# An improved ratiometric wavelength measurement system incorporating fibre comb filters fabricated by $CO_2$ laser irradiation

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**ABSTRACT**

An improved ratiometric wavelength measurement system incorporating two fibre comb filters is presented, which performs both rough and fine wavelength measurements simultaneously. The resolution of the system is significantly improved, compared to a single edge filter system, to better than 5 pm while maintaining the potential for high measurement speed and wide measurable wavelength range.

**Keyword**: Wavelength measurement, ratiometric, edge filter, fibre comb filter, laser irradiation

## 1. INTRODUCTION

A conventional ratiometric wavelength measurement scheme consists of a beam splitter, an edge filter and two photodetectors. The edge filter provides a monotonically increasing spectral response in the measurable wavelength range from $\lambda_1$ to $\lambda_2$ (it can also be monotonically decreasing), which converts the wavelength measurement into a signal intensity measurement. A ratiometric wavelength measurement scheme has the advantage of simple configuration, requiring no mechanical movement and offers the potential for a high-speed measurement as compared with the active wavelength scanning schemes. Previous investigations proposed different types of edge filters such as bulk thin-film filters [1], biconical fibre filters [2], fibre gratings [3], macrobending singlemode fibre filters [4, 5] and multimode interference based multimode fibre filters [6]. Our previous investigations of a ratiometric wavelength measurement system examined 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 appropriate selection of the edge filter spectral response [7] to maximize measurement resolution.

In this paper, an improved ratiometric wavelength measurement system involving two fibre comb filters is presented, which performs rough and fine wavelength measurements simultaneously. In a conventional simultaneous rough and fine measurement system, the fine measurement normally is not capable of improving the resolution but speed, e.g., the rough measurement gets an approximate value quickly, allowing fine measurement to get an accurate value without a large time consuming range of measurands to be covered. For the proposed improved measurement system in this paper, the resolution of the system is also 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).

## 2. RATIOMETRIC WAVELENGTH MEASUREMENT SYSTEM COMBINING TWO FIBRE COMB FILTERS

Fig. 1a 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. 1b. In this measurement scheme, 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: firstly, the wide range edge filter is used for a rough measurement, in order to determine the input signal wavelength with low resolution but over a broad range of wavelengths. Then the comb filter is used for a refined measurement over a narrower range of wavelengths. If only one comb filter is deployed, then the system will fail to measure wavelengths located near a peak or valley of the comb filter transmission sprectrum, due to measurement ambiguity. To overcome this problem the modified measurement system additionally includes 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 a peak or valley of the transmission spectrum first comb filter (see Fig. 1b). To avoid possible measurement ambiguity, a peak separation no less than 2 nm is essential between the comb filter peaks for the improve wavelength measurement system.

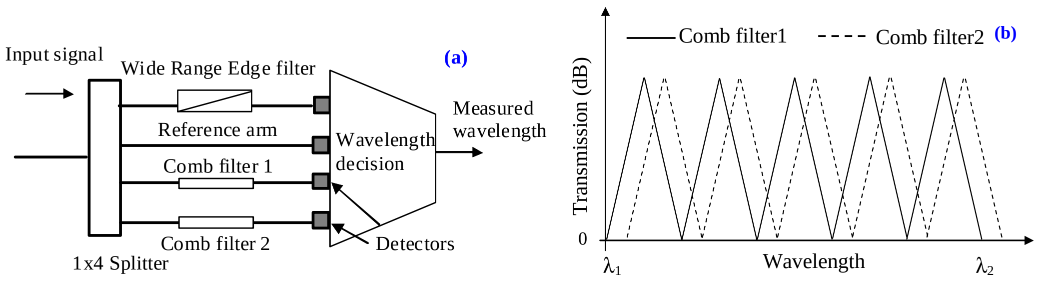


Fig. 1 a) Schematic structure of the modified ratiometric wavelength measurement system involving two comb filters; b) Ideal spectral response of the comb filters.

