig. 4c). Bending and temperature sensitivity equals 18.259 nm/m^{-1} and −285 pm/°C, respectively [23]. A compact, high-sensitivity bending sensor based on a multimode fibre (MMF) embedded chirped long-period grating (ME-CLPG) is depicted in Fig. 4d, in which the Mach-Zehnder interference induced by the core mismatch of the four-core fibre (FCF) could be enhanced. Bending sensitivity equals 53.68 nm/m^{-1} within the range of 0–1.803 m^{-1}. Temperature sensitivity equals −6.67 pm/°C in the range of 30–90°C [24]. Highly sensitive two-dimensional vector bending sensor based on side-grooved LPG (SG-LPG) inscribed on ECF is shown in Fig. 4e. The bend sensitivities in +x, -x, +y and –y directions equal 27.23 nm/m^{-1}, −25.76 nm/m^{-1}, 14.74 nm/m^{-1} and −16.83 nm/m^{-1}, respectively [19]. Temperature-insensitive vector bending sensors have been proposed in [10] (Fig. 4f). It is fabricated by core-offset splicing a segment of FCF between two single-mode fibres (SMFs). Curvature sensitivity 38.16 nm/m^{-1}, 37.46 nm/m^{-1}, 4.99 nm/m^{-1} and −7.12 nm/m^{-1} in different bending directions is within the range of 0.346–0.49 m^{-1}. Fig. 4g presents a multi-parameter sensor based on cascaded multi-core FBG and FPI structure [16]. Maximum sensitivity equals 96.33 pm/m^{-1} for vector bending. Another configuration employs a multi-core FBG Fabry-Pérot (FBG-FPs) sensor, where the bending sensing element is a triangular FCF (TFCF) incorporating FBG-FPs. In this design, short FBGs were inscribed in different fibre cores to form FP cavities [18]. Curvature sensitivity equalled 52.6 pm/m^{-1}.

A reflective all-fibre curvature sensor consisting of Mach-Zehnder interferometer (MZI) and FPI is shown in Fig. 4i. Curvature sensitivity equals −1.19 nm/m^{-1} [3]. An optic-fibre curvature and temperature sensor consisting of a lateral-offset spliced SMF-FCF-SMF based on the Mach-Zehnder interference (MZI) principle is depicted in Fig. 4j. Maximum curvature sensitivity equals −18.75 nm/m^{-1} with the linearity of 0.9743. Temperature sensitivity equals 74 pm/°C with the linearity of 0.9788 in the range of 30–80°C [20]. An all-fibre MZI sensor structure for temperature and curvature measurement is proposed in [11] (Fig. 4k). It consists of two parts of no-core fibre (NCF) and SCF sandwiched between two SMFs. Curvature sensitivity and temperature sensitivity equal 10.22 dB/m^{-1} in the curvature range of 0.82–1.226 m^{-1} and 100.1 pm/°C in the temperature range of 50–100°C, respectively. Fig. 4l presents an MZI sensor, which is fabricated by splicing a section of single-core fibre (SCF) between two single-mode fibres (SMFs), forming an MZI structure used for high-sensitivity bending measurements [26]. Bending sensitivity equals 2.65 nm/m^{-1}.

