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Optimum Design for Maximun Wavelength Resolution for an Edge Filter Based Ratiometric System

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Abstract

This paper provides a straightforward design method for achieving a maximum wavelength resolution for an edge filter based ratiometric system. An analysis of the influence of a range of factors on the resolution of the ratiometric wavelength measurement system was carried out. The investigation shows that, for a given input optical signal and when the working wavelength range is known, it is relatively straightforward to select an optimum slope for the edge filter that will yield a maximum resolution for the system. An experimental verification is carried out using a tunable laser and three macrobending fibre edge filters, with a good match between experimental and simulation results.

Keywords: Ratiometric system, SNR, Edge filter

I Introduction

In 1978 Hill firstly reported fabrication of a Fiber Bragg grating (FBG) [1]. FBGs are widely used in optical communications filtering [2] and in sensing for measurands such as temperature [3], electrical current [4] and temperature compensated pressure [5]. In all these applications, wavelength extraction is an important issue. This could be realised by using either a tunable pulsed laser [6] or a cylindrical piezoelectric ceramic tube (PZT) to translate the wavelength position of a spectral line into a measurable time interval [7]. However these technologies suffer the disadvantage of high cost. Ratiometric wavelength measurement is an attractive technology for interrogating optical wavelength based sensors as a result of several advantages, such as low cost, high speed and high resolution compared to commercial active scanning schemes [8-10]. In a ratiometric wavelength demodulation system, an edge filter is an important component which can be realised by using either a HiBi-PCF Sagnac loop filter [11], or a special designed linearly chirped FBG [12-13], or a single-multiple-single mode (SMS) filter [14]. In order to achieve high wavelength resolution, a simple approach could be to increase the slope of the edge filter to provide a higher ratio versus wavelength slope for the ratiometric system. However in practice it is found that a higher slope for the edge filter will not always result in a higher ratio slope for the system. There is an optimum slope for the edge filter (and thus a maximum wavelength resolution) which is determined by a range of factors such as the slope of the edge filter, the spectral nature of the input optical signal and the working wavelength range. This paper provides a straightforward solution to achieve maximum wavelength resolution for a ratiometric wavelength measurement system. Initially a theoretical model is constructed and then numerical simulations are presented based on the theoretical model. Our investigations show that the slope of the system is influenced by the Signal-to-Noise Ratio (SNR) of the input optical signal along with the working wavelength range of the system and the slope of the edge filter. For a given input optical signal and when the working wavelength range is known, it is relatively straightforward to select an optimum slope for the edge filter that will yield the maximum resolution for the system. Furthermore using the developed theoretical model, for a given ratiometric system edge filter, it is possible to determine the parameters which will maximize the resolution of the system. Finally an experimental verification is also reported with a good match between experimental and simulation results using a tunable laser and macrobending fibre edge filters.

II Theoretical model

The schematic diagram for a ratiometric wavelength measurement system is shown in figure 1.

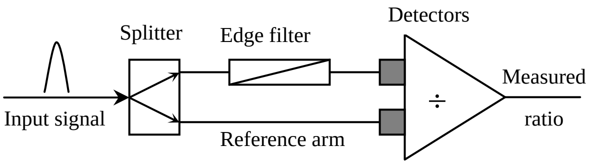

Fig. 1 Schematic diagram of a ratiometric wavelength measurement system

At the end of each output arm of the splitter there is a photodiode to measure the optical power and hence the power ratio of the system. Assuming the splitter is wavelength independent and has a 50:50 split ratio, then the ratio of the outputs of the two photodiodes at a wavelength λ_0 is

$$R(\lambda_0) = -10\log_{10}\left[\frac{\int I_{\lambda_0}(\lambda)T(\lambda)d\lambda + N_e}{\int I_{\lambda_0}(\lambda)d\lambda + N_r}\right] \quad (1)$$

where $I_{\lambda_0}(\lambda)$ is the input signal, $T(\lambda)$ is the transmission response of an edge filter, N_e and N_r are the background noise of the photodiodes at the output of the edge filter and reference signal arms respectively.

