2007-01-01

Effect of Polarisation-dependent Loss on the Performance Accuracy of a Ratiometric Wavelength Measurement System

Ginu Rajan
Dublin Institute of Technology, ginu.rajan@dit.ie

Qian Wang
Dublin Institute of Technology

Yuliya Semenova
Dublin Institute of Technology, yuliya.semenova@dit.ie

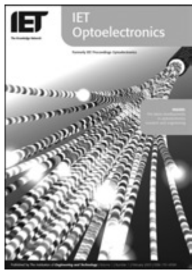
Gerald Farrell
Dublin Institute of Technology, gerald.farrell@dit.ie

Pengfei Wang
Dublin Institute of Technology, pengfei.wang@dit.ie

Recommended Citation

Rajan, G., Wang, Q., Semenova, Y., Farrell, G., Wang, P.:Effect of polarisation-dependent loss on the performance accuracy of a ratiometric wavelength measurement system. *IET Optoelectronics*, Vol.2 (2), 2008, pp.63-68. doi:10.1049/iet-opt:20070028

Published in IET Optoelectronics
Received on 3rd April 2007
Revised on 24th September 2007
doi: 10.1049/iet-opt:20070028



ISSN 1751-8768

Effect of polarisation-dependent loss on the performance accuracy of a ratiometric wavelength measurement system

G. Rajan Q. Wang Y. Semenova G. Farrell P. Wang

Applied Optoelectronics Centre, School of Electronics and Communication Engineering, Dublin Institute of Technology, Kevin Street, Dublin-8, Ireland
E-mail: ginu.rajan@dit.ie

Abstract: The polarisation-dependent loss (PDL) of a ratiometric wavelength measurement system and its influence on system's accuracy are investigated theoretically and experimentally. The PDL of a ratiometric system and the corresponding power ratio fluctuation is modelled, from which the accuracy of the measured wavelength can be estimated. An all-fibre wavelength measurement system is built to allow comparison of modelled and actual results. The measured ratio variation lies within the estimated limits. The measured wavelength error reaches about 1.41 ± 0.09 nm at 1550 nm in the demonstrated example (with an edge filter of average slope 0.22 dB/nm), which indicates the significant influence of PDL on the accuracy of a ratiometric wavelength measurement system.

1 Introduction

Wavelength measurements based on a ratiometric system [1–4] involving edge filters are attractive because of its ease to use, low cost and absence of mechanical movement involved. A typical ratiometric detection system consists of a 3 dB coupler and edge filter, both of which are polarisation sensitive devices. If the system contains more than one polarisation sensitive component connected by standard optical fibres, its global polarisation-dependent loss (PDL) may fluctuate [5] and hence the measured ratio also fluctuates. The fluctuation in the ratio will have an impact on the performance accuracy of the system. The fluctuation arises because of the state of polarisation of the input light to the system may vary randomly [6], for example, because of stress variations in the transmission fibres or change of source etc. Applications such as sensors based on fiber bragg grating (FBG) also change the polarisation state of the input light because of the refractive index variation inside it [7]. A system calibrated at a particular input polarisation state gives errors as the attenuation ratio will be different because of the polarisation dependency of the elements. Prior to the introduction of systems (such as dense wavelength division multiplexing (DWDM)), which demand very high wavelength accuracy, the role of PDL in a ratiometric system was not considered important. DWDM requires an accurate control of each channel's wavelength, for example, the allowable maximal frequency deviation for a DWDM system with a channel spacing of 25 GHz operating at 2.5 Gb/s, the wavelength must be set to within 4–5 GHz or 32–40 pm as defined by ITU-T Recommendation G.692. It has been shown previously that ratiometric wavelength measurement system can achieve an accuracy [2], which allows it to be used for wavelength setting or monitoring in a DWDM system. However, in a system where a prescribed accuracy is required, the effect of errors from a variety of sources must be taken account of. As a contribution to a comprehensive error investigation, in this paper, the error arising from PDL is presented.

