2012

The Use of a Fiber Comb Filter Fabricated By a CO2 Laser Irradiation to Improve the Resolution of a Ratiometric Wavelength Measurement System

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

Gilberto Brambilla
University of Southampton

Ming Ding
University of Southampton

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

Qiang Wu
Unviersity of Southampton

See next page for additional authors

Recommended Citation

Wang, P., Brambilla, G., Ding, M., Semenova, Y., Wu, Q., Farrell, G. The Use of a Fiber Comb Filter Fabricated by a CO2 Laser Irradiation to Improve the Resolution of a Ratiometric Wavelength Measurement System . Journal of Lightwave Technology, Vol.30, 8, 2012, pp.1143-1149. doi:10.1109/JLT.2011.2171319

Authors
Pengfei Wang, Gilberto Brambilla, Ming Ding, Yuliya Semenova, Qiang Wu, and Gerald Farrell

The Use of a Fiber Comb Filter Fabricated by a CO_2 Laser Irradiation to Improve the Resolution of a Ratiometric Wavelength Measurement System

Pengfei Wang, Gilberto Brambilla, Ming Ding, Yuliya Semenova, Qiang Wu, and Gerald Farrell

***Abstract*—An edge filter-based ratiometric wavelength measurement system is modeled and analyzed in this paper. The results confirm that the noise of input signal and photodetectors limits the resolution of the wavelength measurement system. The achievable resolution is calculated for a given noise level of the input signal and photodetectors' resolution. An improved ratiometric wavelength measurement system consisting of two fiber comb filters is presented both theoretically and experimentally, which performs coarse and fine wavelength measurements simultaneously. The resolution of the system is significantly improved to better than 5 pm while maintaining the potential for high measurement speed and wide measurable wavelength range.**

***Index Terms*—Edge filter, fiber comb filter, wavelength measurement, laser irradiation.**

I. INTRODUCTION

WAVELENGTH measurement is required in dense wavelength division multiplexing optical communication systems for monitoring the channel wavelength of the tunable lasers involved, and it is also required in fiber Bragg grating (FBG) or Fabry–Perot (FP) filter-based optical sensing systems for detecting the wavelength shift caused by the environmental factors, such as strain or temperature. Numerous wavelength measurement techniques have been reported recently, which can be mainly divided into passive ratiometric wavelength measurement schemes and active wavelength scanning schemes.

A conventional ratiometric wavelength measurement scheme consists of a beam splitter, an edge filter, and two photodetectors. The edge filter provides a monotonic increasing spectral response in the measurable wavelength range from λ_1 to λ_2 (it can also be monotonic decreasing), which converts the wavelength measurement into a signal intensity measurement. The ratiometric wavelength measurement scheme has the advantages of simple configuration, requires no mechanical movement, and offers the potential for high-speed measurement as compared with the active wavelength scanning schemes. Previous investigations proposed different types of edge filters bulk thin-film filters [1], biconical fiber filters [2], fiber gratings [3], macrobending single-mode fiber filters [4], [5], and multimode interference-based multimode fiber filters [6]. Our previous investigations of the ratiometric wavelength measurement system revealed theoretically and experimentally the impact of the limited signal-to-noise ratio (SNR) of the input signal, e.g., signal to spontaneous-emission ratio (SSE) for the lasers, on the design of the edge filter spectral response [7].

Initially, in this paper, a conventional ratiometric wavelength measurement system is modeled and analyzed, taking account of the noise of both the input signal and photodetectors. The effects of noise on the system performance, such as the measurable wavelength range and the system resolution, are modeled. The achievable measurement resolution is calculated for a given noise scale (within ± 0.5 dB) for a range of input signal noise levels and photodetector resolution values. An improved ratiometric wavelength measurement system involving two fiber comb filters is presented, which performs coarse and fine wavelength measurements simultaneously. The resolution of the system is significantly improved while maintaining the potential for high measurement speed and wide measurable wavelength range (the presented example improves the achievable resolution from about 50 pm to better than 5 pm).

II. MODELING AND ANALYSIS OF THE RATIOMETRIC WAVELENGTH MEASUREMENT SYSTEM

Fig. 1(a) shows the schematic configuration of a conventional ratiometric wavelength measurement system employing a fiber edge filter. The input signal is split into two equal signals. One passes through a reference arm and the other passes through the edge filter. Two photodiodes are placed at the ends of both arms. By measuring the ratio of the electrical outputs of the two photodetectors, the wavelength of the input signal can be determined assuming a suitable calibration has taken place.

In such a ratiometric wavelength measurement system, the narrowband input signal with a center wavelength λ_0 could be a signal from a tunable laser or a reflection from an FBG or FP filter. Such an input signal can be approximated by a Gaussian function with a spectral width $\Delta\lambda$ and a center wavelength λ_0. In practice, the input signal generally has a limited SNR, e.g.,

Manuscript received June 30, 2011; revised September 28, 2011; accepted September 29, 2011. Date of publication October 13, 2011; date of current version March 14, 2012. The work of P. Wang was funded by the Irish Research Council for Science, Engineering and Technology, and co-funded by the European Union Marie-Curie Actions under FP7. The work of Q. Wu was supported by Science Foundation Ireland under Grant 07/SK/I1200.