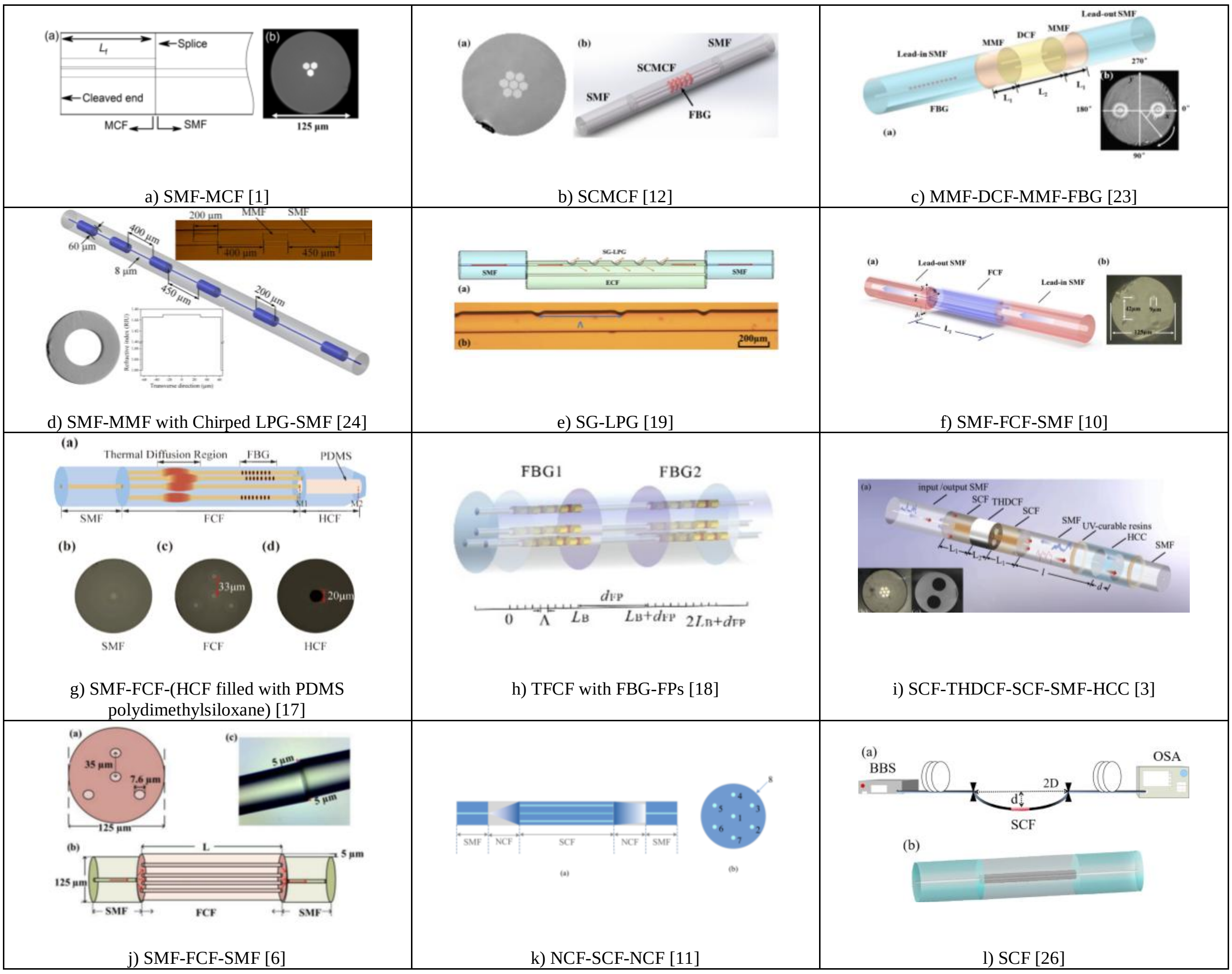

Fig. 4. Schematic diagrams of curvature/bending sensors

For the sensors listed, the temperature sensitivity lies within the range from 6.67 pm/°C to 285 pm/°C, the curvature/bending sensitivity lies within the range from 0.05 nm/m^{-1} to 53.68 nm/m^{-1}. According to analysis, sensor structures (3) and (5) allow curvature/bending measurements also in different bending directions. Bending sensors shown in (10) and (11) allow measuring both curvature and temperature. Analysis of the listed fibre optic bending sensors has shown that the following best sensor parameters were achieved: low temperature sensitivity of 6.67 pm/°C for SMF-MMF with Chirped LPG-SMF sensor (Fig. 4d), high bending/curvature sensitivity 53.68 nm/m^{-1} for SMF-MMF with Chirped LPG-SMF sensor (Fig. 4d), 15.9 dB/m^{-1} for SCMCF sensor (Fig. 4b).

4. Conclusions

This paper presents the main directions in bending optical sensor classification and design. Fibre-optic sensor advantages such as high flexibility, electromagnetic interference immunity, high resistance to harsh conditions and high sensitivity allow them to be used in bend measuring. FBGs and TFBGs are promising for application in optical fibre bending sensors. New manufacturing and measurement technologies available today allow the development and implementation of new designs of optical bending sensors, which in turn leads to an expansion of application areas. Usage of multi-core microstructured fibers combined with the ability to record FBG, enable new designs of sensors based on optical fibres. Novel technology solutions e.g. NORIA which is a tool for fabricating FBGs including UV laser and a phase mask allow for fabrication of FBGs. NORIA tool enables flexible parameter selection, allowing the FBG properties to be adjusted when constructing new sensors. Noria tool enables the selection of the parameters such as phase mask or supplied energy to produce the FBG of certain parameters, e. g. full width at half maximum length (FWHM), Side Mode Suppression Ratio (SLSR) or FBG length. As it was mentioned above, the advantages of optic fibre bending sensors allowed their use in various application fields such as biomedical applications, robotics, aerospace and mechanical engineering.

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