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Macrobending Fiber Loss Filter, Ratiometric Wavelength Measurement and Application

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Macrobending fibre loss filter, ratiometric wavelength measurement and application

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Abstract
A macrobending standard single-mode fibre (SMF28) is optimized as an edge filter, with the optimal bending radius and length determined according to the bend loss and polarization sensitivity of the bending fibre. An all-fibre ratiometric wavelength system is built and calibrated. The system's accuracy and resolution is discussed with the influence of noise of input signal and photodetectors. Finally, the ratiometric system is employed for the demodulation of FBG strain sensing.

Keywords: macrobend, single-mode fibre, ratiometric wavelength measurement, FBG sensing

1. Introduction

Wavelength measurement is required on many occasions. Examples include multi-channel dense wavelength division multiplexing (DWDM) optical communication systems and optical sensing systems based on the wavelength-shift mechanism, such as the fibre Bragg grating (FBG) based optical sensing system. For DWDM optical communications, the accurate setting and maintaining of the transmitter's wavelength is required [1, 2] and for the FBG optical sensing, a cost-effective wavelength demodulation system detecting the wavelength shift of the reflected light from the FBG sensor is crucial in the successful implementation of this optical sensing technique [3]. There are various wavelength measurement schemes and among them is the ratiometric detection scheme. It employs an edge filter and utilizes the transition region of its transmission response, converting the wavelength measurement into the measurement of the ratio of signal powers from the two arms (the edge-filter arm and reference arm). The ratiometric system has a simple configuration and offers a high-speed measurement potential as compared with, e.g., the wavelength scanning based active measurement schemes [4–7]. The proposed edge filters to date for the ratiometric system are bulk thin-film filters [4], biconical fibre filters [7], fibre gratings [8], multimode interference (MMI) couplers [9, 10], directional couplers [2], and so on. Recently, we developed a macrobending standard single-mode fibre (SMF28) to act as a novel all-fibre edge filter and demonstrated the wavelength measurement based on the bending fibre as a proof of concept [11]. As compared to existing edge filters, it has the advantages of much lower fabrication cost, easy interconnection and mechanical stability. In this paper we are going to present the development of macrobending SMF28 based wavelength measurements including (1) optimization of the bend loss filter and (2) ratiometric wavelength measurement and its accuracy and resolution issue and integrating this low-cost wavelength measurement in an FBG sensing system as an interrogator.

The optimization of the macrobending fibre filter in [11] determined the bending radius and bending length according to the bend loss over the desired measurable wavelength range. In this paper, we will refine the optimization including the consideration of polarization sensitivity of the bend loss. A detailed design procedure is presented in section 2. With the developed macrobending fibre edge filter, an all-fibre ratiometric wavelength measurement system is built up and calibrated in section 3. In practice the input signal, e.g., the output from a tuneable laser or the reflected light from a FBG sensor, has a limited signal-to-noise ratio (SNR) and photodetectors also have a limited precision. The characterization of system accuracy and resolution due to these factors is discussed. Finally the ratiometric wavelength system is integrated in a FBG strain sensing system for the demodulation of FBG sensing.