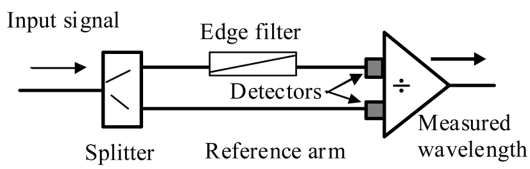
P. Wang was with Photonic Research Centre, Dublin Institute of Technology, Dublin, Ireland. He is now with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, U.K. (e-mail: pw3y09@orc.soton.ac.uk).

G. Brambilla and M. Ding are with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, U.K. (e-mail: gb2@orc.soton.ac.uk; md20d09@orc.soton.ac.uk).

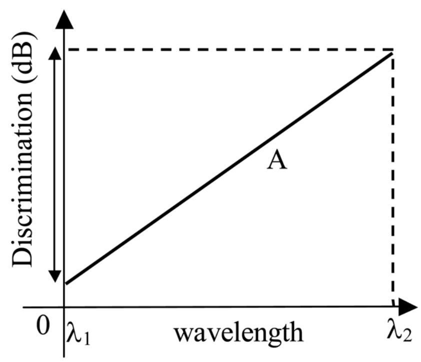
Y. Semenova, Q. Wu, and G. Farrell are with the Photonic Research Centre, Dublin Institute of Technology, Dublin, Ireland (e-mail: yuliya.semenova@dit.ie; qiang.wu@dit.ie; gerald.farrell@dit.ie).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2011.2171319



(a)



(b)

Fig. 1. (a) Configuration of a conventional ratiometric wavelength measurement system. (b) Desired spectral response of the edge filter involved.

due to SSE of the tunable laser as mentioned previously, which means that there is measurable power even far from the center wavelength in spectrum. Therefore, taking into account SNR, the output spectral response of the source can be simply described as (assuming the power at the peak wavelength is 0 dB·m) ([1], [8]–[10])

$$10\log_{10}[I_{\lambda_0}(\lambda)] = \begin{cases} 10\log_{10}\left[\exp\left(-4\ln 2\frac{(\lambda-\lambda_0)^2}{\Delta\lambda_0^2}\right)\right] & |\lambda-\lambda_0|\le\Omega \\ S(\lambda)+\mathrm{rand}([-0.5,0.5])R_s & |\lambda-\lambda_0|>\Omega \end{cases} \quad (1)$$

where $S(\lambda)$ is the SNR of the source. $\mathrm{rand}([-0.5,0.5])$ is a small random number within the range of $[-0.5, 0.5]$ and R_s is the range of noise variation which depends on the source used (for some commercial tunable lasers, the value is about 1 dB). The parameter Ω is determined by the nature of the source noise and the value of the source SNR (S), i.e., $10\log_{10}[\exp(-4\ln 2(\Omega^2)/(\Delta\lambda_0^2))] = -S$ and thus Ω can be expressed as $\Omega = \sqrt{\exp(S/17.372)/2\cdot\Delta\lambda_0^2}$.

The transmission response of the edge filter versus the wavelength λ is denoted as $T_f(\lambda)$ (and $\bar{T}_f(f) = -10\log_{10}(T_f(\lambda))$ denotes the transmission in dB units). A simple case for the transmission response $\bar{T}_f(\lambda)$ of an edge filter in the wavelength range (λ_1, λ_2) is a linear function, i.e.,

$$\bar{T}_f(\lambda) = \bar{T}_f(\lambda_1) + \frac{(\bar{T}_f(\lambda_2)-\bar{T}_f(\lambda_1))}{(\lambda_2-\lambda_1)}(\lambda-\lambda_1). \quad (2)$$

It is well known that the current output from a photodiode is the integral of the optical power over a wavelength range. Therefore, the ratio of the outputs from the two photodetectors at a wavelength λ_0 is

$$R(\lambda_0) = -10\log_{10}\left(\frac{\int P_1(\lambda)\cdot I_{\lambda_0}(\lambda)\cdot T_f(\lambda)d\lambda}{\int P_2(\lambda)\cdot I_{\lambda_0}(\lambda)d\lambda}\right) = P_f - P_r \quad (3)$$

where $P_1(\lambda)$ and $P_2(\lambda)$ are the output powers of the splitter in Fig. 1(a). In an ideal case, it can be assumed that $P_1(\lambda) = P_2(\lambda) = 0.5$ and are independent of the input wavelength within the measurable range. P_f $(= -10\log_{10}[\int P_1(\lambda)\cdot I_{\lambda_0}(\lambda)\cdot T_f(\lambda)d\lambda])$ and P_r $(= -10\log_{10}[\int P_2(\lambda)\cdot I_{\lambda_0}(\lambda)d\lambda])$ are the output powers from the upper arm with an edge filter and from the lower reference arm, respectively. From (3), one also can see that for an ideal source (infinite SNR) and noise-free photodetectors, the ratio $R(\lambda_0)$ is identical to the transmission response $\bar{T}_f(\lambda_0)$. In practice, photodetectors have limited power measurement resolution due to inherent noise, which limits the resolution for commercial optical power monitors to circa 0.01 dB. In our analysis, this resolution of the photodetectors is modeled with a random value number within the resolution range of 0.01 dB as follows:

$$R_r(\lambda_0) = [P_f + \mathrm{rand}([-0.5,0.5])RM_1] - [P_r + \mathrm{rand}([-0.5,0.5])RM_2] \quad (4)$$

where RM_1 and RM_2 are the resolutions of the two photodetectors (e.g., 0.01 dB, as mentioned earlier). Since the two resolutions for the photodetectors are statistically independent, the resolution for the output ratio is $RM_1 + RM_2$.