In our example the source SNR is assumed to be about -50 dB and the resolution of power measurement is 0.01 dB. If the wavelength range is from 1500 to 1600 nm, the achievable resolution with a conventional single edge filter system is about 50 pm. However, if the comb filters scheme shown in Fig. 1a is used (with a free spectral range (FSR) of 20 nm and a discrimination of 10 dB), the resolution can be improved by an order of magnitude. Fig. 2 shows the calculated output ratio [7] 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 resolution of wavelength measurement with the comb filters is improved significantly by comparison to a single edge filter scheme. The resolution can be improved further by optimizing the comb filter specifications, such as the discrimination range and FSR. In practice, these comb filters and their triangular spectral response can be realized by all-fibre Mach-Zehnder interferometers with a periodic Gaussian spectral response.

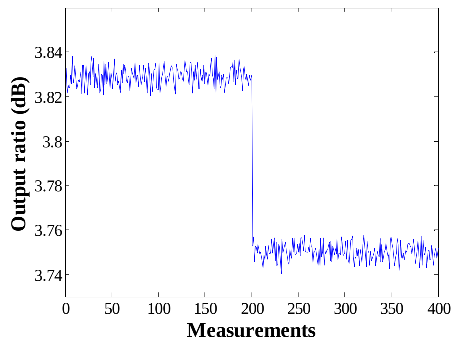


Fig. 2 Output ratio of the modified system as the wavelength shifts by 5 pm; for each wavelength value the photodetectors are sampled 200 times.

## 3. FABRICATION AND CHARACTERIZATION OF THE FIBRE COMB FILTERS

A fibre inline Mach-Zehnder Interferometer (MZI) was fabricated by a two-point $CO_2$ laser irradiation as reported in [8]. A fibre MZI fabricated using the $CO_2$ laser irradiation method offers a number of advantages, such as simple structure, small footprint and greater mechanical strength compared with conventional fibre MZIs [9, 10].

In the experiments, as shown in Fig. 3, a $CO_2$ laser (SYNRAD, Model: 48-2KWL) with a maximum power 30 Watts at a wavelength of 10.6 µm was employed to fabricate the fibre comb filter. A ZnSe cylindrical lens with a focal length of 254 ±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 one-dimensional motorized translation stage (AEROTECH ABL-1500). A Labview program controlled the stage movement and a shutter andtherefore the length of the fibre two-point interferometer based comb filter and the laser exposure time could be accurately controlled. The polymer coating layers of the optical singlemode fibre (Corning SMF-28) was stripped mechanically and the bare fibre was placed on the two dimensional translation stages without external tension; the fibre was kept perpendicular to the laser beam line.

The $CO_2$ laser beam irradiated the bare singlemode fibre and created the first microbend; then, the translation stage with the ZnSe lens and the mirrors then moved the laser beam to a new position. The fibre was irradiated again to create the second microbend. The transmission spectra of the fibre 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 used was 22.5 W and the exposure time was 25 s. Fig. 4a shows the microscopic image of the microbend region created in the fibre. The core mode leaks from the fibre core into the cladding at the first microbend, travels in the cladding region between the two microbends and couples back to the fibre core at the second microbend; as a result interference occurs between the cladding and core modes. Fig. 4b shows the transmission spectrum of the fibre comb filter with a length of 40 mm.

To achieve the desired transmission spectral responses of the two comb filters shown in Fig.1b, the fibre comb filter was fixed to a 5 cm in diameter aluminium base plate, the temperature of which is controlled using a thermoelectric cooler (TEC) driven by a 12 W Laser Diode Temperature Controller (Thorlabs TED200C). Full contact between the fibre comb filter and the base plate is ensured. Using the accurate independent temperature controller for the purpose of calibration, the transmission spectral response was measured at a temperature of 20 $^{o}$C and 70$^{o}$C, respectively. The range of temperatures was limited by the capabilities of the TEC used. The transmission spectral responses measured at temperatures of 20$^{o}$C and 70$^{o}$C are shown in Fig. 4b. From the Figure, it is clear that the peaks of the spectral response shift to a longer wavelength when the temperature increases with a peak separation between 20 and 70 degrees of 2.8 nm. Furthermore, the results also confirm that the same comb filter design can be used as the second comb filter in the improved ratiometric measurement system by changing the operating temperature of the comb filter in order to achieve the appropriate shift in the spectral response, as illustrated in Fig. 1a and 1b. 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 nm to 1560.04 nm. The measured ratio variation is shown in Fig. 4c, which proves that the improved measurement system is very capable of resolving wavelength changes less than 5 pm.