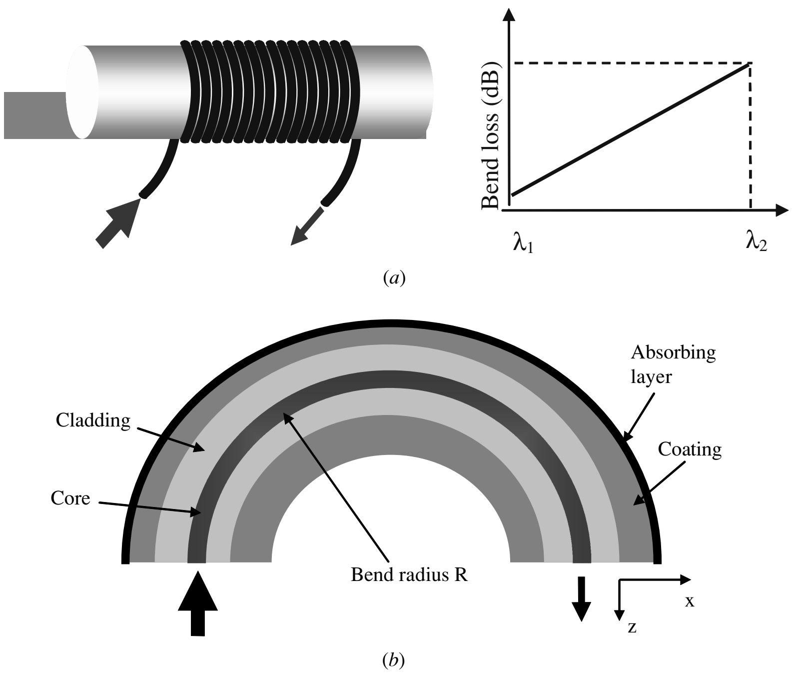


Figure 1. (*a*) Macrobending single-mode fibre rolled over a mandrel and the desired bend loss over the wavelength range from λ_1 to λ_2. (*b*) Bending section with a bending radius R and absorbing layer outside.

2. Macrobending fibre-based edge filter

For a macrobending single-mode fibre, most of the previously published investigations are focused on how to predict and lower the bend loss, which is regarded as an adverse effect in the context of light transmission. In our previous work (see [11]) it was developed as an edge filter.

The schematic structure of a macrobending fibre rolled over a mandrel is presented in the left part of figure 1(*a*) and the right part shows the desired spectral response of the edge filter for the wavelength measurement. A low transmission loss at wavelength λ_1 with a suitable discrimination range over the wavelength range is aimed to be achieved with the optimization. Intuitively, the slope of the transmission response for the edge filters is expected to be as large as possible to ensure a high resolution of the measurement system given the limited precision of power detectors. However, in practice, the slope of the bend loss is limited by the signal-to-noise ratio of input signal and the measurable wavelength range desired as shown in [12]. In the present investigation, the wavelength range considered is from 1500 nm to 1600 nm. The discrimination range in this example is considered to be about 20 dB. To eliminate the reflection of radiated light occurring at the interface between the coating layer and air, which could cause the spectral response of curve to be non-smooth and not suitable for wavelength measurement consequently, an absorbing layer is required outside the polymer coating layer as shown in figure 1(*b*). (The fibre is bent in the x–z plane and the y direction is parallel to the mandrel.)

For SMF28, when the bend radius R is relatively small, e.g., around 10 mm, the polymer coating layer outside the cladding layer, which is designed for mechanical protection, has a significant influence on the bend loss due to the so-called whispering-gallery mode caused by the reflection between the cladding and coating layer [13]. To predict the bend loss of a macrobending fibre under the effect of the whispering-gallery mode precisely is difficult, however, the formulation presented in [13, 14] can model the bend loss for SMF28 with satisfactory agreement as compared to the experimental results. However, these calculations are based on the scalar approximation. The coating layer has a significant influence not only on the bend loss but also on the polarization sensitivity since the refractive index of the coating layer is relatively much higher than that of the cladding layer [15]. To consider the polarization dependence of bend loss caused by the coating layer, the boundary condition at the interface between the cladding and coating layers in the calculation of the bend loss needs to be treated separately for the TE and TM modes. (In the calculation model, the interface between the cladding and coating layers is approximated as a plane. TE mode: the polarization direction is defined in the x–z plane; TM mode: the polarization direction is in the y–z direction; see figure 1(*b*).)

For the present example, the range of bending radius is considered to be from 8 to 13 mm and the bending length is from 50 to 1000 mm. The calculated bend losses of the TE mode (dB) for SMF28 at wavelength 1500 nm under different bending radii and lengths are presented in figure 2(*a*). For a wavelength of 1600 nm, the discrimination of bend loss as compared to that of 1500 nm ($Ls_{1600} - Ls_{1500}$) is presented in figure 2(*b*). In addition to the bend loss, the polarization-dependent loss is also an important design parameter that needs to be minimized. The corresponding polarization-dependent losses for these two wavelengths are also presented in figures 2(*c*) and (*d*). It can be seen that the polarization-dependent loss of the SMF28 differs significantly at different bending radii.

