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# The Use of a Fiber Comb Filter Fabricated by a CO<sub>2</sub> 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  $\lambda_1$  to  $\lambda_2$  (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  $\pm 0.5$  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  $\lambda_0$  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  $\lambda_0$ . In practice, the input signal generally has a limited SNR, e.g.,

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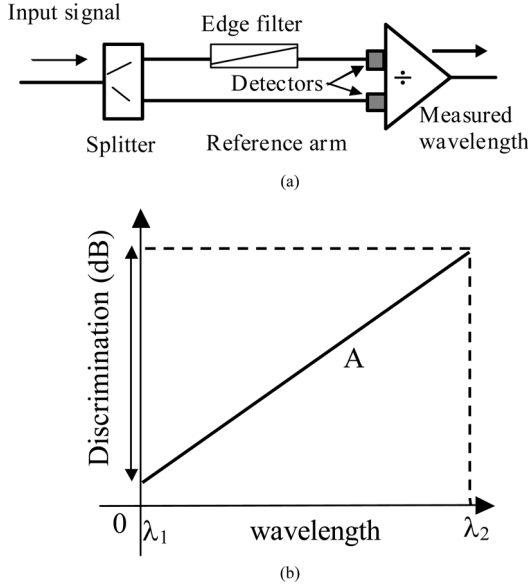


Fig. 1. (a) Configuration of a conventional ratiometric wavelength measurement system. (b) Desired spectral response of the edge filter involved.

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])

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

where  $S(\lambda)$  is the SNR of the source.  $\text{rand}([-0.5, 0.5])$  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  $\Omega$  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  $\Omega$  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  $\lambda$  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  $(\lambda_1, \lambda_2)$  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  $\lambda_0$  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:

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

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

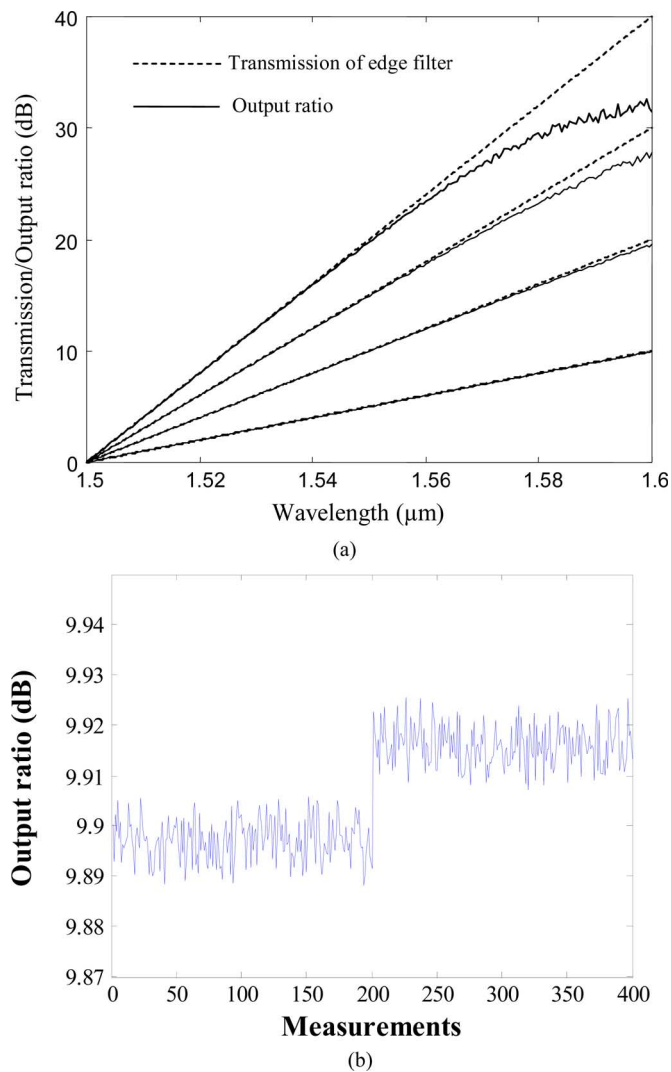


Fig. 2. (a) Dependence of the system output ratio and the edge filter transmission on the input signal wavelength. (b) Output ratio of the system for a wavelength shift of 0.05 nm; for each wavelength, the photodetectors are sampled 200 times.

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.