To demonstrate the aforementioned model of the ratiometric system, a numerical example is presented here. A tunable laser with the wavelength range 1500–1600 nm is assumed as an input signal. The SNR of the laser is -50 dB and the linewidth is 0.24 nm. Four different edge filters are considered in the calculation. The transmission values for the four filters are 0 dB at $\lambda = 1500$ nm and 10, 20, 30 and 40 dB, respectively, at $\lambda = 1600$ nm. The resolution of both the photodetectors is assumed to be 0.01 dB. With the aforementioned formulas, the predicted output ratio for a tunable laser input is presented in Fig. 2(a). In Fig. 2(a), the transmission of the edge filter itself is also presented. One can see that as the slope of the edge filter increases, the output ratio deviates from the edge filter transmission curve; thus, it cannot be used as a wavelength discriminator in the wavelength region near 1600 nm. It is caused by the noise of the input signal as verified experimentally in [7]. Fig. 2(b) presents the corresponding output ratio at 1550 nm for a wavelength shift of 0.05 nm and a slope for the edge filter of 0.2 dB/nm. It can be seen that the detectable wavelength shift is limited, due to photodetector noise and the limited input signal SNR.

It is clear that for a desired measurable wavelength range, the input signal noise limits the slope of the transmission curve; due to the limited photodetector resolution, the system resolution is also limited. That is to say, for a given measurable wavelength range, the achievable resolution of the system is determined by the noise of the input signal and photodetectors involved. To determine the relationship between the measurement resolution and different noise levels for different input signal SNRs and photodetector resolution, wavelength ranges 1500–1600 nm and 1500–1560 nm are taken as two examples; for different noise

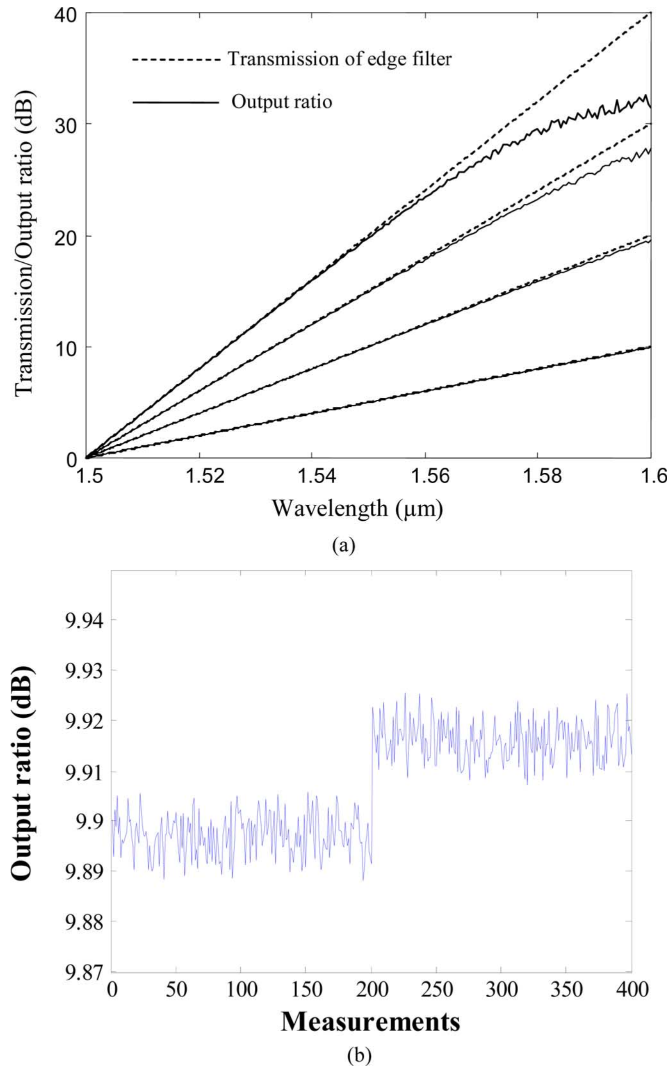


Fig. 2. (a) Dependence of the system output ratio and the edge filter transmission on the input signal wavelength. (b) Output ratio of the system for a wavelength shift of 0.05 nm; for each wavelength, the photodetectors are sampled 200 times.

