Resolution improvement of a ratiometric wavelength measurement system by using an optical microfibre coupler

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***Abstract*—The application of microfibre couplers in a comb-filter-based ratiometric wavelength measurement system is discussed. The fabrication of microfibre coupler is presented and its temperature-dependent performance is investigated. The resolution of the ratiometric wavelength measurement system with a microfiber coupler is significantly improved in comparison with a conventional ratiometric system to better than 4 pm maintaining the potential for high measurement speed and wide measurable wavelength range.**

Keywords-Microfibre coupler, temperature dependence, wavelength measurement, comb filter

I. INTRODUCTION

In recent years, optical microfibres have attracted tremendous interest for a range of both filtering and sensing applications due to the enormous progress in the fabrication of low-loss optical micro/nano wires, that allows for efficient optical beam confinement and low-loss evanescent waveguiding [1]. Optical microdevices fabricated from sub-wavelength fibres offer several prospective benefits by comparison to conventional integrated microphotonic devices, such as low insertion loss, inherent fibre compatibility, ease of integration, stability and flexibility. These optical properties have been shown to be advantageous for a wide range of applications including high-sensitivity optical sensors, nonlinear optics, atom trapping, micro/nano-scale photonic devices and for evanescent coupling to planar waveguides or microcavities.

In a recent work [2], the authors have presented a broadband bi-conical 2x2 optical microfibre coupler made from conventional telecom singlemode fibres that effectively suppresses any higher-order modes present at the input fibre and provides efficient power splitting into the fundamental mode at the two output ports. The microfibre coupler has many potential applications, for example in high performance fibre lasers, fibre sensors and optical coherence tomography systems. In this paper, we present an investigation of the temperature dependence of an optical microfibre coupler and its use within a ratiometric wavelength measurement system in which two optical microfibre couplers are utilized as comb filters. We also demonstrate that such an improved measurement system is capable of performing coarse and fine wavelength measurements simultaneously.

II. PROPOSED IMPROVED RATIOMETRIC WAVELENGTH MEASUREMENT SYSTEM

It is well known that a wavelength measurement system is a basic element in Dense Wavelength Division Multiplexing (DWDM) optical communication systems for monitoring the channel wavelength of the tunable lasers involved. It is also required in Fibre Bragg Grating (FBG) or Fabry-Perot (FP) filter based optical sensing systems for detecting the wavelength shift caused by the environmental measurands, such as strain, refractive index and temperature. Numerous wavelength measurement techniques have been recently reported, and 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. To date different types of edge filters have been developed, such as fibre gratings filter [3], a macrobending singlemode fibre filter [4] and a multimode interference based multimode fibre filter [5]. Our previous investigations of a ratiometric wavelength measurement system revealed theoretically and experimentally the impact of the limited signal-to-noise ratio (SNR) of the input signal [6].

Previous investigations also showed that, for a specified measurable wavelength range, the input Signal-to-Noise Ratio (SNR, namely SSE, Signal to source spontaneous emission) places an upper limit to the usable slope of the edge filter transmission curve, which combined with the limits on the power measurement resolution of the photodetectors, limits the achievable wavelength measurement resolution of the system. To determine the dependence of the measurement resolution on the different input signal SNRs and photodetector resolutions, wavelength ranges from 1500 to 1600 nm with a discrimination range of 20 dB are taken as examples; the achievable resolutions are calculated with the above model. The corresponding results are presented as contour plots in Fig. 1.

