

Low-cost measurement of light polarisation plane rotation using dual-channel tilted fibre bragg grating–fibre bragg grating power-based interrogation

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ABSTRACT

This article presents a new method for measuring the angle of rotation of the light polarisation plane (LPPR) using a dual-channel power-based approach with tilted Bragg gratings (TFBG) and Bragg gratings (FBG), and optical power measurement. Unlike previous solutions based on the analysis of the full transmission spectrum of the TFBG, the proposed method does not require the use of an optical spectrum analyser. The measurement system consists of two optical paths containing TFBGs positioned at a 45° angle to each other, working in conjunction with FBGs acting as spectral filters. The optical power values recorded in both channels are used to determine the angle of rotation of the polarisation plane based on previously determined calibration characteristics approximated by a Fourier series. An analysis was carried out of the effect of the relative positions of the TFBG and FBG spectra on the amplitude of power variations and the distortion of measurement characteristics. It was demonstrated that the appropriate selection of the FBG reflection band position relative to the selected TFBG cladding mode allows the amplitude of the measurement signal to be increased whilst maintaining low distortion of the characteristics. The effectiveness of the developed method was experimentally verified in the range of angles from 0° to 180°. For an independent test set, a mean absolute error of 0.27°, an RMSE of 0.33°, and a maximum error not exceeding 0.76° were obtained. The coefficient of determination reached a value of $R^2 = 0.999$. The results confirm that the proposed method enables precise measurement of the angle of rotation of the plane of light polarisation whilst significantly simplifying the measurement setup, reducing measurement time and lowering costs compared to solutions requiring the recording of the full optical spectrum.

Keywords: TFBG, FBG, light polarisation plane rotation, optical power measurement, fibre-optic sensor, polarisation sensing, low-cost interrogation system.

INTRODUCTION

Fibre-optic Bragg grating sensors are widely used in various applications [1]. They enable the precise measurement of a wide range of physical and chemical quantities [2–7]. In mechanical and structural monitoring, FBG sensors are widely used to measure strain, stress, vibration, deflection, deformation, torsion and thermally induced

expansion. In selected applications, they can also provide a fibre-optic alternative to conventional electrical strain gauges, particularly where immunity to electromagnetic interference, multiplexing capability or operation in harsh environments is required [8–10]. They are widely used in harsh environments, including various hazards. These are exposure to petroleum-based substances [11,12]. In some cases, optical fibres are exposed

to high temperatures [13,14]. Also, the possibility of work under various pressures [15,16] or under radiation [17] is important. Fibre optic sensors are mounted inside batteries [18] to monitor their parameters. They are also used where the risk of explosion is high [19,20]. Creating a tilted Bragg grating (TFBG) in the optical fibre core enables additional sensing capabilities. This is because some of the light is reflected towards the fibre cladding and partially escapes to the outside [21]. The amount of light transmitted to the outside depends heavily on the refractive index (RI) of the surrounding medium. This phenomenon is utilised to construct TFBG sensors for measuring the RI of the surrounding medium, which are often used as solution concentration sensors [22,23]. TFBG sensors are often coated with thin films of materials whose RI changes in the presence of other substances [24–26]. It extends the applicability of these sensors to the detection and analysis of various chemical substances [27]. It is also possible to measure parameters such as pH [28]. Bioactive coatings enable the detection of organic substances [29–31].

In many applications, measurement accuracy is heavily dependent on the state of polarisation of the light propagating through the system. Uncontrolled changes in the angle of rotation of the light's polarisation plane (LPPR) can lead to a deterioration in measurement accuracy and an increase in the uncertainty of the determined parameters [6,32]. Knowledge of the LPPR angle can therefore be used to compensate for polarisation-dependent effects in measurements of other physical quantities. It may also provide additional diagnostic information about changes occurring in the optical measurement path. For this reason, monitoring the angle of rotation of the light's polarisation plane is a significant challenge in fibre-optic measurement systems.

One solution for measuring the LPPR is systems utilising tilted fibre Bragg gratings. A change in the rotation angle of the light's polarisation plane propagating through the TFBG causes changes in the transmission spectrum, particularly in the cladding mode region. The information contained in these changes can be used to determine the value of LPPR.

The paper [33] proposes a method utilising changes in selected Fourier transform coefficients calculated on the basis of the TFBG transmission spectrum. In contrast, the paper [34] presents an approach based on the analysis of

coefficients determined from the sums of selected wave transform levels. Both methods require the recording of the cladding mode spectrum and its numerical analysis. Furthermore, the measurement accuracy depends on the range of variation of the coefficients used, which leads to increased errors for selected ranges of the polarisation plane rotation angle.

To improve measurement accuracy and limit the influence of local flattening of the measurement characteristics, solutions utilising two TFBG elements have been proposed [35,36]. The use of two gratings has increased sensitivity and reduced measurement ambiguities. However, in all the solutions mentioned, it is necessary to record the optical spectrum using an optical spectrum analyser (OSA). These devices are expensive, which significantly increases the cost of the entire measurement system. This is crucial because, in industrial systems, reducing production costs is important [37]. Furthermore, the need to record the spectrum across multiple wavelengths extends the measurement time and complicates measurements in systems where polarisation changes dynamically.

An alternative approach to reducing the complexity of the interrogation system is to replace full-spectrum acquisition with optical power measurement. In [38], a proposal for using a TFBG combined with an FBG acting as a narrowband optical filter is presented. This approach eliminated the need for an optical spectrum analyser during measurement. However, using a single filtered spectral region and a single power value produced a periodic response and limited the range over which the rotation angle could be determined unambiguously. Consequently, the method was suitable for measurements over a restricted angular interval rather than over the full 0° – 180° range.