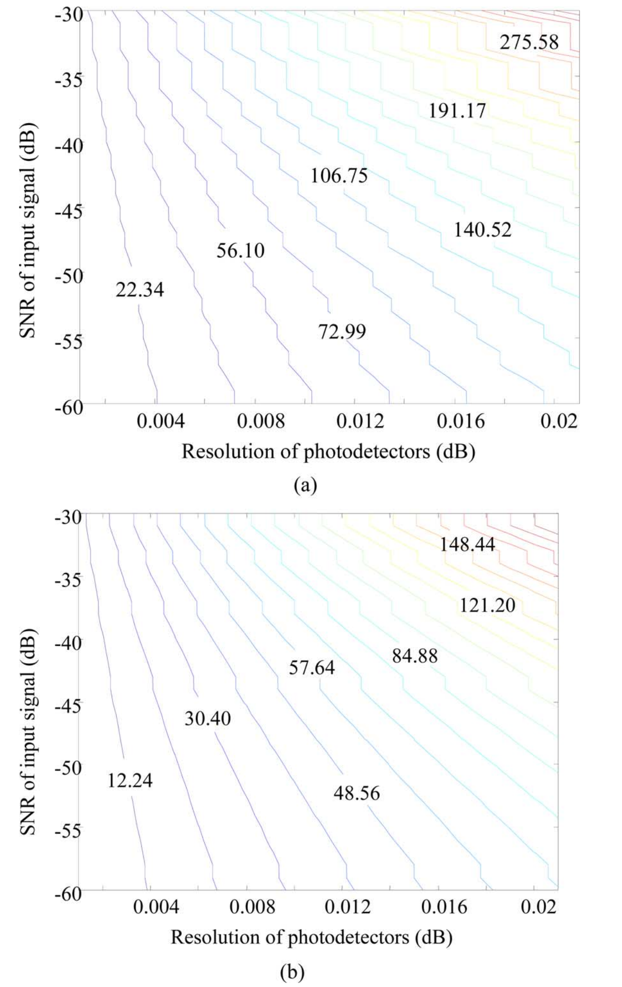


Fig. 3. Contour plots of the achievable measurement resolution for different SNR levels for the input signal and photodetector resolution. (a) Measurable wavelength range is from 1500 to 1600 nm. (b) Measurable wavelength range is from 1500 to 1560 nm.

levels of the input signal and photodetectors, the achievable resolutions are calculated with the aforementioned model. The corresponding results are presented as contour plots in Fig. 3(a) and (b), respectively (resolution is expressed in pm).

From the calculated results, it is seen that a low SNR for the input signal and high resolution of the photodetectors correspond to a high wavelength measurement resolution. In practice, the SNR of the input signal is typically fixed by the design of the source; thus, to improve the measurement resolution for a given wavelength range, photodetectors with a higher resolution are required. However, the use of high-resolution photodetectors is associated with higher cost and slower speeds due to signal averaging required. However, Fig. 3 suggests that a narrower measurable wavelength range corresponds to higher resolution. The challenge is to achieve a higher resolution while maintaining a wide measurable wavelength range. To achieve this, an alternative method is proposed here that involves adding two comb filters with a periodic spectral response to the conventional configuration, as presented next.

III. Ratiometric Wavelength Measurement System Combining Two Fiber Comb Filters

As shown in Fig. 2(a) and (b), calculated by using both (2) and (3), increasing the slope of the edge filter can be an effective method to improve resolution when the noise of the photodetectors and the wavelength range are given. However, as presented in Fig. 2(a), the input signal noise puts a limitation on the edge filter slope. Therefore, the resolution of the ratiometric system is determined by the SNR of the input signal and by the photodetectors noise within a certain wavelength range. The other possible way to increase resolution of the measurements is to divide the entire wavelength range of measurements into several smaller equal ranges and to use edge filters with higher slopes within each of the small wavelength range.

Fig. 4(a) presents the schematic structure of the modified ratiometric wavelength measurement system involving two comb filters. The spectral responses of the two comb filters are presented in Fig. 4(b). For the purpose of measurement, the spectral response within the half-period of each comb filter is used as an edge filter. The operation of this modified ratiometric wavelength measurement system is as follows: first, the edge filter is

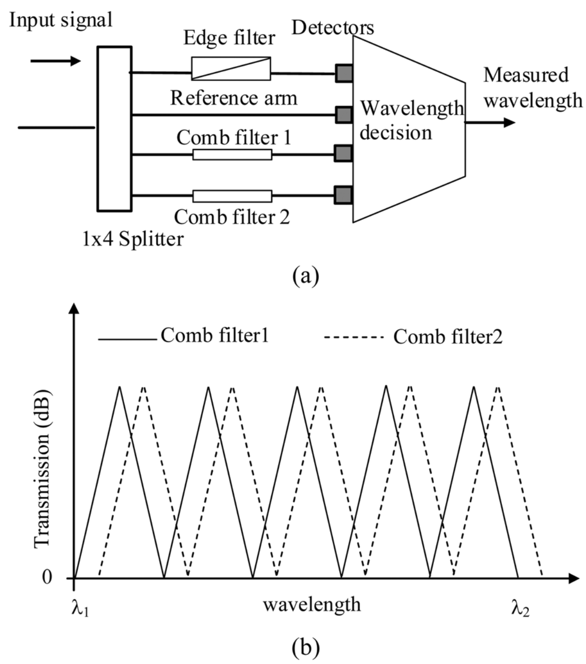


Fig. 4. (a) Schematic structure of the modified ratiometric wavelength measurement system involving two comb filters. (b) Ideal spectral response of the comb filters.

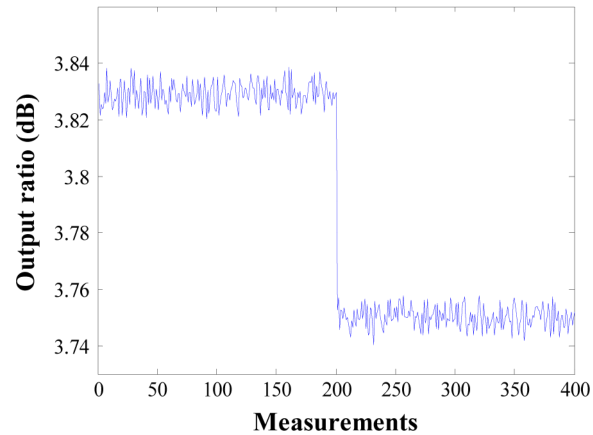


Fig. 5. Output ratio of the modified system as the wavelength shifts by 5 pm; for each of the two wavelength values, the photodetectors are sampled 200 times.

used for a coarse measurement, in order to determine the input signal wavelength with a low resolution. Then, the comb filter is used for a refined measurement. However, if only one comb filter is deployed, then the system will fail to measure wavelengths located near the peak or valley of the comb filter transmission. To overcome this problem, the modified measurement system includes additionally a second comb filter, the spectral response of which is shifted with respect to the first comb filter so that the second comb filter can be used for the measurement if the measurable wavelength is located near the peak or valley of the first comb filter transmission [see Fig. 4(b)].