All ratiometric wavelength measurement systems contain components that exhibit PDL, such as optical connectors, 3 dB couplers, circulators, WDM multiplexers etc. Several authors have investigated ratiometric measurement systems [1–4, 8]; however, the polarisation dependency of the entire wavelength measurement is not well documented. A small amount of work has been done on the wavelength dependency of PDL for bulk optical devices [9] and optical transmission systems [10]. For a commercially available 3 dB coupler, it is known that PDL is not wavelength flat, but varies with wavelength and is one of the core components of any ratiometric wavelength measurement system together with an edge filter. In this paper, we studied the wavelength inaccuracy contributed from the PDL of the components of a wavelength measurement system based on bend fibre filter. The PDL of the filter arm and its range are calculated theoretically from the individual PDL of the components and an experimental verification has been carried out. The variation in ratio because of PDL and the wavelength error because of this ratio variation is measured, which gives a clear picture of how the accuracy of the system is influenced by PDL, which is essential for any wavelength measurement device.

2 Theoretical model to estimate the range of PDL and ratio fluctuation

In the fibre bend loss filter-based ratiometric wavelength measurement system, the PDL components are the bend fibre filter and the 3 dB coupler. The total PDL of the system is not simply the sum of the contribution of each PDL element. If the polarisation sensitive axis of the 3 dB coupler and the fibre filter are not aligned with each other, the resulting PDL depends on the relative orientation of the PDL axes at each connection. In an all-fibre configuration reported by the authors [2], the PDL will fluctuate in the filter arm as it effectively contains two PDL elements. The total attenuation ratio fluctuation of the system depends on the PDL of both the filter arm and the reference arm.

If $T_{\max}$ and $T_{\min}$ are the minimum and maximum transmission coefficients of an optical element, then PDL can be expressed as $\mathrm{PDL}_{\mathrm{dB}} = 10\ \log_{10}\ (T_{\max}/T_{\min})$. But the more convenient way to express PDL as a three-dimensional vector of length $\Gamma = (T_{\max} - T_{\min})/(T_{\max} + T_{\min})$ [5], If $\Gamma_{3\ \mathrm{dB}}$ and Γ_{bend} are the PDL of the 3 dB coupler and the fibre filter, the net PDL of filter arm can be expressed as [11]

$$\vec{\Gamma}_{3\mathrm{dBbend}} = \frac{\sqrt{1-\Gamma_{\mathrm{bend}}^2}}{1+\vec{\Gamma}_{3\mathrm{dB}}\vec{\Gamma}_{\mathrm{bend}}}\vec{\Gamma}_{3\mathrm{dB}} + \frac{1+\vec{\Gamma}_{3\mathrm{dB}}\vec{\Gamma}_{\mathrm{bend}}\left(1-\sqrt{1-\Gamma_{\mathrm{bend}}^2}\right)/\Gamma_{\mathrm{bend}}^2}{1+\vec{\Gamma}_{3\mathrm{dB}}\vec{\Gamma}_{\mathrm{bend}}}\vec{\Gamma}_{\mathrm{bend}} \qquad (1)$$

The maximum value of the PDL will occur when $\Gamma_{3\mathrm{dB}}$ and Γ_{bend} are parallel and minimum occurs when they are anti-parallel. The maximum and minimum global PDL of the fibre filter arm (Γ_{Gmax} and Γ_{Gmin}) can thus be expressed as

$$\Gamma_{\mathrm{Gmax}} = \frac{\Gamma_{3\mathrm{dB}}+\Gamma_{\mathrm{bend}}}{1+\Gamma_{3\mathrm{dB}}\Gamma_{\mathrm{bend}}} \quad \text{and} \quad \Gamma_{\mathrm{Gmin}} = \frac{|\Gamma_{3\mathrm{dB}}-\Gamma_{\mathrm{bend}}|}{1-\Gamma_{3\mathrm{dB}}\Gamma_{\mathrm{bend}}} \qquad (2)$$