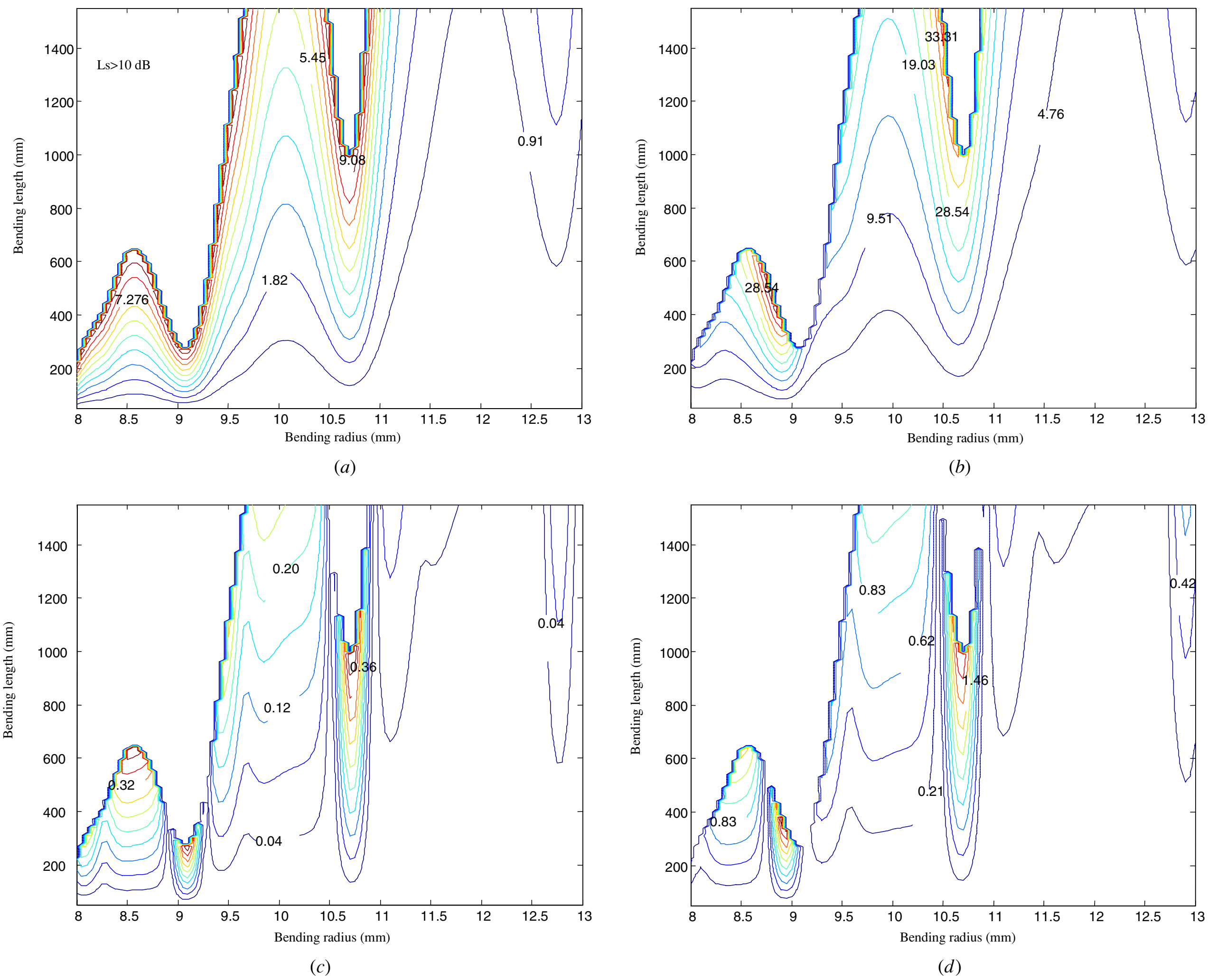


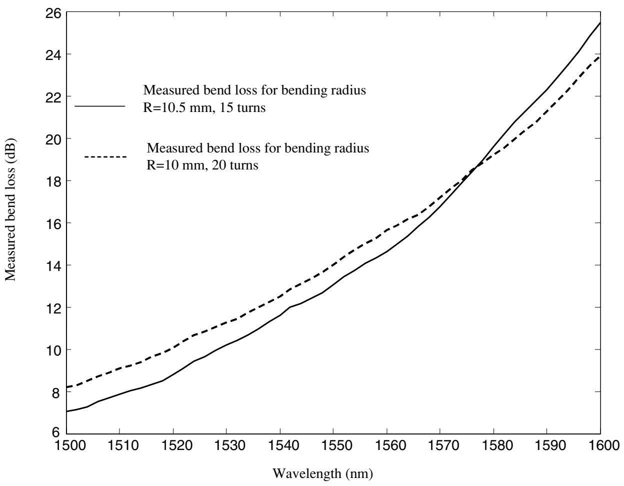
Figure 2. (*a*) TE mode bend loss of SMF28 for wavelength 1500 nm, (*b*) discrimination range of TE mode of SMF28 for wavelength 1600 nm ($Ls_{1600} - Ls_{1500}$), (*c*) PDL for wavelength 1500 nm, (*d*) PDL for wavelength 1600 nm.

As mentioned above, a low bend loss for wavelength 1500 nm and a discrimination range of around 20 dB is desired for the macrobending fibre loss filter. Combining figures 2(*a*) and (*b*), it is found there are multiple solutions of bending radius and bending length for the edge filter. To choose the best solution among these solutions, the need for low polarization dependence is taken into account. Therefore, in this example, the bending radius of 10.5 mm with the length of about 660 mm (about 10 turns) is chosen. According to the calculation results, the corresponding discrimination range is about 20 dB and the PDL at 1500 nm is 0.04 dB and at 1600 nm it is 0.21 dB.

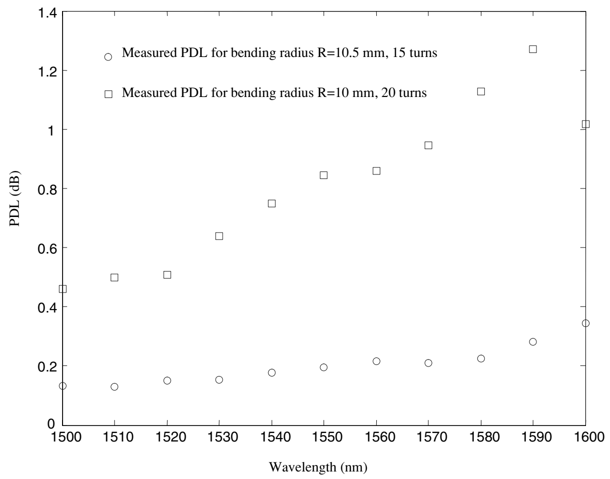
To verify the above-designed result, a SMF28 is rolled over a mandrel with the bending radius of 10.5 mm and the bend loss is measured over the wavelength range from 1500 to 1600 nm with a tuneable laser and optical spectrum analyser. In the experiment, it is found that for the bending radius of 10.5 mm, a bending length of 15 turns corresponds to a discrimination range of about 20 dB. (The designed length of 10 turns corresponds to about 15 dB.) The polarization-dependent loss is also measured through connecting a polarization controller in the system. The measured bend loss and polarization-dependent loss are presented in figures 3(*a*) and (*b*), respectively. For comparison, the bend loss and PDL of bending radius 10 mm with a bending length of 20 turns are also presented. The measured bend losses for both bending radii are close over the wavelength range from 1500 to 1600 nm. However, the maximum polarization-dependent loss for the bending radius 10.5 mm is 0.34 dB and for bending radius 10 mm, it is 1.3 dB. Therefore, in our following ratiometric wavelength measurement, the bending radius 10.5 mm is chosen, underscoring the need to include PDL in the design of the filters.

