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Ratiometric Wavelength Monitor Based on Singlemode-Multimode-Singlemode Fiber Structure

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Ratiometric wavelength monitor based on singlemode-multimode-singlemode fiber structure

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Abstract

An all-fiber ratiometric wavelength monitor for optical wavelength measurement is proposed and is investigated theoretically and experimentally. Two edge filters with opposite slope spectral responses based on singlemode-multimode-singlemode (SMS) fiber structures are developed. A ratiometric wavelength measurement system employing the developed SMS edge filters demonstrates a high discrimination range of 20.41 dB and a potential wavelength measurement resolution of 10 pm over a wavelength range from 1530 to 1560 nm.

1. Introduction

A wavelength monitor is a key component for many optical systems such as multi-channel dense wavelength-division multiplexing (DWDM) optical communication systems and fibre Bragg grating (FBG) based optical sensing systems. A FBG-based optical sensing system requires a wavelength demodulation system capable of accurately estimating the wavelength shift in the reflected light from an FBG element induced by strain or temperature changes.

Wavelength measurement or monitoring can be implemented using a ratiometric power measurement technique. A ratiometric wavelength monitor usually consists of a splitter with two outputs to which are attached an edge filter arm with a well defined spectral response and a reference arm. Alternatively, two edge filters arms with opposite slope spectral responses can be used. The use of two opposite slope edge filters can increase resolution of the ratiometric system [1]. Such a ratiometric wavelength monitor scheme converts the wavelength measurement into a signal intensity measurement. Compared with a wavelength-scanning-based active measurement scheme, it has the advantages of a simple configuration, the potential for high-speed measurement and the absence of mechanical movement. The main element of the ratiometric scheme, the edge filter, can be implemented by either a bulk thin filter [1], a fiber grating [2], biconical fiber couplers [3], or a bending fiber [4, 5]. An all-fiber edge filter has several advantages by comparison to bulk filters, for example, ease of interconnection, mechanical stability and low polarization sensitivity [6].

Singlemode-multimode and singlemode-multimode-singlemode (SMS) fiber structures have been investigated for use in several applications e.g. a fiber lens, a displacement sensor, a refractometer, a bandpass filter and an edge filter [7-11]. Based on our previous investigation [11], this paper proposes and demonstrates a ratiometric wavelength monitor using two edge filters consisting of SMS fiber structures with opposite slope spectral responses. This configuration has the advantage that it can achieve opposite slope spectral responses with a high discrimination range compared to a fiber bend loss edge filter [4, 5] which can only provide a single slope spectral response. Additionally the discrimination range achievable for a fiber bend loss edge filter is limited by the minimum practical bend radius.

2. Proposed configuration and its design

Fig.1.a shows the schematic configuration of a ratiometric wavelength monitor. It contains of a splitter and two edge filter arms based on a pair of SMS fiber structures. The SMS edge filter structure is shown in Fig. 1.b. It is formed by splicing a step-index multimode fiber (MMF) between two standard singlemode fibers (SMF). The target spectral responses of the two arms are shown in the Fig.1.c and the corresponding ratio of the two outputs over the wavelength range is presented in the Fig.1.d. The wavelength of an unknown input signal can be determined by measuring the power ratio between the two arms, assuming a suitable calibration has taken place.