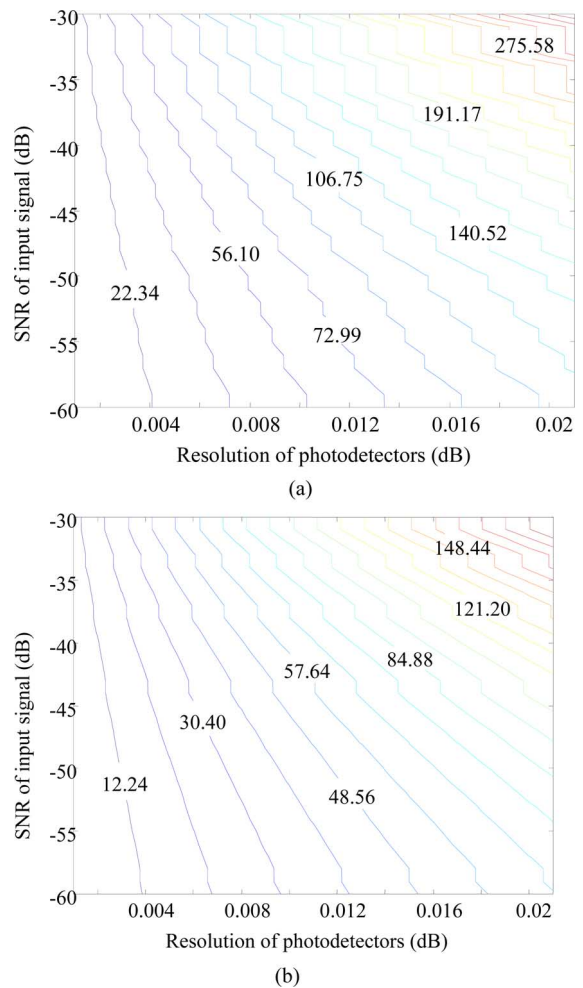


Fig. 3. Contour plots of the achievable measurement resolution for different SNR levels for the input signal and photodetector resolution. (a) Measurable wavelength range is from 1500 to 1600 nm. (b) Measurable wavelength range is from 1500 to 1560 nm.

### III. RATIO-METRIC 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 ratio-metric 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 ratio-metric 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 ratio-metric wavelength measurement system is as follows: first, the edge filter is

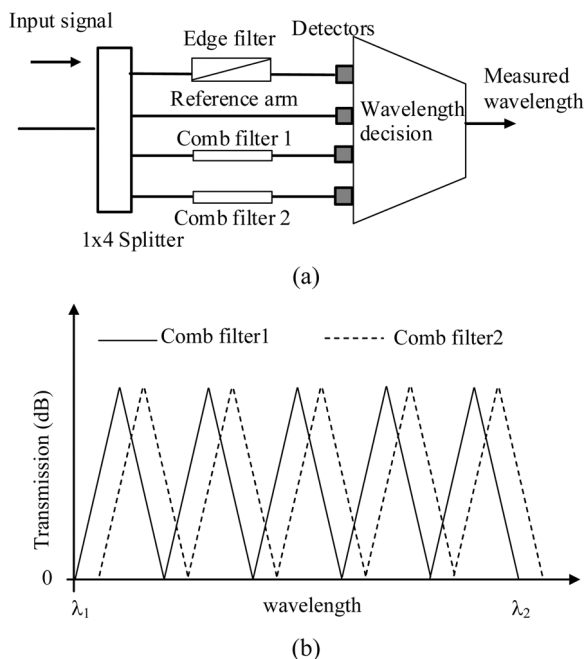


Fig. 4. (a) Schematic structure of the modified ratiometric wavelength measurement system involving two comb filters. (b) Ideal spectral response of the comb filters.

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  $\lambda_1$  to  $\lambda_2$  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  $\lambda_2$ ; 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

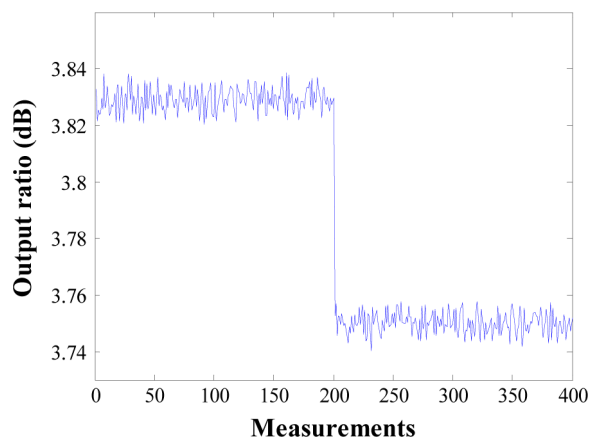


Fig. 5. Output ratio of the modified system as the wavelength shifts by  $5$  pm; for each of the two wavelength values, the photodetectors are sampled  $200$  times.