In our example, the source SNR is assumed to be about -50 dB and the resolution of photodetectors is 0.01 dB. From Fig. 3(a), for a conventional edge filter measurement system, if the wavelength range is from 1500 to 1600 nm, the achievable resolution is about 50 pm. However, if the comb filter arrangement shown in Fig. 4(a) is used (with a free spectral range (FSR) of 20 nm and a discrimination of 10 dB within a wavelength range of 10 nm), the resolution can be improved by an order of magnitude. As shown in Fig. 4(b), the entire wavelength range from λ_1 to λ_2 is divided into ten equal regions, each with a discrimination of 10 dB, with five positive and five negative slopes. If (3) and (4) are applied to the spectral response of any one part of the slopes in Fig. 4(b), resolution can be improved by the factor of 10 compared to that achievable in the whole wavelength range. Generally, to achieve high resolution, the period of the comb filter should be narrow enough to get a high slope; however, Fig. 2(a) shows that the input signal SNR determines the maximum discrimination at λ_2; therefore, the maximum discrimination of an ideal comb filter should be no larger than 30 dB. The relationship between the period and the slope of comb filter in a practical case will be discussed in the next section. Fig. 5 shows the calculated output ratio assuming that the wavelength of the input signal shifts by 5 pm at 1556 nm. With the modified system, resolutions better than 5 pm can be achieved. It is clear that the measurement resolution with the comb filter is improved significantly by comparison to the value of 50 pm achieved with the conventional system shown in Fig. 1(a). The resolution can be improved further by optimizing the comb filter specifications, such as the discrimination and FSR. In practice, these comb filters and their triangular spectral responses can be realized by all-fiber Mach–Zehnder interferometers (MZIs) with a periodic Gaussian spectral response.

IV. Fabrication and Characterization of a Fiber Comb Filter

As shown in Section III, two ideal comb filters can significantly improve the resolution of the whole wavelength measurement system. In order to experimentally verify the claim that resolution can be improved, a fiber inline MZI was fabricated, to provide a comb filter response, by a two-point CO_2 laser irradiation method as reported in [11]. A fiber MZI fabricated using the CO_2 laser irradiation method offers a number of advantages, such as a simple structure, small footprint, and greater mechanical strength compared with the conventional fiber MZIs [12]–[14].

In the experiments, as shown in Fig. 6, a CO_2 laser (SYNRAD, Model: 48-2 KWL) with a maximum power 30 W at a wavelength of 10.6 μm was employed to fabricate the fiber comb filter. A ZnSe cylindrical lens with a focal length of $254 \pm 0.5\%$ mm was used to shape the CO_2 laser beam into a narrow-line range with a width of circa 300 μm. Beam movement was achieved fixing gold-coated mirrors on a 1-D motorized translation stage (AEROTECH ABL-1500). A Labview program controlled the stage movement and a shutter; therefore, the length of the fiber two-point interferometer-based comb filter and the laser exposure time could be accurately controlled. The polymer coating layers of the optical single-mode fiber (Corning SMF-28) was stripped mechanically and the bare fiber was placed on the 2-D translation stages without external tension; the fiber was kept perpendicular to the laser beam line.

The CO_2 laser beam irradiated the bare single-mode fiber and created the first microbend; then, the translation stage with the

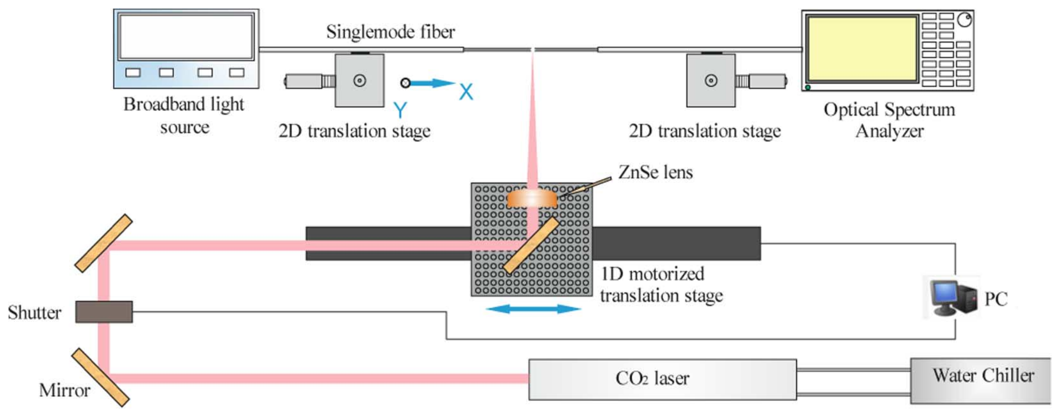


Fig. 6. Experimental setup for fabricating fiber comb filter.