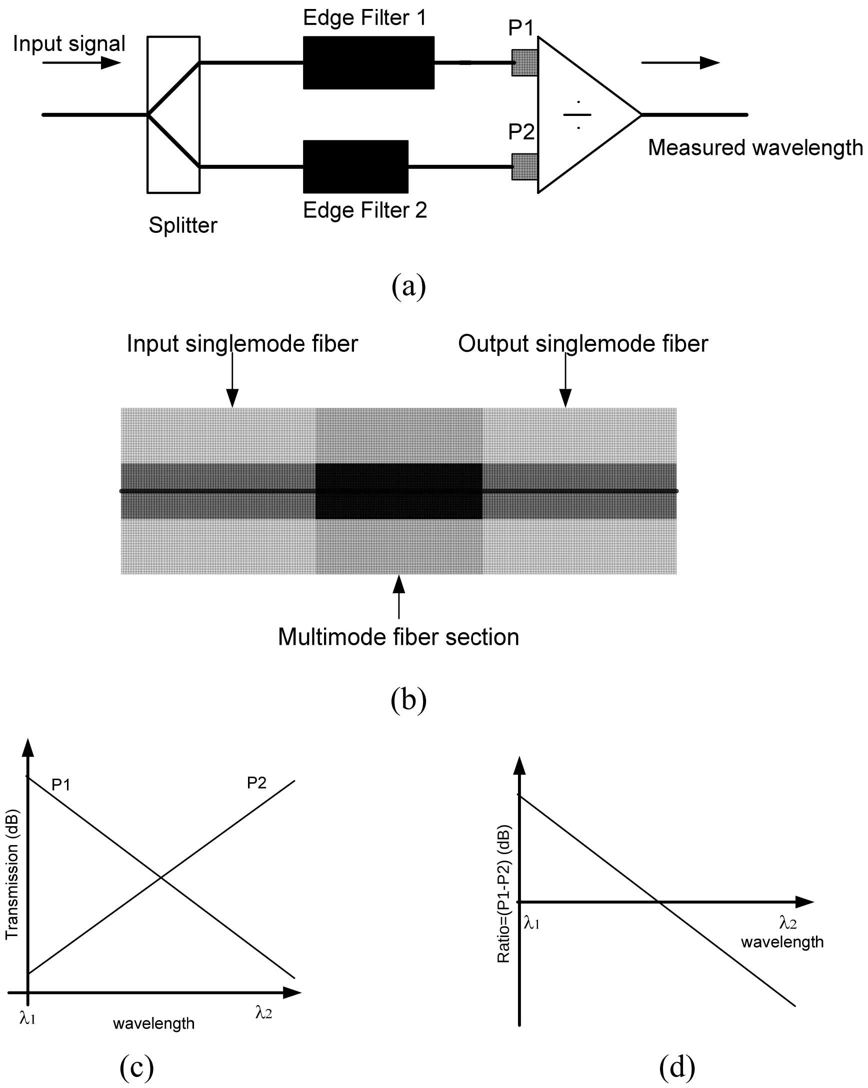

Figure 1 Schematic structure of (a) a ratiometric wavelength measurement system (b) an SMS fiber-based edge filter (c) the desired spectral response of the two edge filter arms and (d) the output ratio between the two arms.

The operating mechanism of the edge filter can be described as follows: the light field propagating along the input SMF enters the MMF section and excites a number of guided modes in the MMF. Interference between the different modes occurs while the light field propagates through the MMF section. By choosing a suitable length for the MMF section, the light is coupled into the output SMF in a wavelength dependent manner due to interference. The input-to-output transmission loss is expected to increase/decrease monotonically, as the wavelength of the propagating light increases in a certain wavelength range.

A modal propagation analysis (MPA) using cylindrical coordinates as in [7, 8, 12] is employed to investigate the propagation of light in the MMF section. The input light is assumed to have a field distribution $E(r,0)$ due to the circular symmetry characteristic of the fundamental mode of the SMF. The input field can be decomposed into the eigenmodes $\{LP_{nm}\}$ of the MMF when the light enters the MMF section. Only the $LP_{0\nu}$ modes can be excited because of the circular symmetry of the input field and assuming ideal alignment of the fibre axes of the SMF and the MMF [7, 8, 12]. Defining the field profile of $LP_{0\nu}$ as $F_\nu(r)$, (the eigenmodes of the multimode fiber are normalized as $\int_0^\infty |E(r,0)|^2 rdr = \int_0^\infty |F_\upsilon(r)|^2 rdr$, $\nu = 1,2,3,...m$, where m is the number of modes in the MMF) the input field at the MMF can be written as:

$$E(r,0) = \sum_{\nu=1}^{m} c_\nu F_\nu(r) \tag{1}$$

where c_ν is the excitation coefficient of each mode. The coefficient c_ν can be calculated by an overlap integral between $E(r,0)$ and $F_\nu(r)$

$$c_\nu = \frac{\int_0^\infty E(r,0) F_\nu(r) rdr}{\int_0^\infty F_\nu(r,0) F_\nu(r) rdr}. \tag{2}$$

As the light propagates in the MMF section, the field at a propagation distance z can be calculated by

$$E(r,z) = \sum_{\nu=1}^{m} c_\nu F_\nu(r) \exp(j\beta_\nu z) \tag{3}$$

where β_ν is the propagation constant of each eigenmode of the MMF.