It is known that the wavelength resolution of the system can be expressed as

$$resolution = \frac{\Delta R(\lambda)}{m_R(\lambda)} \quad (2)$$

$$m_R(\lambda) = \frac{dR}{d\lambda} \quad (3)$$

where $m_R(\lambda)$ is the slope of $R(\lambda)$, the ratio response of the system, $\Delta R(\lambda)$ is the power measurement resolution of the photodiode detectors and associated electronics. In order to increase the wavelength resolution, an effective approach is to increase the slope of the system, $m_R(\lambda)$. However $m_R(\lambda)$ will not always increase in proportion to the slope of the edge filter. This is a result of a number of factors such as the value of source SNR, photodiode noise, input power and signal power spectral density. A means to select a maximum value of $m_R(\lambda)$ is very important in order to achieve a maximum wavelength resolution and accuracy.

A starting point for the analysis is to determine a mathematical description of the optical source signal. Figure 2 shows on the one graph three measured spectra (the tunable laser was set in turn to three different centre wavelengths 1500, 1550 and 1600 nm). Each measured spectrum in figure 2 is also accompanied by a fitted function. The reason a fitted function is used is because the noise floor in figure 2 is not wavelength flat and thus cannot simply be expressed by a fixed value, so in order to take account of this, it is necessary to use such a fitted function in the simulations to describe the tunable laser signal. The fitted function can be expressed as

$$10\log_{10}\left[I_{\lambda_0}(\lambda)\right]=\begin{cases}10\log_{10}\left\{\exp\left[-4\ln 2\left(\dfrac{\lambda-\lambda_0}{\Delta\lambda_0}\right)^2\right]\right\} & |\lambda-\lambda_0|\le\Omega \\ -SNR+S(\lambda)-S(\lambda_0) & |\lambda-\lambda_0|>\Omega\end{cases} \qquad (4)$$

where the signal is assumed to have a Gaussian power spectral density with a -3dB spectral width $\Delta\lambda_0$ and centre wavelength λ_0. The parameter *SNR* is the signal-to-noise ratio of the optical signal, and Ω is determined by the nature of the optical source with a given noise level, which can be expressed as [9]

$$10\log_{10}\left\{\exp\left[-4\ln 2\left(\frac{\Omega}{\Delta\lambda_0}\right)^2\right]\right\}=-SNR \qquad (5)$$

$S(\lambda)$ is the fitted function to the noise and can be expressed in our case as

$$S(\lambda)=195.7\lambda-0.21031\lambda^2+1.00305\times10^{-4}\lambda^3-1.7903\times10^{-8}\lambda^4 \qquad (6)$$

A simple case for the transmission response of edge filter $T(\lambda)$ in the wavelength range from λ_1 to λ_2 is a linear function as expressed below:

$$-10\log_{10}[T(\lambda)]=-10\log_{10}[T(\lambda_1)]+m(\lambda-\lambda_1) \qquad (7)$$

Where *m* is the slope of the edge filter.

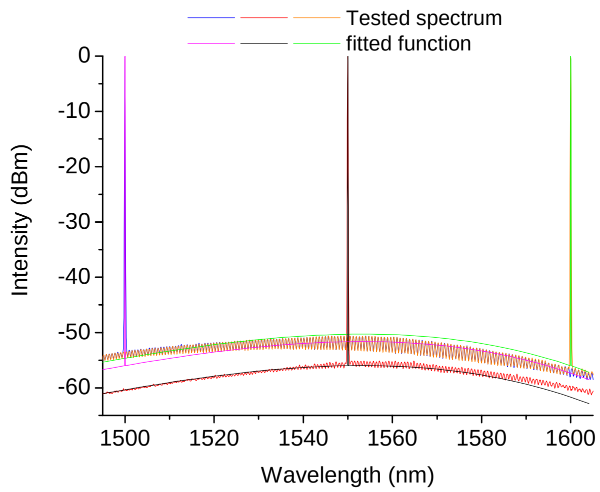

Fig. 2 Measured spectrum of a tunable laser and fitted function in wavelength range from 1495 to 1605 nm