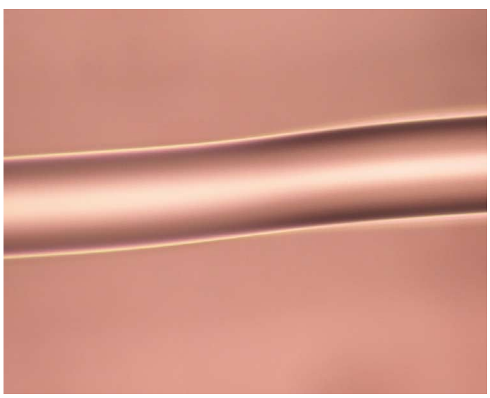


Fig. 7. Microscopic image of the fiber microbent region fabricated by a CO_2 laser irradiation.

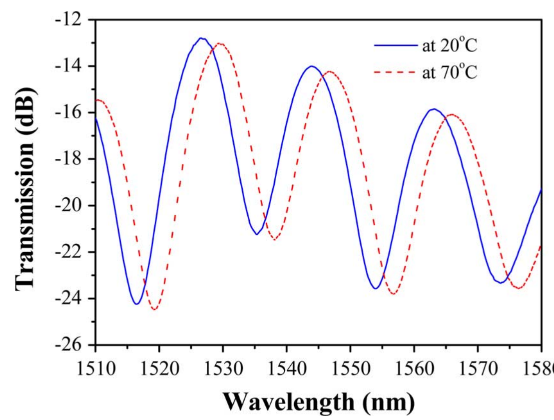


Fig. 8. Transmission spectra of the fiber comb filter with an interference length of 40 mm, at 20° C (solid line) and 70° C (dashed line).

ZnSe lens and the mirrors moved the laser beam to a new position. The fiber was irradiated again to create the second microbend. The transmission spectra of the fiber two-point comb filter were analyzed during fabrication using a broadband LED source and a high-resolution (20 pm) optical spectrum analyzer (YOKOGAWA AQ6370).

The laser output power was 22.5 W and the exposure time was 25 s. Fig. 7 shows the microscopic image of the microbend region created in the fiber. The core mode leaks from the fiber core into the cladding at the first microbend, travels in the cladding region between the two microbends, and couples back to the fiber core at the second microbend; as a result, interference occurs between the cladding and core modes. Fig. 8 shows the transmission spectrum of the fiber comb filter with a length of 40 mm between the microbends created by the CO_2 laser; the entire transmission spectrum is quasi-periodical with respect to the wavelength and this quasi-periodicity can be used to improve the resolution of the measurement system. As shown in Fig. 8, a comb filter with a minimum insertion loss of around 13 dB and an extinction ratio of up to 9.56 dB is achieved. The comb filter response has large variations in transmission, possibly caused by the difference in the CO_2 laser power used for the fabrication of the two microbends. The CO_2 laser used in the experiments has a ±5% power fluctuation; therefore, the two microbends are not identical and the relative weights of the modes which interfere at the microbends are different. A comb filter to be used in the improved wavelength measurement system ideally should exhibit a spectral response with equal wavelength spacing (namely the spectral separation between two adjacent interference fringes), extinction ratio, and low insertion loss. As discussed earlier and also in [15], the baseline loss of an edge filter has to be low within a certain wavelength range (here, the insertion loss of the comb filter is lower than 5 dB), while the discrimination range of edge filter should be less than 20 dB to reduce the influence of the source signal SNR and of the photodetectors resolution on the ratiometric system.

However, the comb filter we fabricated has shown a big transmittance variation over the wavelength range; such variation on the spectral response will cause a significant calibration error and will have a significant influence on the wavelength measurement system. To overcome this shortcoming, the fabrication method needs to be improved to create microbends that are as similar as possible. The idea is to use a laser beam with a low output power programmed to scan across the fiber in the transverse direction with a particular speed. The process of transverse scanning will be repeated along the fiber with certain steps, with each step equal to the length between two microbent points; the scanning cycle will be completed when an ideal transmission spectrum is achieved.

To achieve the desired transmission spectral responses of the two comb filters shown in Fig. 4(b), the fiber comb filter was fixed to a 5 cm diameter aluminum base plate, the temperature of which is controlled using a thermoelectric cooler (TEC)

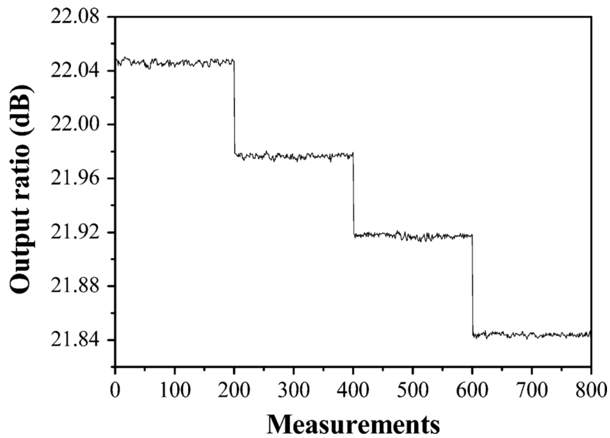


Fig. 9. Measured output ratio of the improved wavelength measurement system as the input wavelength shifts by 10 pm; for each step change of the input wavelength, the photodetectors are sampled 200 times.

driven by a 12 W laser diode temperature controller (Thorlabs TED200C). Full contact between the fiber comb filter and the base plate is ensured. Using the accurate independent temperature controller for the purpose of calibration, the transmission spectral responses were measured at temperatures of 20°C and 70°C. The range of temperatures was limited by the capabilities of the TEC used. The transmission spectral responses measured at temperatures of 20°C and 70°C are shown in Fig. 8. From the figure, it is clear that the peaks of the spectral response shift to the longer wavelength when the temperature increases and the average slope of the temperature sensitivity of the fiber comb filter is circa 0.056 dB/°C; furthermore, the results also confirm that the same comb filter design, but maintained at different temperature, can be used as the second comb filter in the improved ratiometric measurement system by changing the temperature in order to achieve the shifts of the spectral response, as illustrated in Fig. 4(a) and (b).