The transmission loss in dB can be calculated by using overlap integral method between $E(r,z)$ and the eigenmode of the output SMF $E_0(r)$ as in [9]

$$L_s(z) = 10 \cdot \log_{10}\left(\frac{\left| \int_0^\infty E(r,z) E_0(r) rdr \right|^2}{\int_0^\infty |E(r,z)|^2 rdr \int_0^\infty |E_0(r)|^2 rdr} \right). \tag{4}$$

To design the SMS based edge filter, the MMF length needs to be determined. Our study shows that at a re-imaging distance (the transmission loss will reach a peak at a self image of the input) is highly wavelength dependent. If re-coupling into the SMF takes place at the re-imaging distance, then the MMF section of the SMS structure has by definition a length equal to the re-coupling distance and operates as a bandpass filter as in [10, 12]. However for the purpose of designing an edge filter, the bandpass response can be considered as two spectral responses, on the either side of a center wavelength. Consequently the device can behave as an edge filter for a selected wavelength range. Two SMS edge filters with opposite slope spectral responses within a given wavelength range (see Fig.1.c) can be obtained by choosing two bandpass filters with appropriate center wavelengths.

To investigate the wavelength dependence at the re-imaging distance, a numerical calculation is carried out. A standard SMF28 is chosen as the SMF, for which the parameters are: the refractive index for the core and cladding is 1.4504 and 1.4447, respectively (at a wavelength of 1550 nm) and the radius of core is 4.15 μm. Furthermore to illustrate the dependence of the transmission response on the MMF core radius, we use MMFs with core radii of 25, 52.5, 75 and 100 μm. Fig.2 presents the wavelength dependence of the transmission loss at the re-imaging distance for the different MMF cores radii. It can be seen as expected that the overall response is a bandpass response centered on 1550 nm. On either side of the center wavelength each bandpass response can be viewed as consisting of a combination of two spectral responses with opposite slopes over a limited wavelength range. For example from Fig.2, for a MMF radius of 52.5 μm and a length of 42.87 mm, a positive slope edge filter response exists between 1530 and 1550 nm and a negative slope edge filter response exists between 1550 and 1580 nm The peak wavelength of the bandpass filter can be tuned by changing the MMF length as mentioned in [10, 12] and by doing so the range of wavelengths over which an edge filter response exists is also altered. By choosing two bandpass filters with appropriate center wavelengths it is possible to arrange for an intersection of two edge filters with opposite slopes within a given wavelength range. Also from Fig.2 the discrimination range of the edge filters created by appropriate choice of center wavelengths can be controlled by changing the MMF core size. The discrimination range in dB increases as the core size of the MMF increases, but the usable wavelength range decreases. As an example for r = 25 μm, the discrimination range of the positive slope of edge filter is about 7 dB from 1500 to 1550 nm by comparison to r = 100 μm, where the discrimination range is about 20 dB from 1538 to 1550 nm.