Using this equation, the range of PDL of the filter arm can be predicted and together with the PDL of the reference arm of the system ratio error of the system can be estimated. The maximum variation in the ratio from the calibrated value happens when one arm gives the maximum attenuation and the other gives minimum attenuation for a given state of polarisation. From the expression for ratio of the system [8], where the photodiodes give the integral power over the wavelength range, by knowing the maximum and minimum power at the arms of the system when the polarisation state changes, the maximum possible polarisation-dependent change in ratio of the system for any wavelength can be obtained and is expressed as

$$\Delta R_{\max} = 10\log_{10}\left[\frac{\int P_{1\max}(\lambda)I_{\lambda 0}(\lambda)\mathrm{d}\lambda}{\int P_{2\min}(\lambda)I_{\lambda 0}(\lambda)\mathrm{d}\lambda}\right] - 10\log_{10}\left[\frac{\int P_{1\min}(\lambda)I_{\lambda 0}(\lambda)\mathrm{d}\lambda}{\int P_{2\max}(\lambda)I_{\lambda 0}(\lambda)\mathrm{d}\lambda}\right] \qquad (3)$$

where $P_{1\max}$ and $P_{1\min}$ are the maximum and minimum output power of the filter arm when the polarisation state changes and $P_{2\max}$ and $P_{2\min}$ are that of the reference arm. $I_{\lambda 0}$ is the narrow band input signal with central wavelength λ_0, which in this case is from a tunable laser source. By knowing the variation in ratio, the corresponding wavelength variation can be calculated.

3 Estimation of ratio and wavelength fluctuation and its experimental verification

An all-fibre ratiometric wavelength measurement system based on macrobend fibre filter was built to investigate the ratio and wavelength fluctuation because of PDL. A commercially available fused 3 dB coupler was used to split the input signal into two parts, one to pass through the reference arm and the other to the bend fibre edge filter. The fibre edge filter used has a bend radius of 10.5 mm and 15 turns. This configuration of the fibre edge filter gives a very good discrimination range and measurable wavelength range of 1500–1580nm without signal-to-noise ratio (SNR) effects [8, 12]. The average slope of the edge filter was 0.22 dB/nm. The input power level of the signal to the system was 0 dBm, while there is an insertion loss because of splicing and a 3.3 dB loss (including excess loss) from the coupler. The power level of the signal, which goes to the fibre filter and to the reference arm was approximately −4 dBm. When the wavelength exceeds 1580 nm, the bend fibre arm's output power drops below −30 dBm resulting in a poor SNR, which affects the ratio

doi: 10.1049/iet-opt:20070028

response's linearity. So the measurable wavelength range is effectively limited from 1500 to 1580 nm.

Since the PDL is highly dependent on the bend radius [13], it is very important to maintain a constant radius throughout the measurements. The fibre was rolled on a mandrel with fixed radius to maintain the radius of the fibre filter. The input signal is fed to the splitter through a fibre polarisation controller, which allows for changes in the polarisation state of the input signal. For a wavelength range of 1500–1600 nm, with an interval of 10 nm, the PDL is measured independently for the 3 dB coupler, bend fibre filter and for the combination of the coupler and the filter. As the bend fibre is temperature dependent [14] in the experiment, the temperature in the vicinity of the fibre filter is monitored so that the temperature effects can be determined. The temperature was found to be as $22 \pm 0.3°C$. Based on the known variation of bend loss with temperature for the fibre type in use, this introduces a ratio variation less than or equal to ± 0.018 dB. The electrical noise at the receivers and the power fluctuations of the source used produce an uncertainty of 0.01 dB in the measured PDL when the PDL is measured for the 3 dB coupler alone and the bend fibre filter alone. When these components are combined to form the ratiometric system, the source power fluctuations are cancelled out (independence from input power variations is a major advantage of a ratiometric wavelength measurement system). Thus the uncertainty arises only from the electrical noise in both receivers. As the noise in both receivers is uncorrelated, the ratiometric method cannot remove this source of uncertainty. However, the effect of the noise on the ratio was measured and has a maximum value of 0.003 dB, which is a small value and is hence neglected. The experimental arrangement to measure the PDL and ratio is shown in Fig. 1. The measured PDL of the arms of the 3 dB coupler and the bend fibre filter is shown in Figs. 2*a* and 2*b*. The arm 1 of the 3 dB coupler was the reference arm and arm 2 was connected to the bend fibre filter. The error bar shows the uncertainty in the measurements.