The wavelength resolution of the improved system was measured using a tunable laser (Agilent 81600) as an input signal source, with a wavelength step change of 10 pm from 1560.00 to 1560.04 nm. The measured ratio variation is shown in Fig. 9, which proves that the improved measurement system is very capable of resolving wavelength changes less than 5 pm, verifying the claims made by the simulations earlier in this paper.

To increase the resolution of the improved wavelength measurement system, the extinction ratio of the fiber comb filter needs to be reasonably high in order to reach a high discrimination value within a narrow wavelength range. In our experiments, the increase of the length between the two microbent points was found to decrease the spectral separation between two adjacent interference fringes in an approximately inversely proportional fashion; besides, the interference spectrum shows larger irregularity and a reduced extinction ratio, which generally decreases the fiber comb filter performance. In addition, the increase in the interferometer length also increases the insertion loss, resulting in a high baseline loss of the interference spectrum, which indicates a stronger coupling to the radiation modes in the interferometer. For this reason, the fiber comb filter with an interference length of 40 mm is a tradeoff between high-wavelength measurement resolution and an overall performance. Further investigation to improve the performance of the proposed fiber comb filter is underway.

V. Conclusion

A conventional ratiometric wavelength measurement system has been modeled and analyzed numerically. The simulated results have shown that the system performance is limited by both the input signal and photodetectors noise. The achievable resolution has been calculated for a given SNR for the input signal and photodetectors resolution. To improve the resolution of the system, an enhanced ratiometric wavelength measurement system that involves the addition of two comb filters has been proposed. The modified system performs coarse and fine wavelength measurements simultaneously. The resolution of the system is significantly improved while maintaining the potential for high measurement speed and wide measurable wavelength range. The fiber comb filter can be fabricated in single-mode fiber by using CO_2 laser irradiation.

Acknowledgment

Dr. G. Brambilla gratefully acknowledges the Royal Society, London, U.K., for his research fellowship.

References

[1] S. M. Melle, K. Liu, and R. M. Measures, "A passive wavelength demodulation system for guided-wave Bragg grating sensors," *IEEE Photon. Technol. Lett.*, vol. 4, no. 5, pp. 516–518, May 1992.

[2] A. B. L. Ribeiro, L. A. Ferreira, M. Tsvekov, and J. L. Santos, "All-fiber interrogation technique for fibre Bragg sensors using a biconical fibre filter," *Electron. Lett.*, vol. 32, no. 4, pp. 382–383, 1996.

[3] Y. Liu, L. Zhang, and I. Bennion, "Fabricating fiber edge filters with arbitrary spectral response based on titled chirped grating structures," *Meas. Sci. Technol.*, vol. 10, pp. L1–L3, 1999.

[4] Q. Wang, G. Farrell, T. Freir, G. Rajan, and P. Wang, "Low-cost wavelength measurement based on a macrobending single-mode fiber," *Opt. Lett.*, vol. 31, no. 12, pp. 1785–1787, 2006.

[5] P. Wang, G. Farrell, Q. Wang, and G. Rajan, "An optimized macrobending-fiber-based edge filter," *IEEE Photon. Technol. Lett.*, vol. 19, no. 15, pp. 1136–1138, Aug. 2007.

[6] A. M. Hatta, G. Farrell, P. Wang, G. Rajan, and Y. Semenova, "Misalignment limits for a singlemode-multimode-singlemode fiber-based edge filter," *J. Lightw. Technol.*, vol. 27, no. 13, pp. 2482–2488, Jul. 2009.

[7] Q. Wang, G. Farrell, and T. Freir, "Study of transmission response of edge filters employed in wavelength measurements," *Appl. Opt.*, vol. 44, no. 36, pp. 7789–7792, 2005.

[8] M. Bass, E. W. Van Stryland, D. R. William, and W. L. Wolfe, *Handbook of Optics*, 2nd ed. New York: McGraw-Hill, 1995, vol. 1, pt. 4.

[9] M. G. Xu, H. Geiger, and J. P. Dakin, "Modeling and performance analysis of a fiber Bragg grating interrogation system using an acousto-optic tunable filter," *J. Lightw. Technol.*, vol. 14, no. 3, pp. 391–396, Mar. 1996.

[10] Q. Wang, G. Rajan, P. Wang, and G. Farrell, "Resolution investigation of a ratiometric wavelength measurement system," *Appl. Opt.*, vol. 46, no. 25, pp. 6362–6367, 2007.

[11] T. Wei, X. Lan, and H. Xiao, "Fiber inline core-cladding-mode Mach–Zehnder interferometer fabricated by two-point CO2 laser irradiations," *IEEE Photon. Technol. Lett.*, vol. 21, no. 10, pp. 669–670, May 2009.