3. Ratiometric wavelength measurement and application in FBG demodulation

The schematic structure of a ratiometric wavelength measurement system is presented in figure 4, which includes a splitter, an edge filter, a reference arm and two photodetectors. The edge filter discriminates the wavelength of the input signal with the transmission measured by photodetector A. The reference arm is used and based on the ratio between the measured powers from two arms, it can discriminate the



(*a*)



(*b*)

Figure 3. (*a*) Measured bend loss over the wavelength range from 1500 to 1600 nm, for two cases: (1) bending radius 10 mm, bending length 20 turns; (2) bending radius 10.5 mm, bending length 10 turns. (*b*) Measured polarization-dependent loss for these two cases.

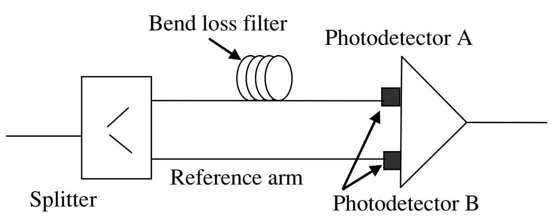


Figure 4. Schematic structure of a ratiometric wavelength measurement system.

wavelength of the input signal regardless the power of the input signal for an ideal input light (monochromatic) and photodetectors (no noise).

For a wavelength measurement system, besides the measurement range, accuracy and resolution are two other important specifications in the characterization of the ratiometric system. There are several factors affecting the system's performance, which can be the signal-to-noise ratio of the input signal, the precision of the photodetectors, the polarization dependence and further the ambient temperature. In this section, we are going to present the influence of the SNR of the input signal and the precision of the photodetectors on the system's accuracy and resolution.

It is known that photodiodes give the integral power over a wavelength range in measuring the power, therefore, the basic equation for the ratio of the system is $R(\lambda_0) = \frac{\int I(\lambda)P_1(\lambda)T(\lambda)\,d\lambda}{\int I(\lambda)P_2(\lambda)\,d\lambda}$, where $I(\lambda)$ is the spectrum of the input signal, $P_1(\lambda)$ and $P_2(\lambda)$ are the output from the two arms of the splitter and $T(\lambda)$ is the transmission of the edge filter. Although the responsivity of a photodetector is wavelength dependent, the commercial optical power meter is calibrated with the corresponding spectral response over the measurable wavelength range so that the optical power meter can offer the actual optical power measurement independent of the wavelength. Therefore, the photodetector's spectral response is regarded as wavelength independent and treated as a unit in the above basic equation. The typical input signal has a limited SNR in practice and from this basic equation one can see that the SNR of the input signal will affect the output ratio. Thus, it suggests that the calibration curve will depend on the SNR of the calibration source and after the system is calibrated with a source of a certain SNR, there will be an issue of accuracy if the measured input signal has a different SNR. In practice the photodetectors have a limited precision due to the noise of the optical-to-electronic conversion so that the measured ratio has fluctuations. Therefore, the basic ratio becomes $R(\lambda_0) = \frac{\int I(\lambda)P_1(\lambda)T(\lambda)\,d\lambda + s_1}{\int I(\lambda)P_2(\lambda)\,d\lambda + s_2}$, where s_1 and s_2 are random numbers within a range related to the practical noise of a photodetector. Through including the noise of the photodetectors, the ratio equation also shows that the ratio is dependent on the power of the input signal even when the SNR remains the same. To investigate the influence of SNR of the input signal and noise of photodetectors on the system's accuracy, a comparison experiment is carried through changing the power of the input signal with and without retaining the SNR.

In our experiment, the tuneable laser has a different SNR if we set the output power of the peak wavelength to different values. However, using a wavelength insensitive variable optical attenuator can change the output power of the tuneable laser while retaining the same SNR. Figure 5(*a*) gives the spectrum of the tuneable laser with the peak wavelength at 1520 nm for three cases: (1) output power for the peak wavelength is 0 dBm and the SNR is about 47 dB; (2) output power for the peak wavelength is −5 dBm through setting the tuneable laser directly and the corresponding SNR is about 42 dB; and (3) output power for the peak wavelength is −5 dBm through using the attenuator. The SNR remains 47 dB.