III Numerical simulations

It was shown above that $m_R(\lambda)$ in equation (2) is a very important factor that influences the wavelength resolution of a ratiometric system. To investigate the influence of SNR on the system slope, a number of simulations were carried out. Figure 3 shows the simulation results for the ratiometric system at different SNRs as a function of both the output ratio and also the slope of the system $m_R(\lambda)$ versus wavelength. In our simulation, the parameters used are set as: baseline loss *10 dB*, background noise of photodiode $N_e=N_r=-90$ *dBm*, input peak power *-10 dBm/nm*, $\Delta\lambda_0=0.05$ *nm*, $\lambda_1=1495$ *nm* and $\lambda_2=1605$ *nm*.

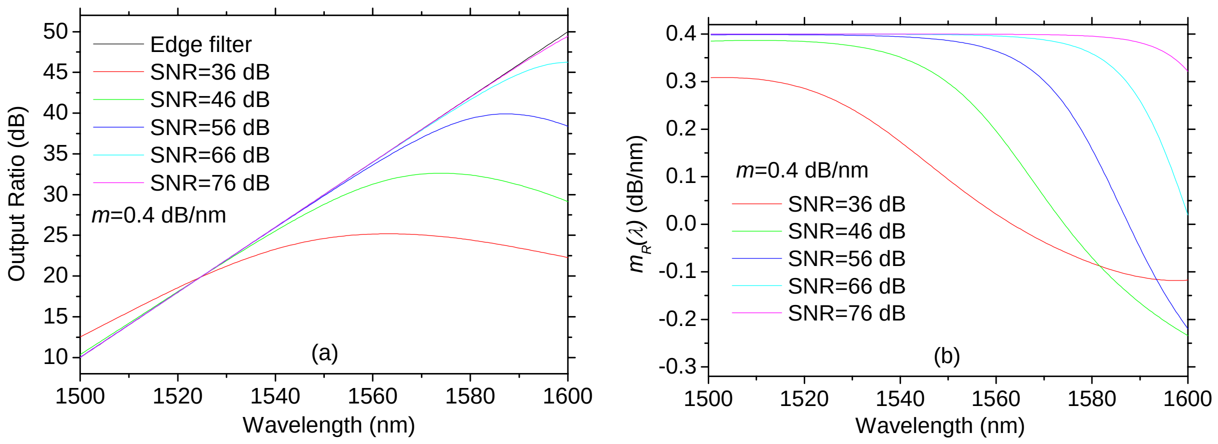

Fig. 3 Simulated result for the output ratio and $m_R(\lambda)$ vs. wavelength with different SNR

Figure 3 shows that the system slope $m_R(\lambda)$ decreases as wavelength increases. At a certain wavelength, the higher the SNR, the higher the system slope $m_R(\lambda)$. This indicates that improving the SNR of optical source is an effective way to improve the resolution of the ratiometric system.

Simulation investigations for $m_R(\lambda)$ vs. wavelength with different slopes for the edge filter were also carried out as shown in figure 4.