The photodiodes used at the receiver end and the connection fibres are also polarisation dependent but with very small values compared with the other elements. The measured PDL of the photodiodes along with the connection fibres and the fibre polariser are 0.021 and 0.017 dB, respectively, and are included in the PDL values of the components and hence not considered separately in simulation. The measured PDL

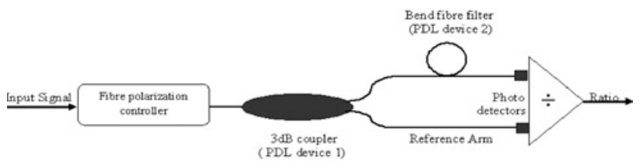


Figure 1 *Experimental arrangement to find the PDL of the system*

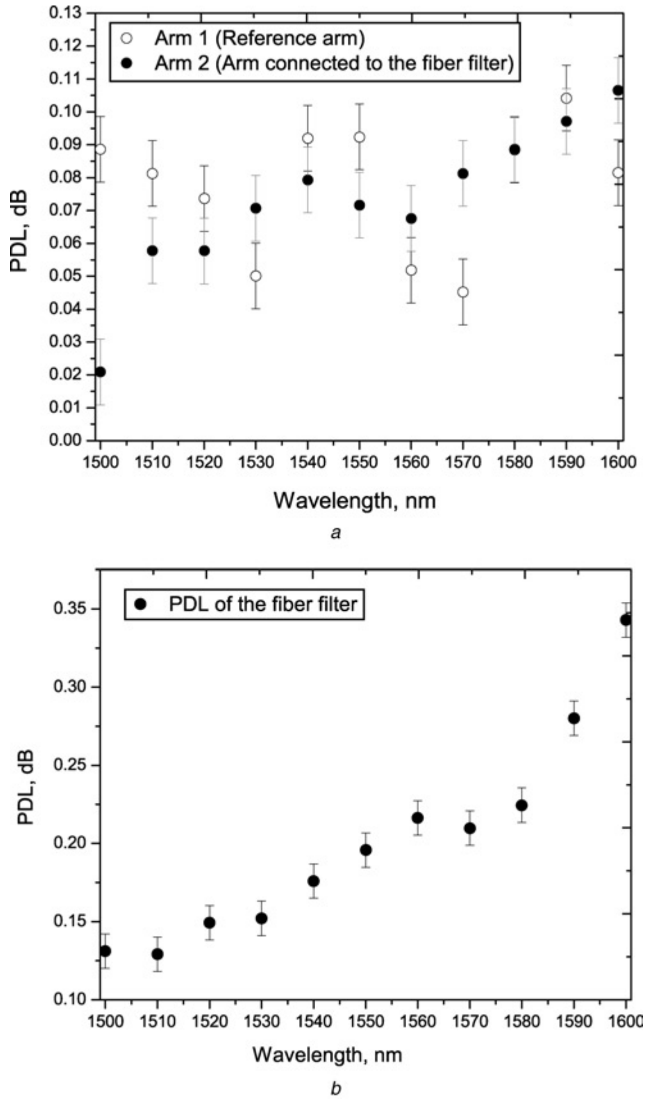


Figure 2 *Measured PDL of the components of the system*

a Measured PDL of the arms of the 3 dB coupler
b Measured PDL of the fibre filter

of the 3 dB coupler, fibre filter and the fibre filter arm includes the PDL of the photodiode, connection fibres and the fibre polarisation controller. The ratio spectrum of the system is also measured at different polarisation states to allow an estimation of the maximum wavelength error from the calibrated value. The shift in the ratio spectral response of the system at different polarisation states gives rise to the variations in the measured wavelength. Fig. 3*a* shows the overall response from 1500 to 1600 nm, which is obtained by tuning the laser from 1500 to 1600 nm with a 1 nm interval, whereas Fig. 3*b* focuses on the response over a narrower wavelength range, 1545–1555 nm, to better illustrate the variation in ratio that occurs with polarisation state changes. The ratio response for polarisation state A is used as the calibrated response, whereas the response curves for the two other states B and C show the variation in ratio response from the calibrated response as the polarisation state changes. For the measured ratio spectrum, the slope is