To illustrate the influence of SNR on the system's accuracy, we choose the first case (0 dBm output from the tuneable laser with an SNR of about 47 dB) for the calibration and save the corresponding curve as the calibration for wavelength discrimination. First, we use the calibrated system to measure the same input signal and after some time we adjusted the output of the tuneable laser leading the SNR of the input signal to be 42 dB while retaining the same input wavelength and the corresponding results are presented in figure 5(*b*), from which one can see that the measured wavelength shifts about 0.13 nm due to the change of the SNR.

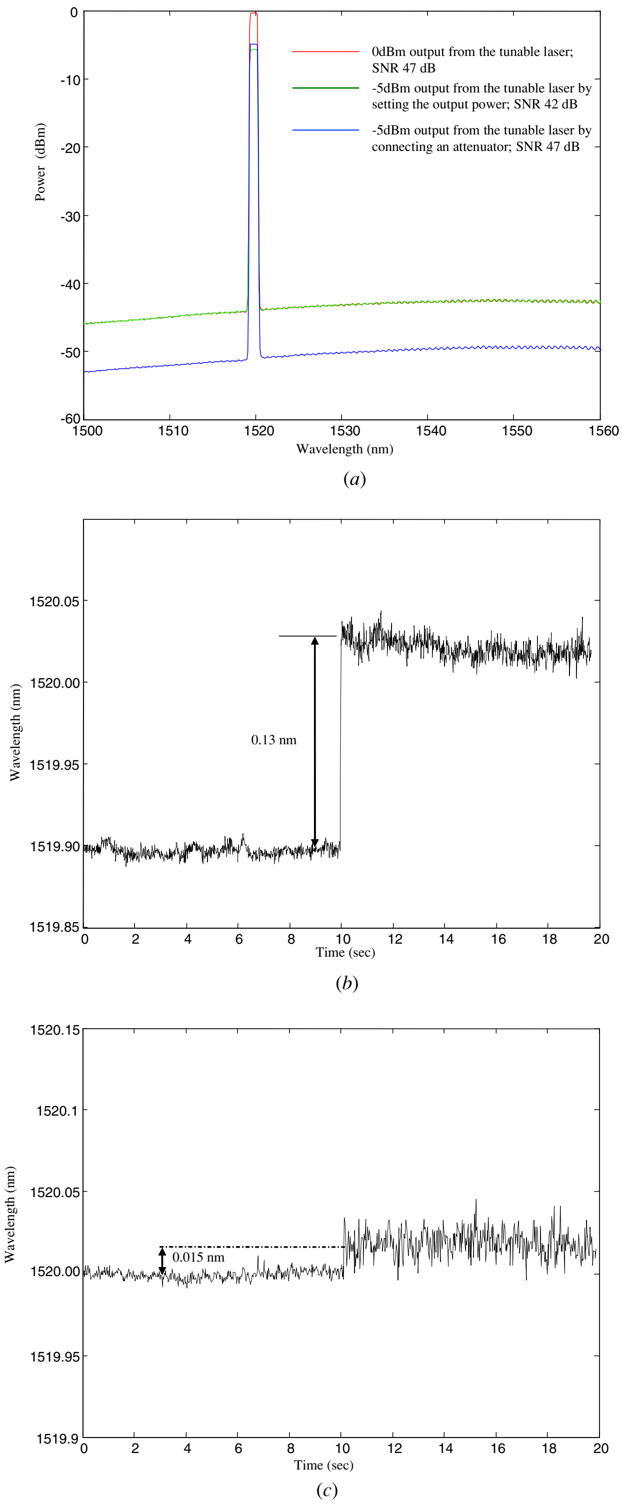


Figure 5. (*a*) Spectrum of tuneable laser for the three cases; (*b*) wavelength shift due to the change of input power in case 2; (*c*) wavelength shift due to the change of input power in case 3.