[12] S.-T. Lee and C.-J. Chae, "Low-cost bidirectional optical amplifier using a unidirectional Er-doped fiber amplifier and a fiber Mach–Zehnder interferometer," *IEEE Photon. Technol. Lett.*, vol. 13, no. 1, pp. 76–78, Jan. 2001.

[13] H. Y. Choi, M. J. Kim, and B. H. Lee, "All-fiber Mach–Zehnder type interferometers formed in photonic crystal fiber," *Opt. Exp.*, vol. 15, no. 9, pp. 5711–5720, 2007.

[14] P. Lu, L. Men, K. Sooley, and Q. Chen, "Tapered fiber Mach–Zehnder interferometer for simultaneous measurement of refractive index and temperature," *Appl. Phys. Lett.*, vol. 94, pp. 131110–131112, 2009.

[15] P. Wang, G. Farrell, and Y. Semenova, "A generalized design process for fiber bend loss based edge filters for a wavelength measurement system," *Appl. Opt.*, vol. 48, no. 18, pp. 3055–3061, 2009.

Pengfei Wang received the Ph.D. degree from the Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland, in 2008.

He was a Visiting Research Scientist at the Institute of Microelectronics and Microsystems, Section of Bologna, Italian National Research Council, in 2004, and a Research Associate in the Photonics Research Centre, Dublin Institute of Technology, in 2009. In 2010, he joined the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., as an IRCSET Marie Curie Research Fellow. He has authored or coauthored more than 90 articles in both academic journals and international conferences in these areas to date. His research interests include nonlinear microresontors, computational photonics (modeling, simulation, and optimization), photonic devices (such as microfiber/nanowire-based fiber devices, fiber-optic sensors, photonic integrated circuits, liquid crystal devices, laser machining, etc.) and applications development (optical communication and optical sensing).

Gilberto Brambilla received the M.Sc. degree (cum laude) in engineering from the Politecnico di Milano, Milan, Italy, in 1996, and the Ph.D. degree in optoelectronics from the Optoelectronics Research Centre (ORC), University of Southampton, Southampton, U.K., in 2002.

In 2007, he was awarded a Royal Society University fellowship. He is currently a Principal Research Fellow at the ORC. He has been consultant to various companies in Europe. He is the author or coauthor of more than 180 papers in journals/international conferences, two book chapters, and three patents. His research interests include the fabrication of devices and sensors based on optical fiber nanowires, couplers, and tapers, the study of photosensitivity in silica-based glasses, the manufacture of Bragg gratings for sensors and the investigation of their thermal stability, and the fabrication of fiber sensors for X-rays and nuclear radiations.

Ming Ding received the B.Sc. (Hons.) degree from Beijing Jiaotong University, Beijing, China. She is currently working toward the Ph.D. degree with Optical Fiber Nanowires and Related Devices Group in Optoelectronics Research Centre, University of Southampton, Southampton, U.K.

Her research interests include light confinement with nanostructured optical fiber taper, nanocavity on fiber taper, and microfiber Bragg grating.

Yuliya Semenova received the Graduate degree from Lviv Polytechnic National University, Lviv, Ukraine, in 1992, and the Ph.D. degree in physics of liquid crystals from the Ukrainian Academy of Sciences, Kharkov, Ukraine, in 1999.

She was a Researcher at the Faculty of Electrophysics, Lviv Polytechnic National University from 1997 to 2001. Since 2001, she has been with the School of Electronic and Communications Engineering, Dublin Institute of Technology, where she is also a Lecturer and Senior Researcher in the Photonics Research Center. She is the author or coauthor of more than 100 journal and conference papers. Her research interests include liquid crystals, photonics, and fiber-optic sensing.

Qiang Wu received the B.S. and Ph.D. degrees from Beijing Normal University, Beijing, China, and Beijing University of Posts and Telecommunications, Beijing, in 1996 and 2004, respectively.

From 2004 to 2006, he was a Senior Research Associate in the Optoelectronics Research Centre, City University of Hong Kong, carrying out research on polymer optical waveguides. From 2006 to 2008, he took up a Research Associate post in Applied Optics and Photonics Group, Heriot–Watt University, where he was focused on laser joining in micromanufacture. He is currently a Stokes Lecturer at Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland. His research interests include the design and fabrication of fiber Bragg grating devices for sensing, study of single-mode–multimode–single-mode fiber structures for novel fiber optical couplers and sensors, and the study of surface plasmon resonant.

Gerald Farrell received the Graduate (Hons.) degree in electronic engineering from University College Dublin, Dublin, Ireland, in 1979, and the Ph.D. degree from Trinity College Dublin, Dublin, for research in all-optical synchronization using self-pulsating laser diodes.

He is the Founder and Director of the Photonics Research Centre, Dublin Institute of Technology (DIT), Dublin. He has been the Head of the School of Electronic and Communications Engineering at the DIT since 2001. He spent a number of years as a Communications Systems Design Engineer developing optical fiber transmission systems before joining the DIT. Between 1997 and 2003, he was a Director of the startup company PX Instrument Technology, focusing on optical fiber system test and measurement systems. He is the author or coauthor of more than 190 publications in the area of photonics. His current research interests include several areas of optical sensing including fiber Bragg grating interrogation systems, the modeling and applications of fiber bend loss to optical sensing, single-mode–multimode–single-mode and other fiber structures for sensing applications, photonic-crystal fiber (PCF) sensors for environmental sensing and for sensing strain in composite materials and medical devices, liquid-crystal-infiltrated PCF sensors, and microfiber and nanowire sensors for biosensing.