In contrast to the single-channel power-based TFBG–FBG solution reported in [38], the novelty of the present work lies in combining two complementary TFBG–FBG branches with a 45° relative TFBG orientation and joint numerical angle estimation from both measured optical powers. This configuration removes the ambiguity of the single-channel response and enables LPPR estimation over the full 0° – 180° range. In addition, the influence of the FBG spectral position relative to the selected TFBG cladding mode is analysed to identify a configuration that provides a high signal amplitude while limiting characteristic distortion.

The limitations of existing methods motivated the development of a dual-channel power-based interrogation system for LPPR measurement. The proposed method does not require full-spectrum acquisition during measurement. Instead, it uses two TFBG–FBG branches and two optical power meters. The TFBGs are oriented with a relative 45° offset, providing complementary response characteristics. This architecture enables the LPPR angle to be determined unambiguously over the full range from 0° to 180° , including angular regions where a single-channel response becomes locally flattened or reaches an extremum. The main contributions of this work are as follows:

- the development of a dual-channel power-based TFBG–FBG architecture in which two TFBGs are oriented with a relative 45° offset, providing complementary angular responses;
- the joint numerical estimation of the LPPR angle from both optical power values, enabling unambiguous measurement over the full 0° – 180° range;
- a systematic analysis of the influence of the FBG reflection-band position relative to the selected TFBG cladding mode on the signal amplitude and characteristic distortion;
- experimental verification of the method using a hold-out set of angular positions not included in the calibration data.

The rest of the paper is organised as follows. The materials and methods section describes the design of the measurement setup, the calibration procedure, and the method for determining

the rotation angle of the polarisation plane. This is followed by an analysis of the influence of the relative positions of the TFBG and FBG spectra on the metrological properties of the developed solution. The Results section presents the results of the experimental investigations and an assessment of measurement accuracy. The remainder of the paper discusses the results obtained and compares them with methods described in the literature. The article concludes with conclusions and directions for further research.

MATERIALS AND METHODS

Measurement setup

Two laboratory measurement setups were constructed for this study. The first, shown in Figure 1, is a proposed setup for low-cost measurement of light polarisation-plane rotation. The second system, shown in Figure 5, is an auxiliary system used to record the spectra of light propagating through the TFBG grating at various LPPR angles.

The setup shown in Figure 1 consists of a light source (1), a polarisation control system (components 2, 3, 4, 5, 14, 15) and a splitter, beyond which there are two optical paths. In each of these, the light propagates through a TFBG grating with a structure tilt angle of $\Theta=7^\circ$, then passes through a circulator to an FBG grating, which reflects a selected, narrow range of light wavelengths. The light reflected by the FBG is directed to an optical power meter, which measures its power.

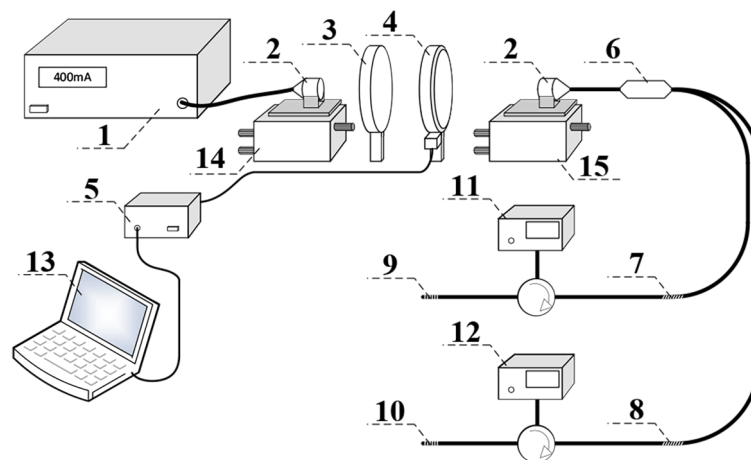


Figure 1. The interrogation setup. 1 – superluminescent diode (SLED), 2 – optical lenses, 3 – polariser, 4 – electronically driven half-wave plate, 5 – half-wave plate controller, 6 – optical splitter, 7 – TFBG₁, 8 – TFBG₂, 9 – FBG₁, 10 – FBG₂, 11 – first optical power meter (OPM₁), 12 – second optical power meter (OPM₂), 13 – PC, 14, 15 – 3D positioning table

The polarisation control system comprises a polariser (3), which polarises the light transmitted through the optical fibre. A half-wave plate (4) is positioned behind the polariser; its rotation angle is electronically controlled by a controller (5), allowing the specified rotation angle of the light's polarisation plane to be set. It was used to change and control the angle of the light transmitted through the system. The optical system responsible for controlling the polarisation and its angle was aligned coaxially using positioning stages (14, 15).

Polarised light with a specified angle of rotation of the polarisation plane enters a 50:50 splitter (6), where it is split into two beams, each of which enters one of the two branches of the optical path. The key feature of the system is the positioning of the TFBG₁ (7) and TFBG₂ (8) in such a way that the angle between the plane of polarisation of the light reaching TFBG₁ and the tangent to the axis of symmetry of that grating is α , whilst the angle between the plane of polarisation of the light reaching TFBG₂ and the tangent to the axis of symmetry of that grating is $\alpha+45^\circ$.

Polarised light, as it propagates through the TFBG, changes its spectrum. Particularly strong changes, caused by a change in the angle of rotation of the light's polarisation plane, are observed in the cladding modes. Each cladding mode consists of two modes, P and S, each of which corresponds to a minimum in the TFBG's transmission spectrum. These minima vary in value as the LPPR angle changes (Figure 2). In the proposed method, the power of light propagating at a wavelength corresponding to one of the cladding modes is used to calculate the LPPR angle. The FBG gratings mounted behind the TFBG gratings have been designed to reflect light at a wavelength corresponding to one of the modes. The light reflected by each of the FBG gratings is directed to a circulator, which routes it to an optical power meter.