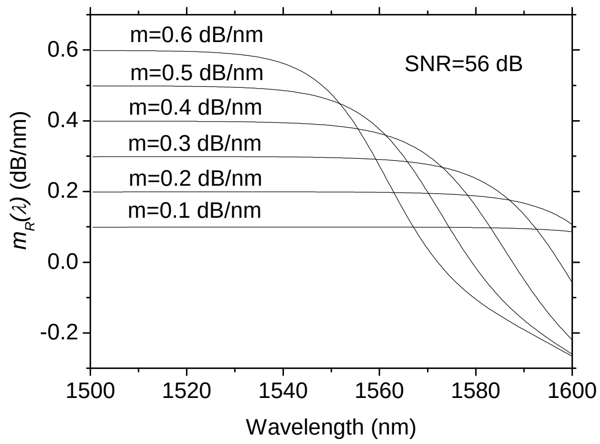

Fig. 4 Simulated result of $m_R(\lambda)$ vs. wavelength with different slope of edge filter

As shown in figure 4, the slope of the ratiometric system $m_R(\lambda)$ decreases as wavelength increases regardless of the slope *m* of the edge filter. However the scale of decrease is significantly different for different values of *m*. Equation (2) indicates that for a certain wavelength, the larger the value of $m_R(\lambda)$, the higher the resolution of the system. For a given wavelength range, the worst-case or lowest slope occurs at the top end of the range. The choice of slope is based on a compromise between achieving the highest resolution and the widest wavelength range. For example for a wavelength range from 1500 to 1560 nm using an edge filter with a slope of 0.5 dB/nm, the worst-case resolution occurs at a wavelength of 1560 nm. However a system using an edge filter with a slope of 0.5 dB/nm, will nevertheless offer the highest resolution over the full range, better than that achieved by using any of the other edge filters with slopes of 0.6, 0.4, 0.3, 0.2 and 0.1 dB/nm. This situation changes for a wavelength range from 1500 to 1600 nm. In this case, system using an edge filter with 0.2 dB/nm slope offers the highest resolution over this range, higher than that achieved using an edge filter with any of four other slopes.

A further investigation of the effect of SNR on the ratiometric system slope $m_R(\lambda)$ as a function of the edge filter slope were also carried out for a wavelength ranges from 1500 to 1540 and 1500 to 1560. As the worst case slope will occur at the top end of a given range, the results were calculated at 1540 nm and 1560 nm and are shown in figure 5.

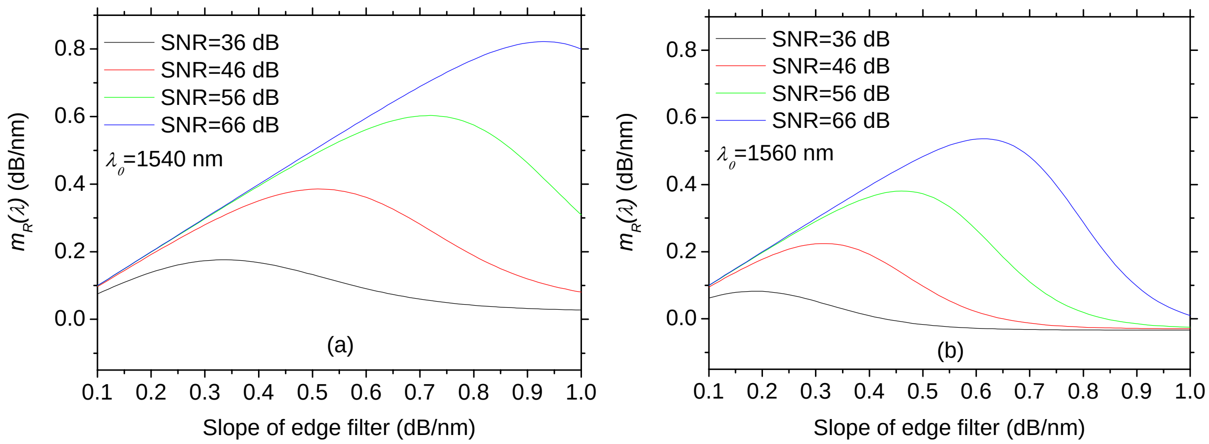

Fig. 5 Simulated result of $m_R(\lambda)$ vs. slope of edge filter at different wavelength