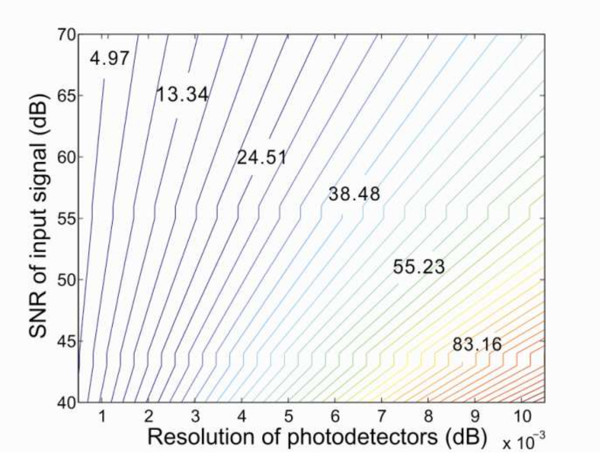

Fig. 1 Contour plots of the achievable measurement resolution (in picometers) for different input signal SNR levels and photodetector resolutions when the measurable wavelength ranges from 1500 to 1600 nm.

Simulations show that a high SNR for the input signal and high resolution of the photodetectors corresponds to a high wavelength measurement resolution. For the above example, when the resolution of the photodetector is 0.001 dB, the wavelength shift of circa 5 pm can be detected clearly through the system output ratio. 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. The challenge is to achieve high resolution whilst 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 below.

Fig. 2a 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. 2b. 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: firstly, the edge filter is 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 reliably measure wavelengths located near the peak or valley of the comb filter transmission. 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 unknown wavelength is located near the peak or valley of the first comb filter transmission (see Fig. 2b).

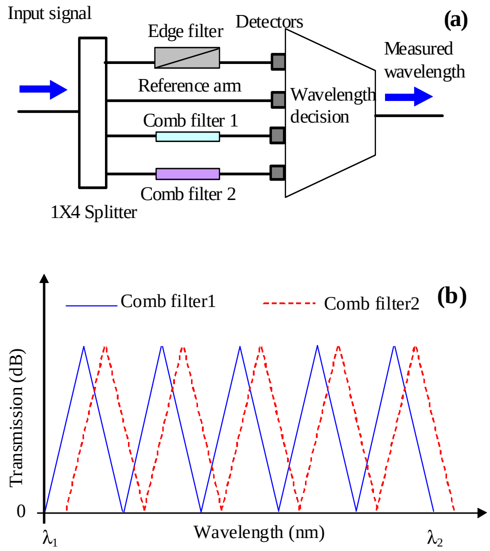

Fig. 2 (a) Schematic structure of the modified ratiometric wavelength measurement system involving two comb filters; b) Ideal spectral response of the comb filters.

In our example the source SNR is assumed to be circa -50 dB and the resolution of the photodetectors is 0.001 dB. The resolution of the measurement system can be improved further by optimizing the comb filter specifications, such as discrimination and free spectral range. In practice, these comb filters and their triangular spectral responses can be realized by conventional all-fibre Mach-Zehnder interferometers (MZIs) with a periodic Gaussian spectral response.

III. FABRICATION OF MICROFIBRE COUPLER AND ITS TEMPERATURE DEPENDENCE

In order to experimentally verify the claim above that the resolution can be improved as described in Fig. 2, a microfibre coupler was fabricated to provide a comb filter response, by the well-established single-stage "microheater-brushing" technique [7]. A microfibre coupler offers a number of advantages, such as a simple structure, small footprint and low insertion loss compared with the conventional fibre MZIs. The output transmission spectra of microfibre couplers were measured using a supercontinuum source (Fianium, wavelength coverage 450~1800 nm) in conjunction with an optical spectrum analyzer (YOKOGAWA AQ6370). Figure 3 shows the spectral outputs of a microfibre coupler made from a standard SMF28 singlemode fibre for different diameters of the uniform waist region: the significant modal interference induced by mode coupling between the lower-order symmetric and anti-symmetric supermodes can be observed when the diameter of the waist is decreased from 3 to 1.9 μm: both the period and strength of the sinusoidal modulation in the transmission spectrum significantly decreased with a reduction in the waist diameter.