The fragments of the TFBG and FBG gratings' spectra, showing their relative positions, are shown in Figures 3 and 4.

Due to the time-consuming nature of repeated measurements, an auxiliary measurement system was employed to record the spectra of light propagating through the TFBG (Figure 5). This

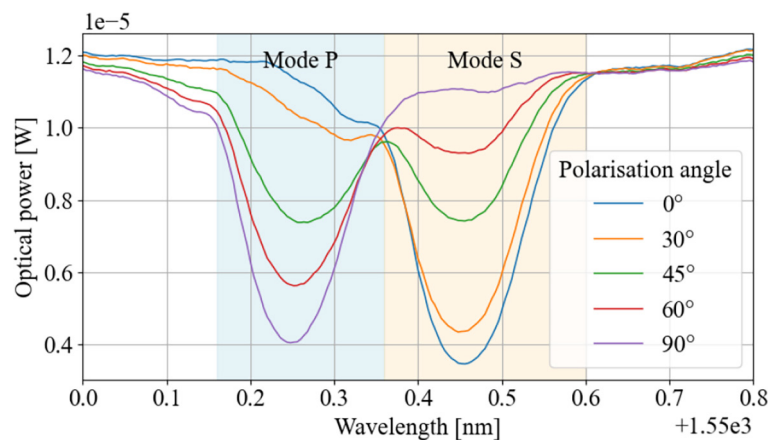


Figure 2. S and P modes for various LPPR angles

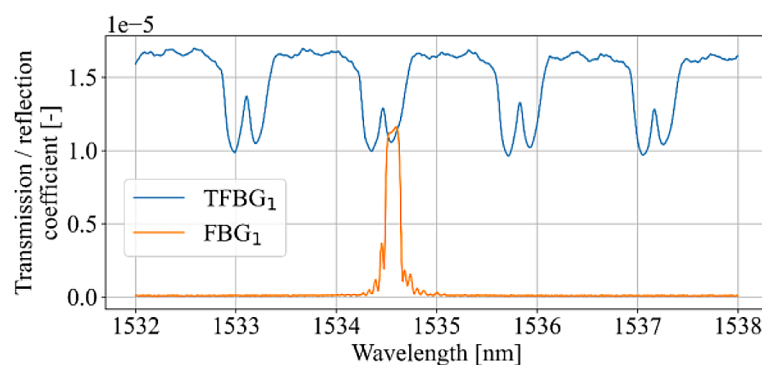


Figure 3. The spectra of the TFBG₁ and FBG₁ gratings, showing the overlap of their spectra

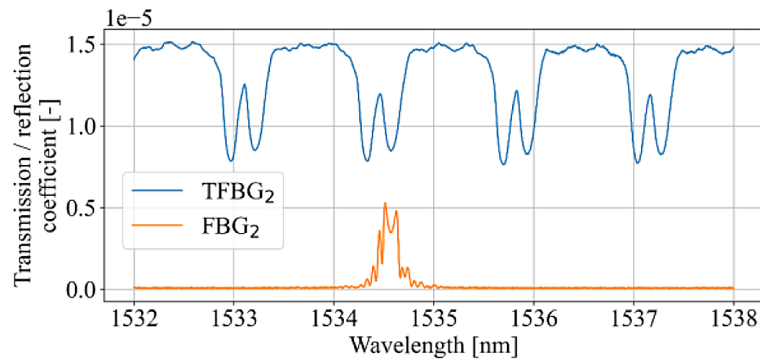


Figure 4. The spectra of the TFBG₂ and FBG₂ gratings, showing the overlap of their spectra

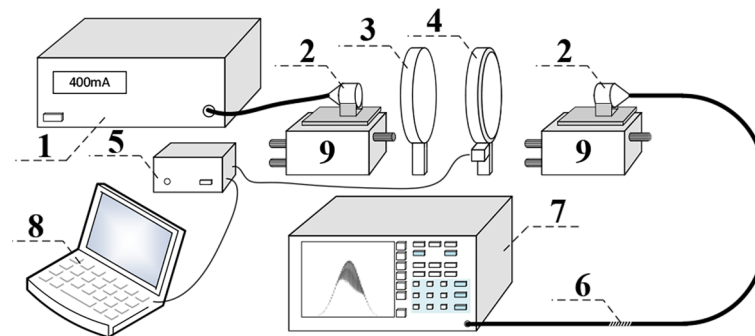


Figure 5. An auxiliary measurement system for recording the spectra of light propagating through a TFBG: 1 – superluminescent diode (SLED), 2 – optical lenses, 3 – polariser, 4 – electronically driven half-wave plate, 5 – half-wave plate controller, 6 – TFBG, 7 – optical spectrum analyser, 8 – PC, 9 – 3D positioning table

system was used to measure the spectra of light propagating through the TFBG grating at various rotation angles. In the remainder of this work, these spectra were used to carry out a series of simulations to select the optimal configuration of the system shown in Figure 1.

All measurements were performed at a controlled laboratory temperature of 23 °C. The optical fibres and components were mounted on a vibration-isolated laboratory table to minimise mechanical disturbances and fibre-bending-induced power variations. An electronically stabilised light source was used to minimise fluctuations in source power.