In the second experiment, the power of the peak wavelength from the tuneable laser is changed from 0 dBm to −5 dBm and the corresponding SNR is still 47 dB by adjusting the connected variable optical attenuator. The experiment also shows a slight wavelength shift by 0.015 nm. Therefore, both

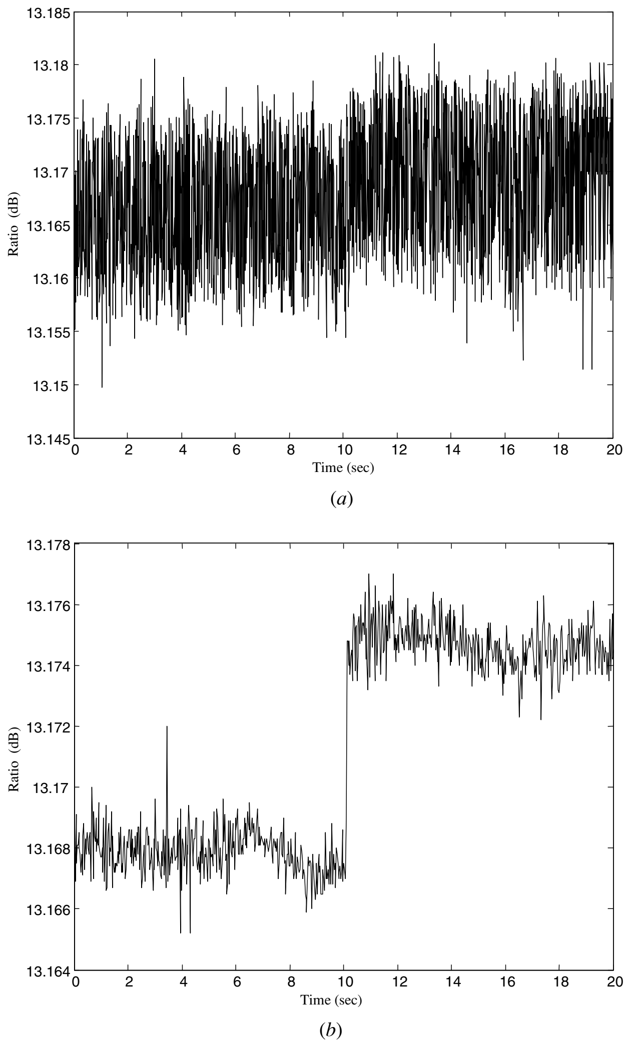
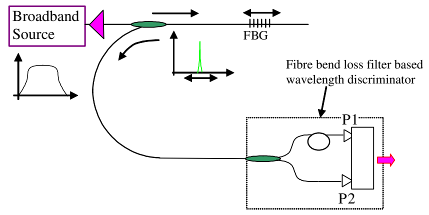


Figure 6. (*a*) Ratio measured by photodetectors without any averaging; (*b*) Ratio measured by photodetectors with an averaging value of 256.

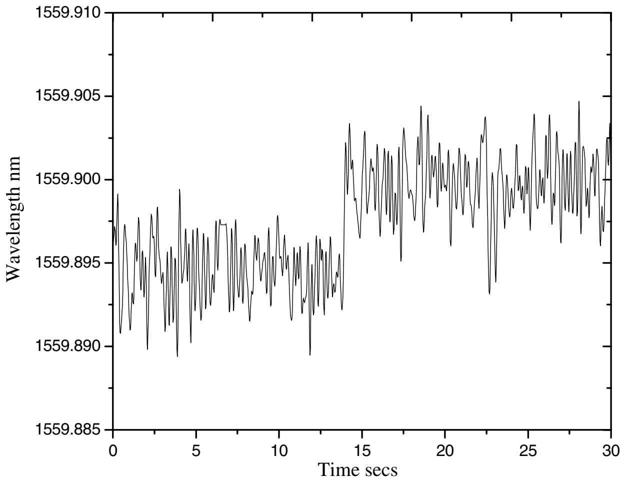
cases show that a practical ratiometric system is not ideally independent of the input power of the input signal as claimed conventionally. Particularly, the change of SNR of the input signal can have a significant influence on the system accuracy.