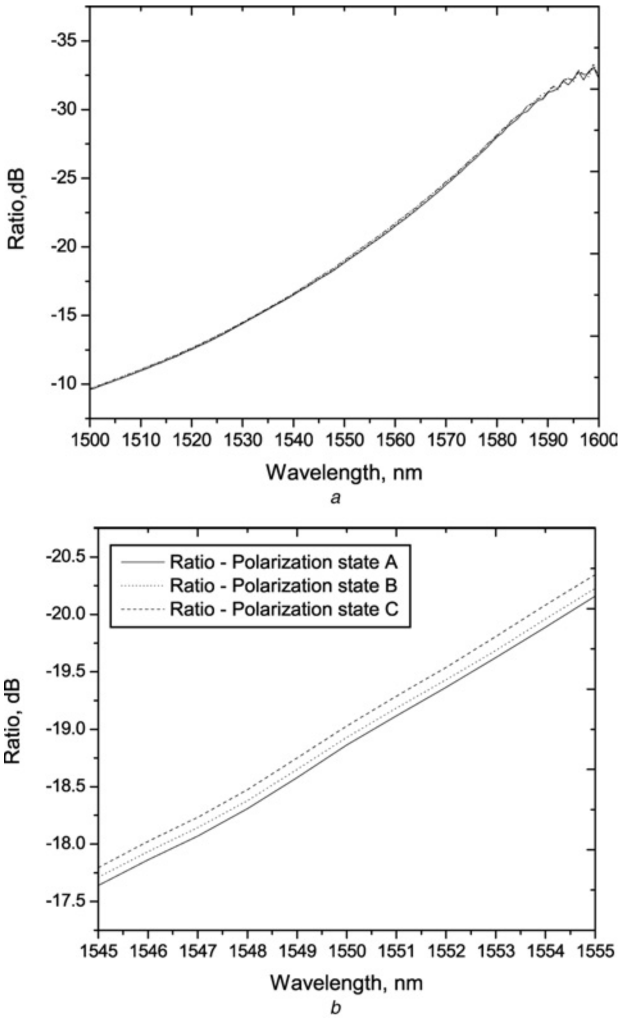


Figure 3 *Overall ratio response and expanded ratio response at different polarisation states*

a Overall ratio response at different polarisation states
b Expanded ratio response showing ratio variation at different states of polarisation for a narrower wavelength range

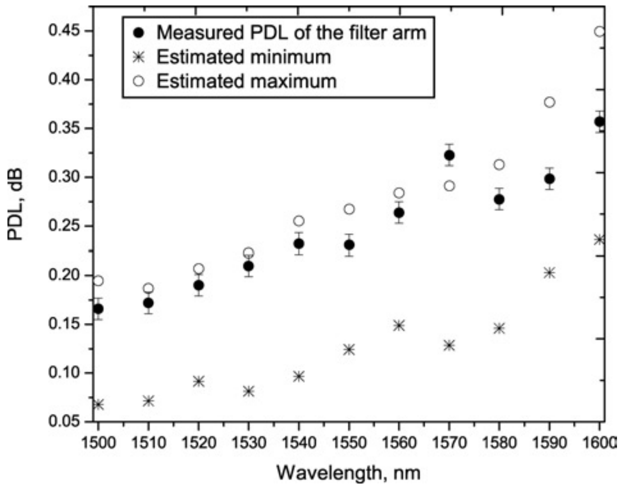


Figure 4 *Estimated maximum and minimum PDL of the filter arm and its comparison with the measured PDL*