Light power changes

The light emitted by the superluminescent diode passes through a polarisation control system, where it is polarised, and the angle of rotation of the polarisation plane is adjusted. The light is then split into two beams, each directed into a separate branch of the optical path. Each power meter (OPM₁ and OPM₂) records the

power (P₁ and P₂) of the light propagating at the wavelength corresponding to the selected cladding mode. This allows two light power values to be recorded. Due to the use of different rotation angles of the TFBG gratings relative to the plane of light polarisation, these values will differ significantly. Graphs showing the variation in light power recorded for both gratings at different rotation angles of the plane of light polarisation are shown in Figure 6.

Each of the recorded power values (P₁ and P₂) varies with changes in the angle of rotation of the plane of polarisation of the light. However, using a single power value does not allow the angle of rotation of the plane of polarisation to be determined unambiguously, as identical values will be obtained for angles α and $\alpha+90^\circ$ [38,39]. Furthermore, the measurement accuracy will be lower for those angle ranges where a change in the angle of rotation of the light's polarisation plane causes only a slight change in the measured power. This situation occurs in those ranges of rotation angles for which the measured power is close to the maximum or minimum value of the light power. For

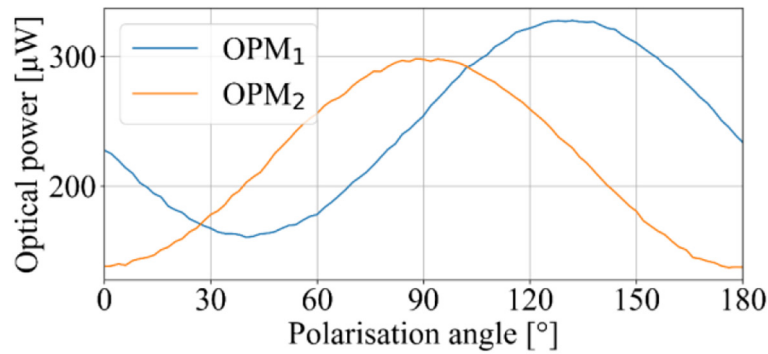


Figure 6. Variation in the light intensity recorded by the OPM₁ and OPM₂ optical power meters as a function of the angle of rotation of the light's plane of polarisation

this reason, the proposed method uses two independent power values to calculate the result. Furthermore, the rotation of the gratings relative to the plane of light polarisation has been selected such that, for rotation angles where the power readings from one branch of the optical path are close to an extremum, the power readings from the other branch change significantly (Figure 6).

Calibration and measurement

Due to differences in the structures of FBG and TFBG gratings and the impossibility of producing identical Bragg gratings, each measurement system must be calibrated. Calibration involves measuring the power of the light reaching OPM₁ and OPM₂ at various LPPR angles across the range 0°–180°. The plane of polarisation is rotated through specified angles. For each position, the optical power values P_1 and P_2 are recorded. As a result, two data sets are obtained that describe the relationship between power and the angle of rotation of the polarisation plane.

To maintain continuous calibration characteristics, the measurement data are approximated by a Fourier series. For each branch of the system, a function is determined describing the optical power as a function of the angle of rotation of the plane of polarisation:

$$P_i(\alpha) = a_0 + \sum [a_k \sin(k\omega\alpha) + b_k \cos(k\omega\alpha)] \quad (1)$$

where: $P_i(\alpha)$ is the power predicted by the model, a_0 , a_k and b_k are the approximation coefficients, and k denotes the harmonic number.

The measurement involves recording the power in both branches of the measurement

system (P_{1m} and P_{2m}) using the OPM₁ and OPM₂ meters. Based on the powers P_{1m} and P_{2m} for successive values of the angle α , an error function is calculated to determine the difference between the measured powers and the values derived from the calibration characteristics:

$$E(\alpha) = \left(\frac{P_1(\alpha) - P_{1m}}{\sigma_1} \right)^2 + \left(\frac{P_2(\alpha) - P_{2m}}{\sigma_2} \right)^2 \quad (2)$$

where: σ_1 and σ_2 denote the standard deviations of the power values in the calibration data for the first and second measurement channels, respectively.

They are calculated separately for each channel and used to normalise differences in their power ranges, preventing a channel with greater signal variation from dominating the error function. The final value of LPPR angle is determined as the value that minimises the error function:

$$\alpha_m = \arg \min E(\alpha), \alpha \in [0^\circ, 180^\circ] \quad (3)$$

The calculations are performed numerically over the entire measurement range. Using the power measured in both branches of the optical path allows LPPR to be determined unambiguously and limits the influence of measurement noise and local deviations in the calibration characteristics.

Data collection

Using the proposed measurement setup (Figure 1), light power measurements were carried out at rotation angles from 0° to 180° in 2° increments. In each measurement, the power readings from the OPM₁ and OPM₂ meters were recorded.

Auxiliary measurements, carried out using the setup shown in Figure 5, were performed at 1°

intervals for rotation angles of the light polarisation plane from 0° to 180°. Each measurement involved recording the light spectrum from 1480 nm to 1610 nm with a sampling interval of 0.004 nm, resulting in a spectrum consisting of 32,501 samples.

FBG alignment

Cladding modes are the wavelength ranges of light that respond most strongly to changes in the polarisation of light propagating through the TFBG. Each cladding mode consists of two minima – the S and P modes (see Figure 2). The values of these minima vary in opposite directions – an increase in one of the minima results in a decrease in the other. This is due to stronger attenuation of the wavelengths corresponding to a given minimum. In the method proposed in this article, the final result is calculated from an analysis of changes in light power. It is therefore necessary to select the wavelength range reflected by the FBG so that the power changes caused by the change in LPPR are as large as possible. Two phenomena must be taken into account here. Firstly, the wavelength range reflected by the FBG should cover only one of the minima (S or P) without overlapping the other. Secondly, the FBG should reflect as much of the transmitted power as possible at the selected minimum to obtain a strong signal and thus a high signal-to-noise ratio. However, due to the presence of sidebands (local maxima in the FBG reflection spectrum, coincident with the global maximum), determining the optimal central reflection wavelength requires further analysis.