Figure 5 shows that for a certain wavelength, there is an optimum slope for the edge filter which will give a maximum slope and hence a maximum wavelength resolution for the ratiometric system. As shown in figure 5(a), at a wavelength of 1540 nm, the optimum slope of the edge filter is around 0.35 ($m_R=0.18$), 0.51 ($m_R=0.39$), 0.72 ($m_R=0.60$) and 0.91 ($m_R=0.82$) dB/nm corresponding to SNRs of 36, 46, 56 and 66 dB respectively. However at a longer wavelength of 1560 nm as shown in figure 5(b), the optimum slope of edge filter drops to around 0.19 ($m_R=0.08$), 0.30 ($m_R=0.22$), 0.46 ($m_R=0.38$) and 0.61 ($m_R=0.54$) dB/nm corresponding to SNRs of 36, 46, 56 and 66 dB respectively. From figure 5 one can conclude that the higher the SNR, larger values of the slope of the edge filter can be used and hence the higher the resolution one could achieve for the ratiometric system. For a certain SNR, the shorter the upper limit of the wavelength range, a higher resolution is achieved by using a larger slope of edge filter.

The analysis above shows that for a certain wavelength range, once the parameters of the optical source are fixed, there is an optimum slope for the edge filter used in a ratiometric system which can achieve the best resolution. In summary although one could use an edge filter whose slope is larger than the optimum value, the resolution of a ratiometric system at the maximum wavelength will be worse than that using an edge filter with an optimum slope.

IV Experiments

An experimental investigation was carried out by using a tunable laser and three edge filters. The spectrum of the tunable source (OSICS ECL-1560) is measured with an optical spectrum analyzer (OSA, Agilent 86142B) is shown in Figure 2. The 3 dB spectral width of the tunable laser is around 0.05 nm. The tunable laser has three output options for SNRs of 50, 56 and 60 dB respectively and the edge filters used in the experiments are marcobending single mode fibre SMF28 filters similar to those in [9]. The experimental results are shown in figure 6.