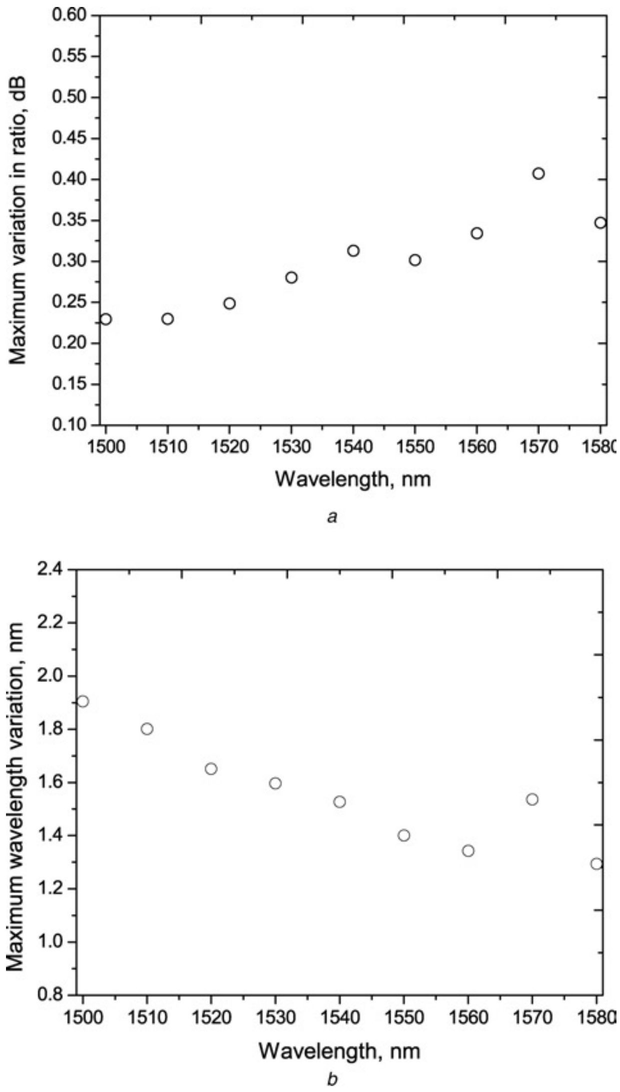


Figure 5 *Estimated maximum variation*

a Estimated maximum variation in the ratio of the system
b Estimated maximum variation in the wavelength of the system

not linear and hence one has to find the local slope to determine the wavelength error.

3.1 Estimation of maximum ratio and wavelength fluctuation

Estimation of the maximum variation in measured wavelength is important as we can determine the system's worst-case performance. The maximum and minimum values of the fluctuation of PDL of the filter arm because of the 3 dB coupler and the fibre filter are calculated using (2). A comparison of the estimated maximum and minimum of the PDL of the filter arm with the measured PDL of the filter arm is shown in Fig. 4. The measured PDL lies within the estimated range. For the system, the combination of both of the arms gives the total ratio variation. The PDL of the reference and filter arms obtained from the experiment provides the maximum and

IET Optoelectron., 2008, Vol. 2, No. 2, pp. 63–68
doi: 10.1049/iet-opt:20070028

Table 1 PDL of the components and the estimated maximum error in ratio and wavelength at 1550 nm

Components contributing to PDL	PDL	Estimated maximum ratio/wavelength error
3 dB coupler (arms 1 and 2)	arm 1(reference arm) −0.09dB, arm 2 (arm connected to fibre filter) −0.07dB	ratio −0.301dB/wavelength −1.402nm
bend fibre filter	0.1958 dB	—

minimum power levels of each arm. Based on that a numerical simulation has been carried out to find the maximum ratio variation and is estimated using (3). The estimated variation in ratio and wavelength of the system is shown in Figs. 5*a* and 5*b*. To estimate the wavelength error, the local slope of the ratio spectrum shown in Fig. 3*a* is calculated with a 5 nm window at 10 nm intervals from 1500 to 1580 nm. The wavelength error, which is a consequence of ratio variation, in practice, depends on the slope of the system, which is low at lower wavelength regions and high at higher, which obviously gives more error at lower wavelengths than higher wavelengths. It is estimated that the maximum wavelength change at 1500 nm is 1.9 nm from the original value, which is the highest. Any measured error in wavelength should be within this range. The PDL of the different components involved in the ratiometric system and the estimated variation in ratio and wavelength at 1550 nm is summarised in Table 1.