To determine the optimal setting of the FBG central wavelength relative to the selected TFBG cladding mode, a numerical analysis was carried out using spectra of light propagating through the TFBG, recorded at various LPPR angles, and the spectrum of the selected FBG.

Mode S, with a central wavelength of 1534.95 nm, was selected for the analysis. This is one of the cladding modes with the largest amplitude, which is crucial for maintaining a high SNR [34]. The selected S-mode was used as a representative high-amplitude cladding mode. Other S- or P-modes may result in different signal amplitudes and distortions, although the same FBG-alignment procedure can still be applied. Their systematic comparison was beyond the scope of this study. The FBG reflection spectrum was positioned relative to the chosen mode, and its central wavelength was calculated using the formula:

$$\lambda_c = \frac{\sum_i \lambda_i R_i}{\sum_i R_i} \quad (4)$$

where: λ_i is the wavelength at which the i th spectral value was measured, R_i is the reflected power at wavelength λ_i , and i is the index of the i th spectral sample.

The calculations were performed within the FBG's main reflection band to limit the influence of sidebands on the determined value of λ_c . For the numerical analysis, the relative reflected power was calculated from the TFBG transmission and FBG reflection spectra:

$$P(\alpha) = \sum_i T(\lambda_i, \alpha) R(\lambda_i) \quad (5)$$

where: α denotes the LPPR angle, λ is the wavelength of light, $T(\lambda, \alpha)$ is the TFBG transmittance at wavelength λ_i and LPPR angle α , $R(\lambda)$ is the FBG reflectance spectrum, and $P(\alpha)$ is the power reflected by the FBG.

Since this calculation uses dimensionless transmission and reflection coefficients rather than the absolute source power, the resulting values are expressed in arbitrary units and are not directly comparable with the measured optical powers in Figure 6.

The light power $P(\alpha)$ was calculated for all measured spectra corresponding to successive LPPR angles. From these, power variation functions $F_p(\alpha)$ were derived, and the amplitude of the power variations was determined:

$$A_p = P_{max} - P_{min} \quad (6)$$

where: P_{max} and P_{min} denote the maximum and minimum values of the function $F_p(\alpha)$.

The distortion of the $F_p(\alpha)$ characteristic was assessed by analysing the curve's local linearity. For this purpose, every second point on the characteristic was used as a reference point, whilst the intermediate values were determined by linear interpolation. For a point situated between two adjacent reference points, the interpolated value was calculated as:

$$\hat{P}_{2i+1} = \frac{P_{2i} + P_{2i+2}}{2} \quad (7)$$

where: P_{2i} and P_{2i+2} denote the power values for adjacent reference points, and P_{2i+1} is the predicted value for the intermediate point.

The mean relative error was then calculated:

$$MAE_{rel} = \frac{\frac{1}{M} \sum_{i=1}^M |P_{2i+1} - \hat{P}_{2i+1}|}{P_{max} - P_{min}} \quad (8)$$

and the relative root mean square error:

$$RMSE_{rel} = \sqrt{\frac{\frac{1}{M} \sum_{i=1}^M (P_{2i+1} - \hat{P}_{2i+1})^2}{(P_{max} - P_{min})^2}} \quad (9)$$

where: M is the number of intermediate points analysed.

The applied normalisation enables comparison of distortions in the characteristics obtained at different FBG positions, regardless of the amplitude of the power variations.

The FBG spectral shift is defined as the difference between the central wavelength of the FBG reflection and the minimum of the selected S-mode of the TFBG. Positive values indicate a shift of the FBG reflection band towards longer wavelengths, whilst negative values correspond

to a shift towards shorter wavelengths. In the studies, the central wavelength of the FBG reflection was shifted within the range from -0.3 nm to $+0.3$ nm relative to the selected TFBG minimum.

Figure 7 shows example positions of the FBG reflection spectrum relative to the TFBG spectra recorded for two polarisation angles – 0° and 90° . At 0° , S-modes are visible in the spectrum. A 90° change in polarisation causes them to disappear and P-modes to appear. Figure 7 also shows three positions of the FBG spectrum corresponding to shifts of -0.3 nm, 0 nm and $+0.3$ nm. This figure illustrates how a change in the central wavelength of the FBG reflection affects the overlap of the FBG spectrum with a selected TFBG cladding mode.

For each analysed shift, the power characteristic $F_p(\alpha)$ was calculated. Subsequently, for each characteristic, the average reflected power, the amplitude of power variations and the relative error MAE_{rel} were determined. The results of this analysis are presented in Figure 8. The graph shows the effect of changes in the FBG spectrum