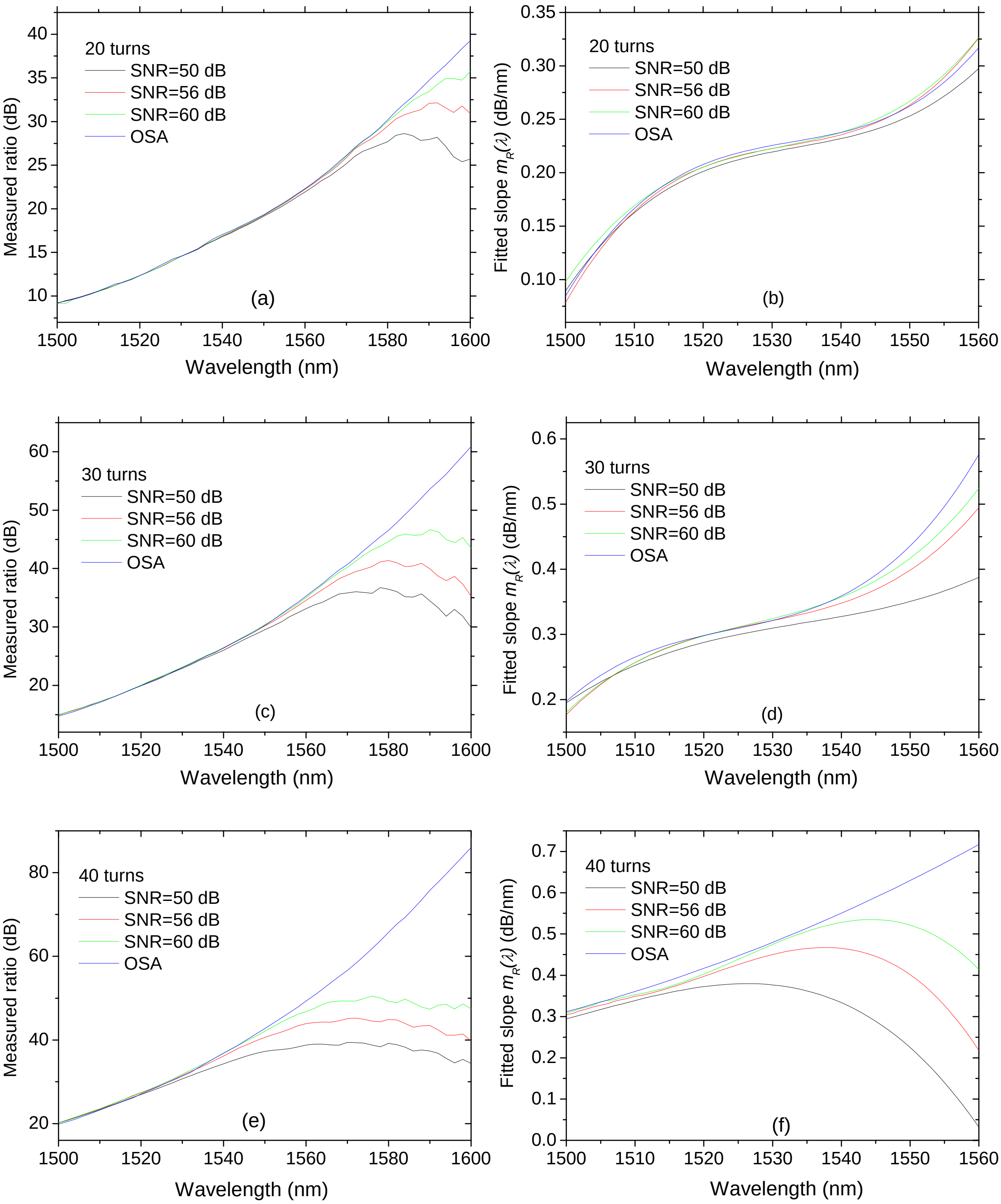

Fig. 6 Measured results with (a-b) 20, (c-d) 30 and (e-f) 40 turns of macrobending SMF28 filters

Figure 6(a) (c) and (e) show that as the SNR decreases from 50 to 60 dB, the deviation of the measured ratio from the transmission response of the edge filter measured by the OSA becomes significant, especially at longer wavelengths. This verifies the earlier analysis and conclusion, as shown in figure 3, that a higher source SNR will mean a better system ratio performance. In order to derive the slope values of the measured ratio, it is necessary to fit the measured ratio to a function and determine the derivative of the function. Since the random variation of the measured ratio is large when the wavelength is longer than 1560 nm, in order to get a well fitted function, function fitting was only carried out up to 1560 nm. The fitted slope (derivative of the fitted function) is shown in figure

6(b) (d) and (e). From figure 6(b) (d) and (e), one can firstly see that the slope of edge filter is not a constant and increases as wavelength increases. Secondly when the slope of the edge filter is relatively small (20 turns), the fitted slope of the measured ratio is close to that of the edge filter (measured using an OSA) for all three SNRs of 50, 56 and 60 dB. However as the slope of the edge filter increases (30 and 40 turns), the fitted slope of the measured ratio deviates from the edge filter slope – the lower the SNR, the higher the deviation. To illustrate this further Figure 7 shows the fitted slope for marcobending SMF filters with three different turns of 20, 30 and 40 turns, for the same SNR of 50 dB.