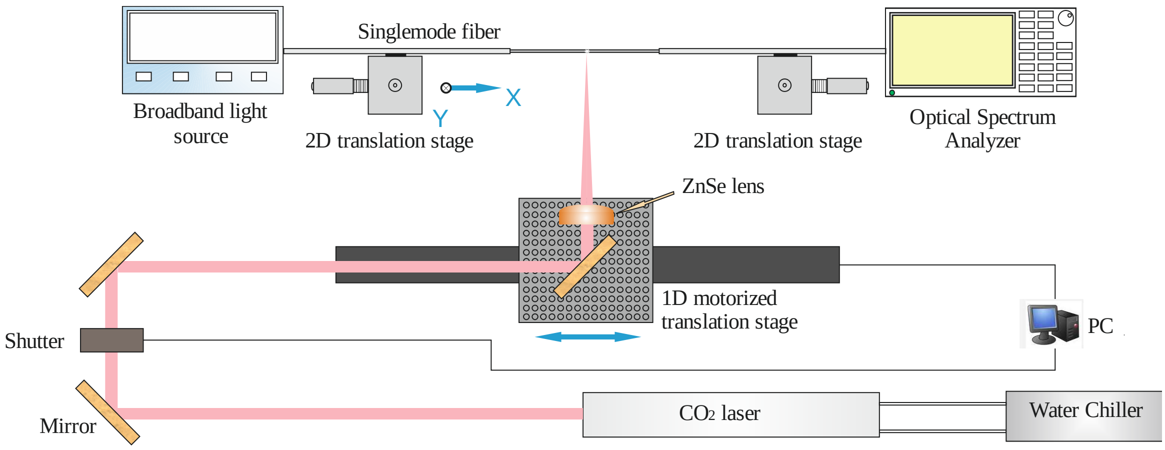


Fig. 3 Experimental set-up for fabricating fibre comb filter.

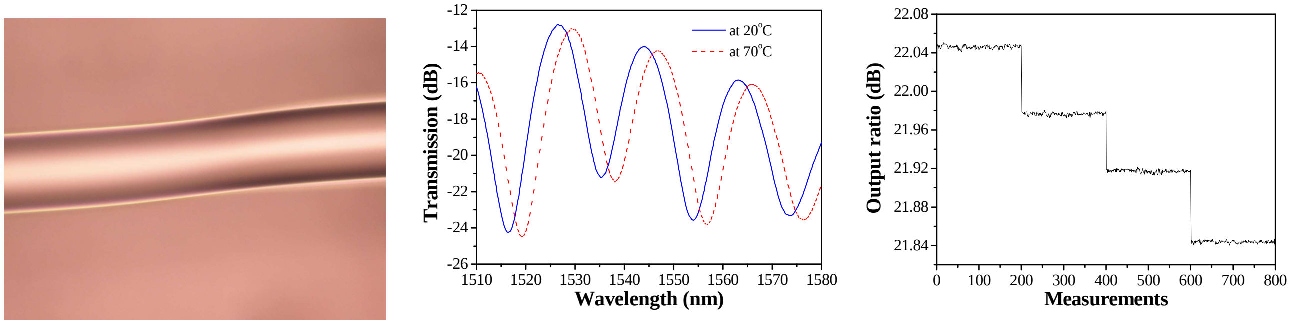


Fig. 4. a) Microscopic image of the fibre microbent region fabricated by a $CO_2$ laser irradiation; b) Transmission spectra of the fibre comb filter with a length of 40mm, at 20$^o$C (solid line) and 70$^o$C (dashed line); c) Measured output ratio of the improved wavelength measurement system as the input wavelength shifts by 10 pm; for each step change of the input wavelength, the photodetectors are sampled 200 times.

## 4. CONCLUSIONS

In order to improve the resolution of the system, a ratiometric wavelength measurement scheme incorporating two extra comb filters, fabricated using $CO_2$ laser irradiation, has been proposed. The modified system performs both rough and fine wavelength measurements simultaneously. The measurement resolution is significantly improved using the proposed scheme, whilst also maintaining the potential for high measurement speed and a wide measurable wavelength range

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