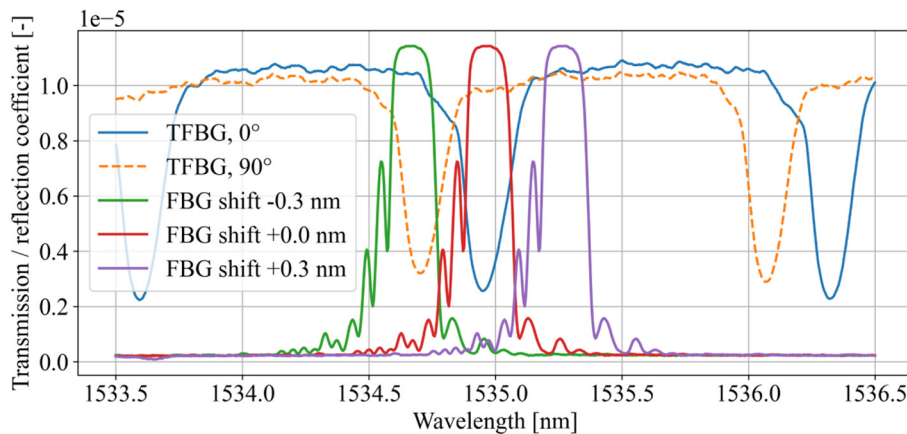


Figure 7. TFBG and FBG spectra for various central FBG wavelength shifts

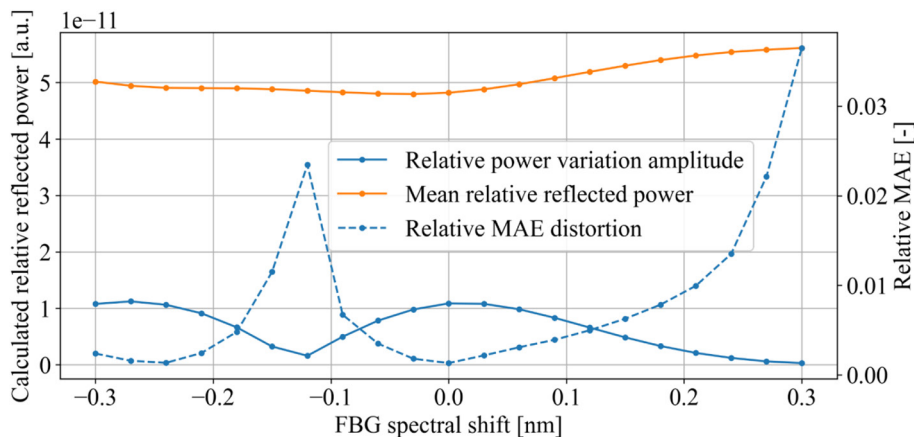


Figure 8. Influence of the FBG spectral position on the reflected power and distortion

position on the signal level, the amplitude of power variations and the distortion of the measurement characteristic. The optimal FBG position should ensure the highest possible amplitude of power variations whilst maintaining a low value of the relative error MAE_{rel} . The application of such criteria enables the selection of an appropriate FBG spectrum position to achieve optimal measurement results.

The influence of the FBG bandwidth was also evaluated numerically by scaling the measured FBG reflection spectrum while keeping its central wavelength fixed. Five FWHM values, ranging from approximately 0.09 to 0.37 nm, were analysed. Increasing the bandwidth increased the mean reflected power, whereas the amplitude of the power variation peaked near the experimentally used FBG bandwidth of 0.184 nm and decreased for broader spectra. Broader FBG spectra also led to greater characteristic distortion. Since the numerical analysis did not include a noise model, SNR was not quantified directly. However, the increase in mean reflected power may improve SNR if the detector and electronic noise remain approximately unchanged.

RESULTS

In the first stage of the experiment, the interrogation system was calibrated using measurements of polarisation plane rotation angles in the range 0° – 180° , recorded at 4° intervals. Based on the recorded optical power values, calibration characteristics were determined for both branches of the system, along with Fourier approximation coefficients describing the relationship between power and the LPPR angle.

The method was verified using an independent test set comprising measurements taken at intermediate values of the polarisation plane rotation angle (2° , 6° , 10° , ..., 178°), which were not used during calibration. For each measurement point, the LPPR angle was determined using the error function minimisation method described in the section “calibration and measurement”.

The measurement results are presented in Figure 9. The graph compares the reference values of the polarisation plane rotation angle with those determined by the developed measurement method. The results are close to the actual LPPR values, confirming the high agreement between the actual and determined values.

A more detailed assessment of measurement quality is presented in Figure 10, which shows the measurement errors at all test points. Across the entire measurement range from 0° to 180° , the errors remain small and do not show a clear dependence on the rotation angle of the polarisation plane. This indicates that the calibration procedure employed and the use of two independent measurement channels effectively eliminate the ambiguities characteristic of methods based on a single power measurement.

A quantitative summary of measurement accuracy is presented in Table 1. The mean absolute error was 0.27° , whilst the RMSE was 0.33° . The maximum recorded error did not exceed 0.76° . The mean error of -0.03° indicates a virtually complete absence of systematic error. The standard deviation of the error was 0.33° , demonstrating the high stability of the results obtained. Additionally, the coefficient of determination reached a value of $R^2 = 0.999$, confirming almost perfect agreement between the reference and measured values.