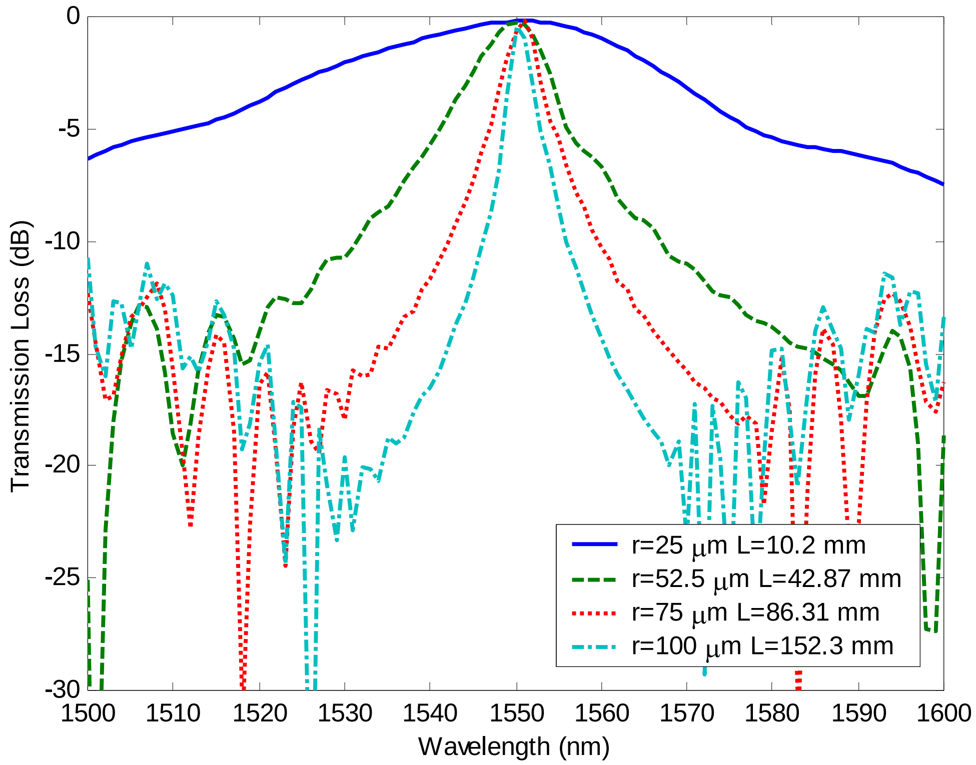

Figure 2 Spectral responses at re-imaging distance for different core radii and MMF section lengths.

3. Design and experimental results

As an example to illustrate the design process, a target wavelength range for wavelength measurement from 1530 to 1560 nm is chosen. This range is chosen as it corresponds to the typical center wavelengths for many FBG sensors. Based on the proposed configuration in Fig.1.a and the design approach above, the two SMS edge filters are designed. An MMF type AFS105/125Y is chosen, for which the parameters are: refractive index for the core and cladding is 1.4446 and 1.4271, respectively, with a core radius r = 52.5 μm. This fibre type was chosen based on the results from the previous section where it is shown that there is a trade-off between the slope of the edge filter response and the usable wavelength range. A core radius r = 52.5 μm (in Fig.2) can provide an edge filter response 30 nm wide with a reasonable discrimination range. As mention above, for the specified wavelength range, two opposite response slope edge filters (SMS-1 and SMS-2) can be obtained by designing two bandpass filters with peak wavelengths: ≤1530 nm and ≥1560 nm, respectively. Based on our calculation for SMS-1, peak wavelengths from 1520 to 1530 nm correspond with the MMF length L = 43.7 to 43.4 mm, respectively. For SMS-2, peak wavelengths from 1560 to 1570 correspond with the MMF length L = 46.625 to 42.42 mm. We found suitable peak wavelengths for the targeted wavelength range are 1523 nm and 1560 nm with the corresponding MMF lengths are L = 43.6 mm and L = 42.625 mm for the SMS-1 and SMS-2, respectively. The peak wavelength 1523 nm and 1560 nm are chosen for the two SMS edge filters because their transmission loss responses have a suitable linear spectral response over the targeted wavelength range of 1530 to 1560 nm. The calculated transmission loss by using (4) for the designed SMS edge filters is shown in Fig.3. As shown in Fig.3, the calculated negative slope response of the SMS-1 structure 1530 to 1560 nm has a transmission loss from -5.73 to -15.76 dB, respectively. The calculated positive slope response of the SMS-2 structure from 1530 to 1560 nm is -13.22 to -0.29 dB, respectively.

For the purpose of experimental verification of the performance of the edge filters the SMS structures were fabricated by using a Fujikura CT-07 cleaver and a Sumitomo type-36 fusion splicer. For each SMS structure the process is the same. Firstly, the input SMF and the input end of the MMF are cleaved and spliced together. The cleaver is then used again to cleave the unterminated end of the MMF fibre so that its length is set to the desired value. Finally the output end of MMF section is spliced to the cleaved end of the output SMF.

The spectral response of each fabricated filter is measured using a tunable laser and optical spectrum analyzer (OSA). The measured results are shown in Fig.3 and show a good agreement with calculated results. For operation as edge filters over the wavelength range 1530 to 1560 nm the measured negative slope of SMS-1 and positive slope of SMS-2 are -5.09 to -15.71 dB and -13.16 to -1.75 dB.