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  $\text{CO}_2$  laser irradiation method as reported in [11]. A fiber MZI fabricated using the  $\text{CO}_2$  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  $\text{CO}_2$  laser (SYNRAD, Model: 48-2 KWL) with a maximum power  $30$  W at a wavelength of  $10.6 \mu\text{m}$  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  $\text{CO}_2$  laser beam into a narrow-line range with a width of circa  $300 \mu\text{m}$ . 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  $\text{CO}_2$  laser beam irradiated the bare single-mode fiber and created the first microbend; then, the translation stage with the

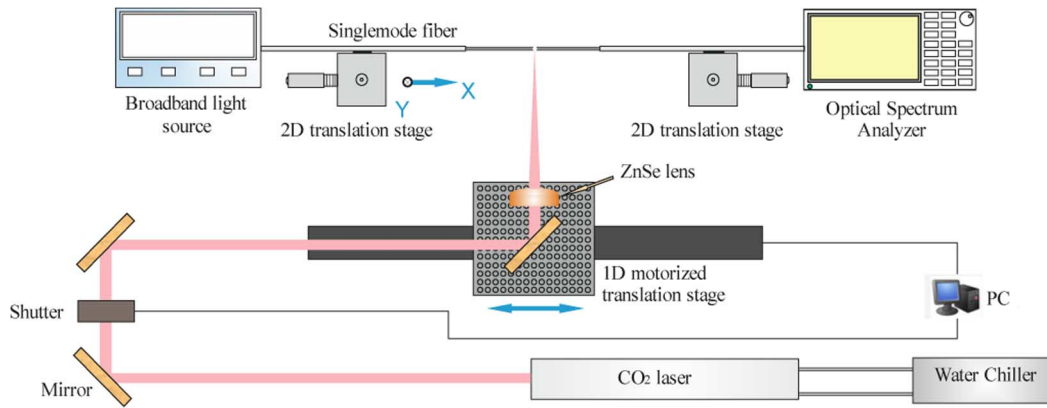


Fig. 6. Experimental setup for fabricating fiber comb filter.

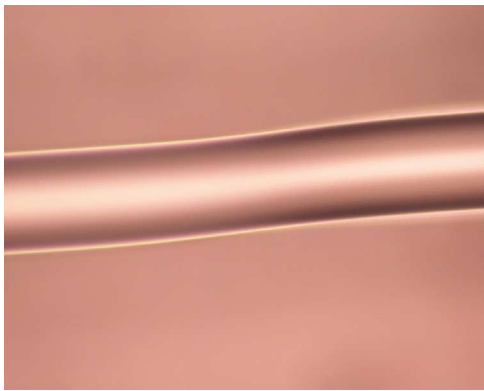


Fig. 7. Microscopic image of the fiber microbend region fabricated by a CO<sub>2</sub> laser irradiation.

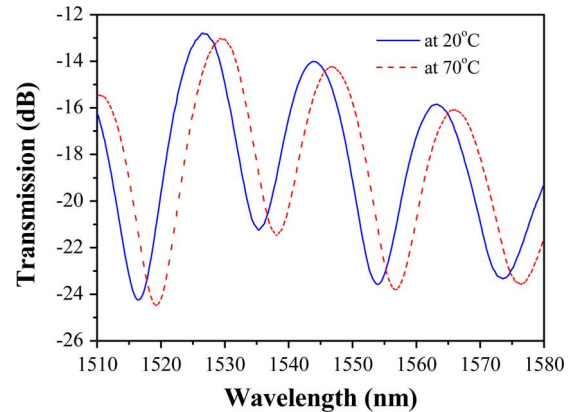


Fig. 8. Transmission spectra of the fiber comb filter with an interference length of 40 mm, at 20°C (solid line) and 70°C (dashed line).

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<sub>2</sub> 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<sub>2</sub> laser power used for the fabrication of the two microbends. The CO<sub>2</sub> laser used in the experiments has a  $\pm 5\%$  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 microbend 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)

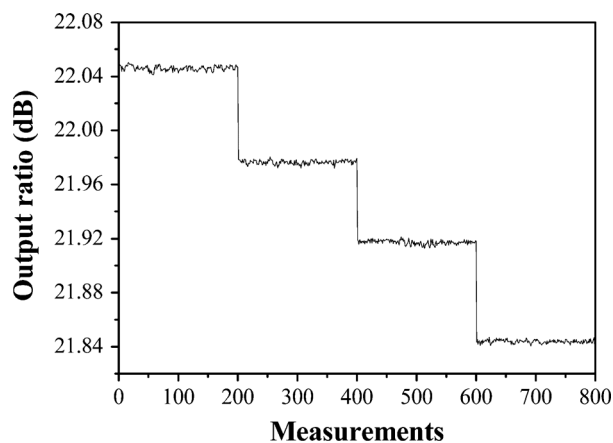


Fig. 9. Measured output ratio of the improved wavelength measurement system as the input wavelength shifts by 10 pm; for each step change of the input wavelength, the photodetectors are sampled 200 times.

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<sub>2</sub> laser irradiation.

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