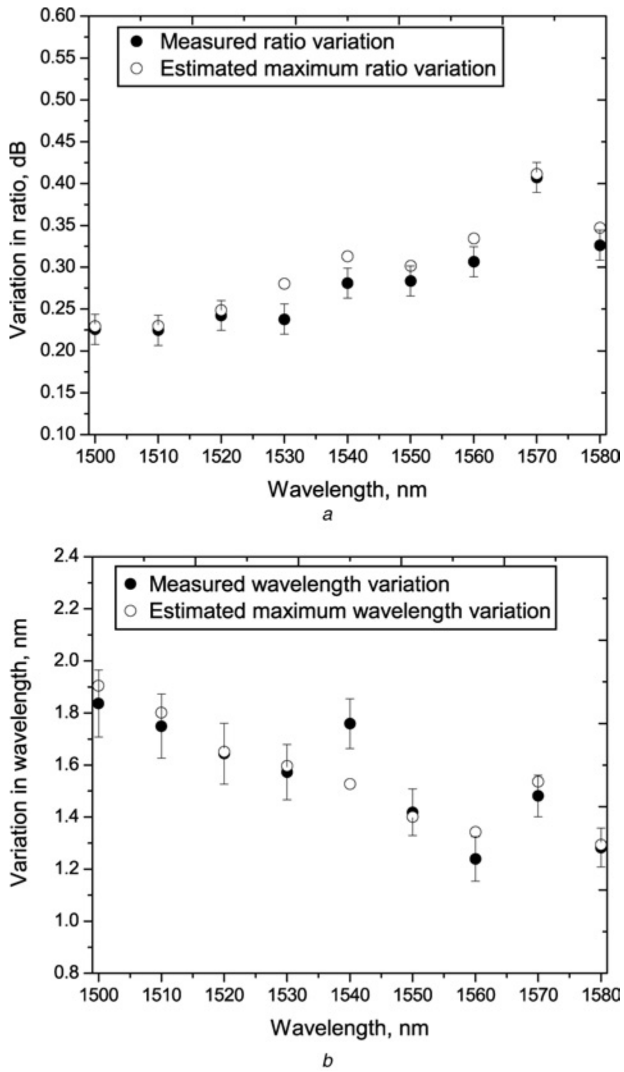


Figure 6 *Variation in the ratio and wavelength of the system because of PDL is measured and its comparison with the estimated maximum variation*

a Comparison of measured ratio error with the estimated maximum ratio error because of PDL
b Comparison of the measured wavelength error with the estimated maximum wavelength error because of PDL

3.2 Experimental verification of ratio and wavelength fluctuation because of PDL

Using the experimental system as shown in Fig. 1, the variation in the ratio and wavelength of the system because of PDL is measured and its comparison with the estimated maximum variation is shown in Figs. 6*a* and 6*b*. The error bars represent the possible variation in the measured ratio and the wavelength error because of the temperature variations monitored during the course of the experiment. It is seen that the ratio variation increases as the wavelength goes higher. As in the estimated case, the wavelength error changes with wavelength because of the difference in slope of the ratio spectrum, which being lower at lower wavelengths gives a greater error at lower wavelengths. In practice, when the measurement system is used for live measurements at any spot wavelength, the system estimates the slope of the ratio response in the vicinity of the spot wavelength. Therefore small irregularities in the calibrated ratio response can result in errors. The discrepancy between the estimated and the measured wavelength variation at 1540 nm originates as a result of these small irregularities in the calibrated response. At 1550 nm, the measured wavelength error was 1.41 ± 0.09 nm. The measured ratio and wavelength variation of the system are well within the estimated limits. The fundamental fact about the fluctuation in attenuation because of PDL, which leads to the variation in ratio and wavelength, is experimentally confirmed with the above results. Without predicting the wavelength error because of PDL of the components used in the system, characterising a system to a wavelength resolution or accuracy of 0.01 nm is meaningless. Thus for determining the accuracy and resolution of the system the

doi: 10.1049/iet-opt:20070028

PDL of the system and its effects on the system has to be determined.