The SNR of the input signal limits the slope of the spectrum of the edge filter and thus, the system has a limited discrimination range over the measurable wavelength range. The noise of the optical-to-electronic conversion leads to the measured ratio having fluctuations. This fluctuation limits the resolution of the ratiometric wavelength measurement system, i.e., the minimum wavelength shift it can detect. A simple way to improve the resolution of the wavelength measurement system is to suppress the fluctuation, e.g., using averaging or filtering techniques. We carried out a comparison experiment on the influence of noise of photodetectors on the system's resolution. The photodetectors used in our experiment can be set with different averaging values for measurements, which correspond to different fluctuations of the ratio.

We tuned the wavelength of the input signal by 10 pm in the middle of the measurement duration. First, we use



(*a*)



(*b*)

Figure 7. (*a*) Configuration of FBG sensing system including the ratiometric wavelength measurement unit, (*b*) measured wavelength when a 5 $\mu\varepsilon$ is applied on the FBG in the middle of the duration.

the photodetectors without any averaging. Then we set the averaging value of the photodetectors to be 256 and repeated the experiment. The corresponding results for these two cases are presented in figures 6(*a*) and (*b*). From figure 6(*a*) it can be seen that the fluctuation of the ratio is about 0.03 dB and the wavelength shift occurring at the 10th second could not be detected due to the fluctuation caused by the noise of the photodetectors. In figure 6(b), due to the average setting of the photodetectors, the fluctuation of the ratio is reduced to about 0.004 dB and for this case the wavelength shift can be detected more readily. So we can conclude that for a ratiometric wavelength measurement, the noise of photodetectors plays a very important role in the characterization of the system's resolution.

For this ratiometric wavelength measurement system, one application example is interrogation for the FBG sensing. Compared to other interrogation techniques this macrobending fibre-based wavelength measurement has a very low fabrication cost and ease of interconnection due to the all-fibre configuration. As an experimental demonstration, we build a typical FBG sensing system as shown in figure 7(*a*), which includes a broadband source, an isolator, a coupler, a FBG sensor bonded on a stage with a micrometer and the ratiometric wavelength measurement unit developed above.

In our experiment, the strain was applied on the FBG sensor through tuning the micrometer to elongate the FBG. For the static strain measurement, the micro-strain is applied on the FBG and the corresponding wavelength shift from the FBG sensor is measured. Figure 7(*b*) presents the measured wavelength when a 5 $\mu\varepsilon$ is applied on the FBG in the middle of the duration. As shown in figure 7(*b*), this applied stress can be discriminated by the measured wavelength shift with this low-cost macrobending fibre-based ratiometric wavelength measurement system. The resolution of this FBG demodulation can be further improved by reducing the measurable wavelength range and increasing the slope of the edge filter's transmission response if there is only one FBG involved. The above-demonstrated ratiometric wavelength measurement covers a wavelength range of 100 nm (from 1500 to 1600 nm), which can be employed potentially for a WDM-FBG sensing system through inserting a tuneable channel drop filter.

4. Conclusion

In this paper, we have presented an overview of a macrobending fibre filter, ratiometric wavelength system for application to the demodulation of FBG strain sensing. For the optimization of macrobending SMF28, we considered both the bend loss and polarization sensitivity over the desired wavelength range, and the bending length and bending radius are determined correspondingly. With the developed macrobending fibre filter, an all-fibre ratiometric wavelength measurement system has been built up and characterized regarding the accuracy and resolution. Experimental results have shown that the SNR of the input signal and noise of photodetectors involved have a significant influence on a ratiometric wavelength measurement system's accuracy and resolution. Finally, we integrated the ratiometric wavelength system in a FBG strain sensing, demonstrating that a competitive interrogation technique with a very low fabrication cost is possible.

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