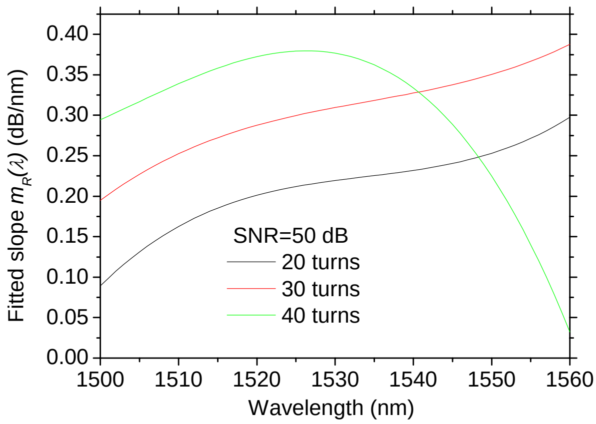

Fig. 7 Fitted slope of the measured ratio with different turns of macrobending SMF28 filters for the same *SNR=50 dB*

From figure 7, it is clear that it is not the case that the higher the edge filter slope, the higher the measured slope of the system (and thus the resolution). At wavelengths shorter than 1536 nm, the system with 40 turns has the largest slope in the three curves. However when the wavelength is longer than 1550 nm, the system with 40 turns has smallest slope. This confirms that the choice of slope is based on a compromise between achieving the highest resolution and the widest wavelength range. To illustrate the effect of slope changes, an incremental step change of 0.1 nm with *SNR=50* dB at wavelength 1530 and 1550 nm are applied to the ratiometric system over a period of 20 s for each wavelength. The measured ratio variations vs. time are shown in figure 8.

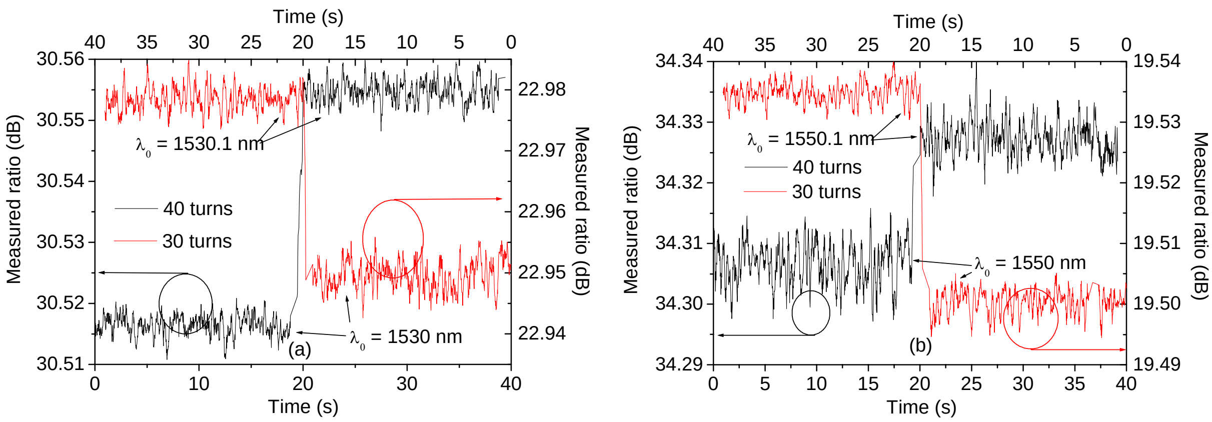

Fig. 8 Measured ratio variation for step change of 0.1 nm at wavelength (a) 1530 nm and (b) 1550 nm with 30 and 40 turns respectively

Figure 8(a) shows that at a wavelength 1530 nm, the resolution of the interrogation system with 40 turns' marcobending SMF filter is higher than that with 30 turns. However this case is reversed at wavelength 1550 nm as shown in figure 8(b). This is consistent with the predicted results.

V Conclusions

Ratiometric wavelength measurement is a cost effective technology to extract wavelength information. How to achieve high wavelength resolution is a key issue for this technology. Intuitively a straightforward view is that the higher the slope of the edge filter, the higher the ratio slope system. However in practice it is found that this is not the case. The maximum slope of the ratiometric system is determined by not only the slope of the edge filter, but also by the SNR of the input optical signal, along with the working wavelength range of the system. This paper provides a solution for achieving maximum resolution for the ratiometric wavelength measurement system and experiments have verified the method with a good match between experimental and simulation results.

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