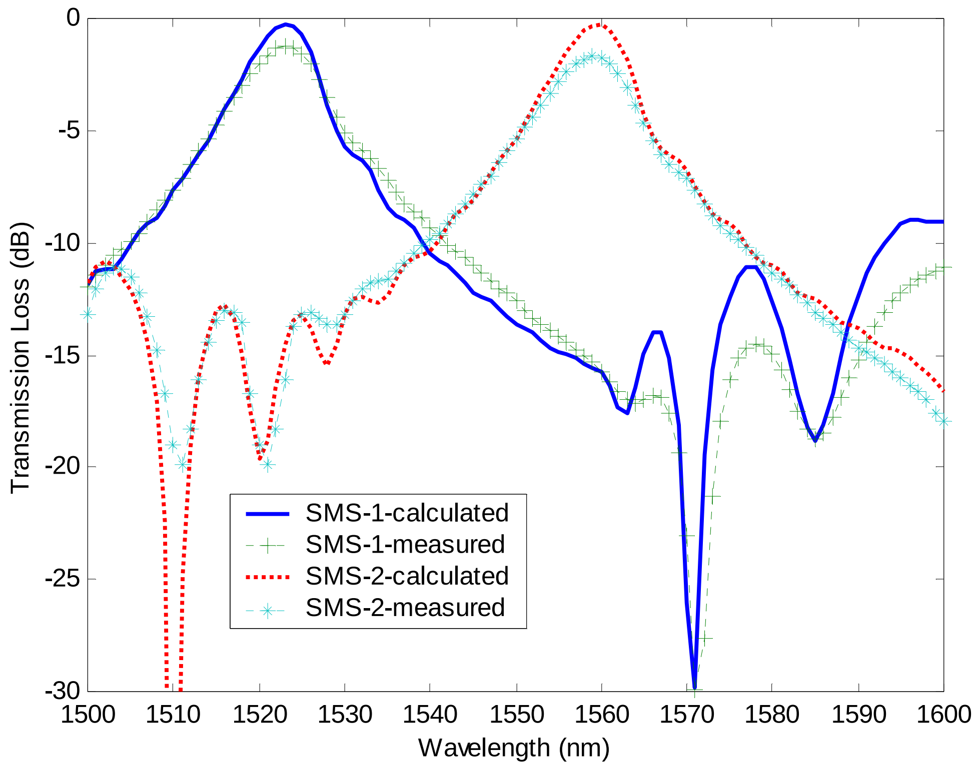

Figure 3 Calculated and measured spectral responses of the SMS edge filters

To demonstrate the use of the edge filters in a functioning wavelength measurement system a ratiometric measurement system is built as shown in Fig.1a. The input signal is split into two equal intensity signals using a 3 dB fiber splitter. One signals passes through SMS-1 and the other passes through SMS-2. A high speed dual channel power meter is placed at the ends of both arms. Fig.4 shows the measured ratio of the optical power. The ratio measured between 1530 to 1560 nm has a linear slope with a discrimination range of 20.41 dB from 7.72 to -12.69 dB which is suitable for wavelength measurement.

Finally the minimum wavelength shift or resolution of the developed ratiometric system is also investigated. In order to investigate the resolution, the tunable laser is used to provide an input signal and the corresponding output ratio is recorded. The minimum tuning step for the laser used is 10 pm. The source wavelength is set to 1540 nm and is tuned by successively increasing increments of 10, 20 and 30 pm. The dual channel power meter is used to sample the SMS outputs for 6-7 s without averaging and the ratio in dB of the power levels is determined for each sample with a sampling rate 50 measurements/second. Fig. 5 shows the complete time series of the measured ratio values as a function of sample time and the wavelength increments. From Fig. 5, it is clear that the minimum detectable change in the wavelength is better (lower) than 10 pm.