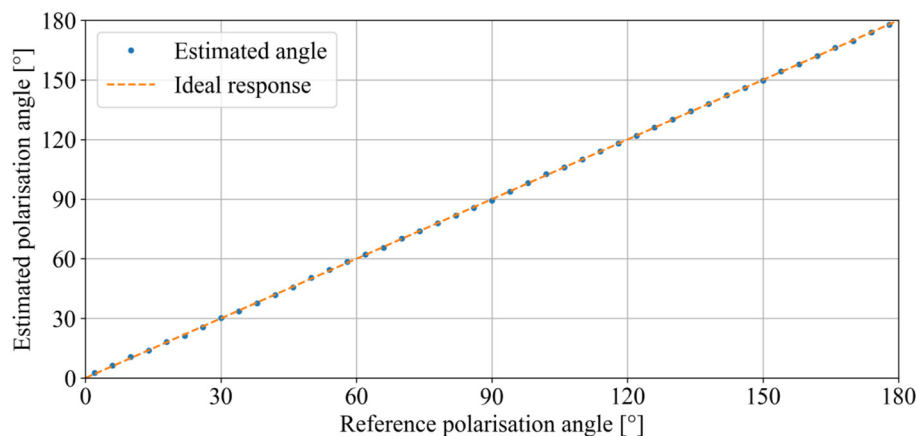


Figure 9. Comparison of estimated and reference LPPR angles

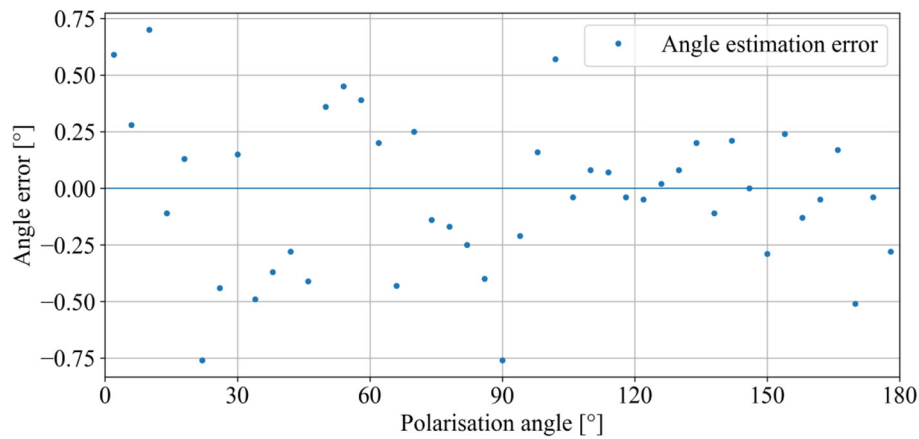


Figure 10. Measurement errors

Table 1. Statistical evaluation of the proposed method's accuracy

Metric	Value
Number of calibration points	46
Number of test points	45
MAE [°]	0.27
MSE [° ²]	0.11
RMSE [°]	0.33
Mean error [°]	-0.03
Standard deviation of error [°]	0.33
Max absolute error [°]	0.76
R ² [-]	0.999

The results confirm that the angle of rotation of the plane of light polarisation can be measured precisely over the full range of 0°–180° using only two optical power measurements. The proposed method eliminates the need for an optical spectrum analyser during measurement, significantly simplifying the system design and reducing the time required to obtain the measurement result.

DISCUSSION

The results confirm that the proposed method enables precise measurement of the angle of rotation of the plane of polarisation of light over the range 0°–180°. An average absolute error of 0.27° and a coefficient of determination $R^2 = 0.999$ indicate a very high degree of agreement between the reference and measured values. A significant advantage of the developed solution is the ability to unambiguously determine the angle across the entire measurement range using only

optical power measurements, without recording the full TFBG transmission spectrum.

The first methods for measuring the angle of rotation or twist using tilted fibre Bragg gratings were based on analysing changes in the amplitude of individual cladding modes in the transmission spectrum. In [38], a system utilising a TFBG combined with an FBG acting as an optical filter was proposed, thereby enabling the replacement of an optical spectrum analyser with a simple optical power measurement. The method was based on analysing a single section of the spectrum, and no detailed assessment of measurement accuracy was provided. Furthermore, the response characteristics remained monotonic only over a limited range of polarisation changes, limiting measurements to 0°–90°.

Similar limitations were observed in the solutions described in [39]. A method for measuring rotation and twist using a TFBG was proposed. High sensitivity was reported for limited LPPR ranges, particularly between 30° and 70°. However, the authors noted that the sensor response, based on the change in amplitude of a selected cladding mode, is periodic, which limits the ability to unambiguously determine the angle of rotation across the entire measurement range; the method provided measurements in the range 0°–90°.

Significant progress has been made with methods utilising numerical analysis of the entire TFBG transmission spectrum. One such approach was a method based on the discrete wavelet transform (DWT) [34]. The use of the wavelet transform enabled the analysis of changes in the TFBG spectrum across the full range of 0°–180°, whilst eliminating the need for the operator to manually select parameters. An average measurement error

of approximately 1.1° was obtained for a TFBG with a tilt angle of 7° , with the largest errors occurring near 90° , where the used characteristics flattened. The authors also demonstrated that measurement accuracy depends on the TFBG tilt angle – better results were obtained for gratings with larger periodic-structure tilt angles, but only TFBGs with 3° , 5° , and 7° tilts were examined.

The next stage of development involved methods utilising the Fourier transform. Proposed in [33] was an analysis of FFT coefficients calculated from a selected portion of the TFBG transmission spectrum. The method enabled measurement of the LPPR angle over the full range of 0° – 180° , with an average error of approximately 0.076° . However, increased measurement errors were observed for angles close to 0° , 45° , 90° , 135° and 180° , which resulted from the flattening of the characteristics of the selected FFT coefficients. Additionally, the calibration procedure required an experienced operator to select the most useful FFT coefficients.

In subsequent studies, the FFT approach was further developed. In [36], it was proposed to use two TFBGs rotated relative to one another, along with new algorithms for analysing the selected region of the cladding-mode area using FFT. This approach mitigated the problem of characteristic flattening, improved measurement stability, and achieved mean errors of the order of 0.06° – 0.08° . Consequently, significantly higher accuracy was achieved than with the first DWT method, albeit at the cost of increased optical system complexity and the need to analyse two full transmission spectra.

The concept of using a larger number of TFBG gratings was applied in [35], where a cascaded TFBG setup was proposed to detect

spectral shifts in two TFBGs using a single optical spectrum analyser. This solution utilised measurements of light power at multiple wavelengths corresponding to selected cladding mode minima. This approach helps mitigate characteristic flattening and improve measurement stability across the entire measurement range. Mean errors of the order of 0.064° – 0.076° were achieved. This method also requires registering and analysing the full spectrum of transmitted light, using two TFBGs and light spectrum features extraction [40].