4 Conclusion

The effect of polarisation-dependent loss on macrobend fibre filter-based ratiometric system was discussed. The PDL of the individual components are measured and maximum and minimum limits of the PDL of the filter arm are calculated from that. The measured PDL of the filter arm lies within the estimated limit. The total ratio variation of the system, which comes from the PDL of the filter and reference arms, is measured and compared with the estimated maximum limit. Because of PDL, for a system with an average slope 0.22 dB/nm, the measured wavelength error was 1.41 ± 0.09 nm at 1550 nm. From our investigations, we can conclude that PDL is an important factor in determining the accuracy of a macrobend fibre filter-based ratiometric wavelength measurement system. A recalibration of the system is necessary to avoid the wavelength error and to achieve the accuracy required for systems like DWDM when the source's polarisation state changes.

5 References

[1] RIBEIRO A.B.L., FERREIRA L.A., TSVEKOV M., SANTOS J.L.: 'All-fiber interrogation technique for fiber Bragg sensors using biconical fiber filter', *Electron. Lett.*, 1996, **32**, (4), pp. 382–383

[2] WANG Q., FARRELL G., FREIR T., RAJAN G., WANG P.: 'Low-cost wavelength measurement based on a macrobending single-mode fiber', *Opt. Lett.*, 2006, **31**, (12), pp. 1785–1787

[3] MELLE S.M., LIU K., MEASURES R.M.: 'A passive wavelength demodulation system for guided wave Bragg grating sensors', *IEEE Photonics Technol. Lett.*, 1992, **4**, (5), pp. 516–518

[4] DAVIS M.A., KERSEY A.D.: 'All fiber Bragg grating sensor demodulation technique using a wavelength division coupler', *Electron. Lett.*, 1994, **30**, (1), pp. 75–77

[5] GISIN N.: 'The statistics of polarization dependent losses', *Opt. Commun.*, 1995, **114**, pp. 399–405

[6] VAN WIGGEREN G.D., ROY R.: 'Transmission of linearly polarized light through a single-mode fiber with random fluctuations of birefringence', *Appl. Opt.*, 1999, **38**, (18), pp. 3888–3892

[7] ZHU Y., SIMOVA E., BERINI P., GROVER C.P.: 'A comparison of wavelength dependent polarization dependent loss measurements in fiber gratings', *IEEE Trans. Instrum. Meas.*, 2000, **49**, (6), pp. 1231–1239

[8] WANG Q., FARRELL G., FREIR T.: 'Study of transmission response of edge filters employed in wavelength measurements', *Appl. Opt.*, 2005, **44**, (36), pp. 7789–7792

[9] CRAIG R.M.: 'Accurate spectral characterization of polarization dependent loss', *J. Lightwave Technol.*, 2003, **21**, (2), pp. 432–437

[10] XIE C., MOLLENAUER L.F.: 'Performance degradation induced by polarization dependent loss in optical fiber transmission systems with and without polarization mode dispersion', *J. Lightwave Technol.*, 2003, **21**, (9), pp. 1953–1957

[11] ELAMARI A., GISIN N., PERNY B., ZBINDEN H., ZIMMER C.W.: 'Statistical prediction and experimental verification of concatenations of fiber optic components with polarization dependent loss', *J. Lightwave Technol.*, 1998, **16**, (3), pp. 332–339

[12] WANG Q., FARRELL G., FREIR T.: 'Theoretical and experimental investigations of macro-bend losses for standard single mode fibers', *Opt. Express*, 2005, **13**, (12), pp. 4476–4484

[13] WANG Q., RAJAN G., WANG P., FARRELL G.: 'Polarization dependence of bend loss for a standard singlemode fiber', *Opt. Express*, 2007, **15**, (8), pp. 4909–4920

[14] MORGAN R., BARTON J.S., HARPER P.G., JONES J.D.C.: 'Temperature dependence of bending loss in monomode optical fibers', *Electron. Lett.*, 1990, **26**, (13), pp. 937–939

doi: 10.1049/iet-opt:20070028