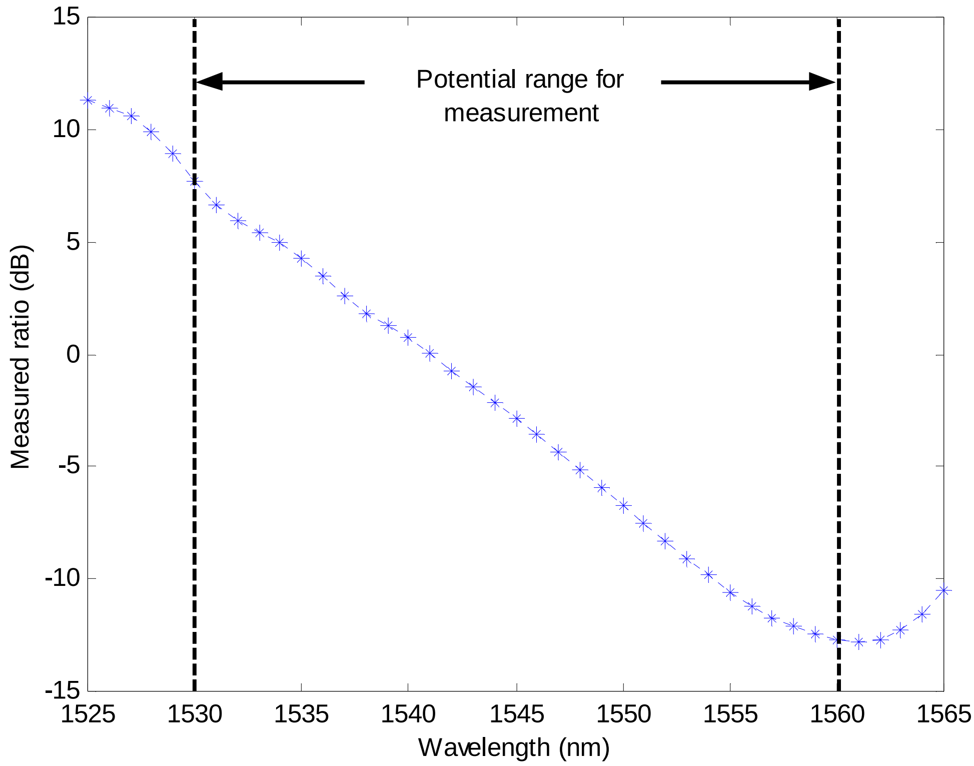

Figure 4 Measured ratio

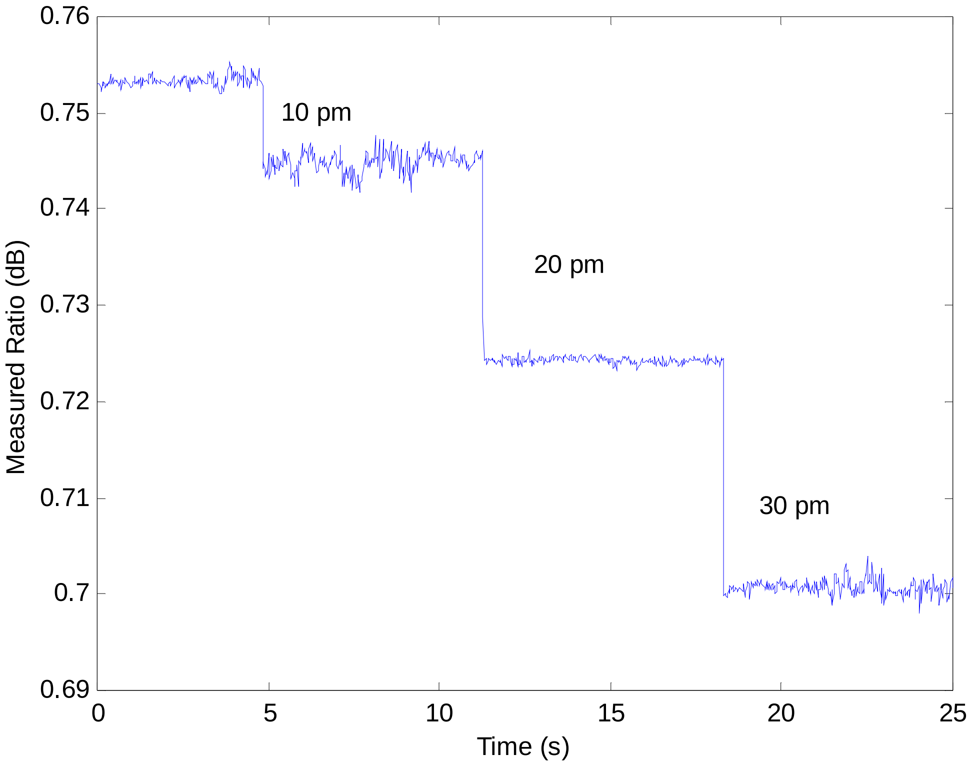

Figure 5 Measured ratio as the wavelength is tuned

4. Conclusion

In this paper we have proposed and demonstrated a ratiometric wavelength monitoring scheme based on a pair of SMS-fiber structures. The two opposite spectral response edge filters used are realised by a pair of SMS-fiber structures. When applied in a ratiometric wavelength measurement, a discrimination range of 20.41 dB in the wavelength range 1530 to 1560 nm and a resolution better than 10 pm have been demonstrated.

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