Compared with the solutions described, the proposed method strikes a balance between hardware simplicity and measurement accuracy. Importantly, the novelty relative to [38] is therefore not the use of power-based interrogation itself, but the combination of two complementary 45° -offset sensing branches with joint numerical processing of both power signals. Unlike [33–36] methods, it does not require recording the full optical spectrum or performing complex signal processing. The LPPR angle is determined directly from two optical power values and previously determined calibration characteristics. Using two independent measurement channels allowed the elimination of the ambiguities characteristic of methods [38,39] based on a single amplitude characteristic.

The summary comparison of the proposed method and other existing solutions is presented in Table 2. The proposed method is not intended to outperform full-spectrum analysis approaches solely in terms of accuracy. Its main advantage is the combination of full-range, unambiguous measurement, limited hardware complexity, and rapid measurement, achieved by eliminating full-spectrum acquisition during operation. The lower accuracy achieved in this work compared

Table 2. Comparison of the proposed method with existing TFBG-based LPPR measurement methods

Method	Interrogation signal	Number of TFBGs	OSA required	Measurement range	Accuracy
[38]	Single, FBG filtered optical power	1	no	0° – 90°	Not assessed, range dependent
[39]	Single, selected cladding mode amplitude	1	yes	0° – 90°	Not assessed, range dependent
[34]	Full spectrum, DWT-based processing	1	yes	0° – 180°	MAE= 1.1°
[33]	Full spectrum, FFT-based processing	1	yes	0° – 180°	MAE= 0.076°
[36]	Two full spectra, FFT-based processing	2	yes – two OSAs	0° – 180°	MAE= 0.06° – 0.08°
[35]	Full spectrum, many cladding modes amplitude	2	yes	0° – 180°	MAE= 0.074°
Proposed	Two FBG filtered optical power values	2	no	0° – 180°	MAE= 0.27°

to full-spectrum methods is due to the limited number of parameters used to describe the polarisation state. On the other hand, simplifying the measurement setup allows for a significant reduction in system cost, increased resistance to environmental conditions, reduced measurement time, and enables implementation in industrial applications where the use of optical spectrum analysers is often impossible. It should be noted that the accuracy values reported in different studies were obtained under different experimental conditions. Therefore, the comparison should be interpreted mainly in terms of interrogation principle, measurement range, and hardware complexity.

The elimination of spectral acquisition makes the proposed approach suitable for developing compact, low-cost measurement modules based on optical power detection. Such modules could be used for direct polarisation monitoring or integrated into fibre-optic sensing systems to compensate for polarisation-dependent measurement effects. The present validation was limited to a single measurement system and one TFBG–FBG sensor pair under controlled laboratory conditions. Further studies should therefore address sensor-to-sensor reproducibility, long-term stability, temperature and source-power sensitivity, and performance under dynamically changing polarisation.

The influence of temperature and mechanical stress was not investigated in the present study. Since both TFBG and FBG spectra are sensitive to temperature and strain, these changes may shift their relative spectral alignment, thereby affecting the measured optical powers and the LPPR estimate.

Because the method relies on absolute optical power measurements, source power fluctuations, splitter imbalance, connector losses and bending-induced optical losses may affect the estimated LPPR angle. Power normalisation, a reference channel or periodic recalibration could improve robustness under less-controlled operating conditions. In the present setup, an electronically stabilised SLED was used to minimise this effect. No separate reference channel or numerical source-power compensation was employed.

The present system was validated over the 0° – 180° range. Because the response of linearly polarised light is periodic with 180° , angles differing by 180° cannot be distinguished from the two power measurements alone; therefore, extension to 0° – 360° would require additional directional or reference information.

The research indicates that further improvements in accuracy can be achieved by increasing the power of the light propagating through the system, optimising the selection of wavelengths used in both measurement channels, applying more advanced methods for approximating calibration characteristics, or expanding the system with additional branches. Another promising avenue for further work appears to be combining the proposed solution with machine learning methods or multi-parameter analysis, which could enable the simultaneous measurement of the LPPR angle and other physical quantities affecting the TFBG response.

CONCLUSIONS

This paper presents a new method for measuring the angle of light polarisation plane rotation using two tilted fibre Bragg gratings, two FBG gratings, and optical power measurements in two independent channels. The proposed solution eliminates the need to record the full TFBG transmission spectrum using an optical spectrum analyser, which significantly simplifies the measurement setup, reduces measurement time and lowers the cost of implementation.

The research shows that using two measurement branches with a 45° offset in the orientation of the TFBGs allows unambiguous determination of the LPPR angle across the full range of 0° – 180° . The developed calibration procedure and the algorithm for determining the angle by minimising the error function enable high measurement accuracy. For an independent test set, a mean absolute error of 0.27° , an RMSE of 0.33° , and a maximum error not exceeding 0.76° were obtained, with a coefficient of determination $R^2 = 0.999$. These results confirm very high agreement between the reference and determined values.

The analysis also revealed a significant influence of the relative positions of the TFBG and FBG spectra on the system's metrological parameters. The most favourable results were obtained when the FBG reflection band was positioned so that the minimum of the selected cladding mode coincided with the wavelength at which the FBG reflection spectrum reached its maximum, thereby filtering the selected wavelength range.

The results indicate that the proposed method is an attractive alternative to solutions based on full optical spectrum analysis. Although the accuracy achieved is slightly lower than that of

the best methods utilising advanced TFBG spectral analysis, the simplicity of the hardware, low implementation cost and the ability to rapidly determine the LPPR angle make it particularly interesting for industrial applications and systems requiring real-time measurements.

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