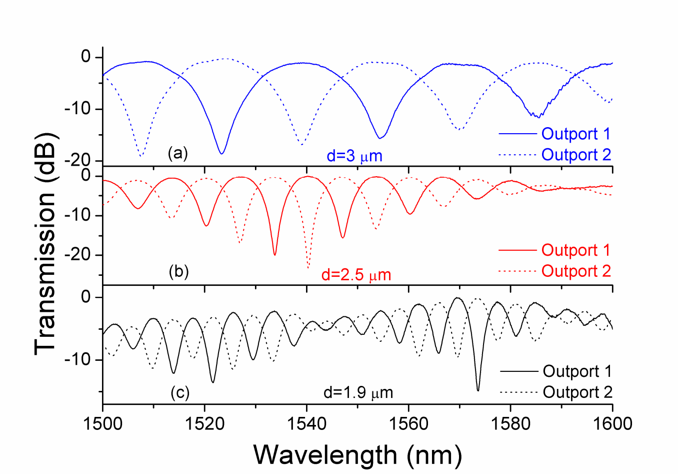

Fig. 3 Spectral responses of microfibre couplers: Transmission spectra of output ports for different microfibre diameters at (a) 3 μm, (b) 2.5 μm and (c) 1.9 μm.

To examine the microfibre coupler temperature (T) characteristic, its uniform tapered region was placed in a resistive heater. Figure 4(a) shows the transmission spectra of the microfibre coupler at T~701 °C, 865 °C and 1029 °C, respectively. For increasing T, the dip A redshifts from 1507.9 to 1516.5 nm, while the background loss decreases, possibly because of the change induced by the thermal expansion and the thermo-optic effect of silica. Figure 4(b) shows the experimental relationship between temperature and the resonant wavelength shift. The experimental temperature sensitivities of microfibre couplers with a diameter of 3 μm, 2.5 μm and 1.9 μm are estimated as 25.91, 36.59 and 31.1 pm/°C, respectively. The temperature sensitivity of the microfibre coupler is about 3.6 times higher than that of an FBG (~ 10 pm/°C), therefore this microfibre coupler temperature sensor could be also used for a high temperature environmental monitoring.

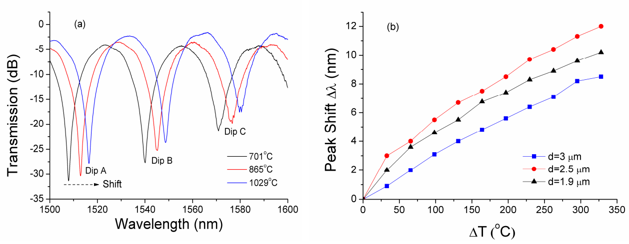

Fig. 4. (a) Thermal shift of the spectral response of a microfibre coupler with an outer diameter of 3 μm (output port 1); (b) Measured peak wavelength shifts versus the temperature changes for microfibre couplers with different microfibre outer diameters.

From Figure 4a, it is clear that the peaks of the spectral response red-shift to longer wavelengths when the temperature increases and the average slope of the fibre comb filter temperature sensitivity is circa 25.91 pm/°C for the microfibre coupler sample with a diameter of 3 μm. Furthermore, results also confirm that the same comb filter design, at different temperatures, can be used as the second comb filter in the improved ratiometric measurement system, as illustrated in Fig. 2a and b.

IV. USE OF MICROFIBRE COUPLE AS A COMB FILTER

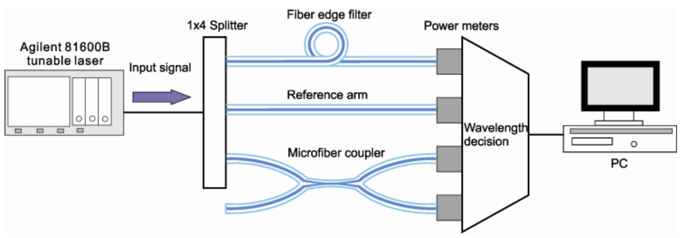

Fig. 5. Experimental setup of the improved wavelength ratiometric measurement system.

As shown in Fig. 2, 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, the experimental setup is shown in Fig. 5. A fibre bend loss edge filter did a coarse wavelength measurement within the entire measurable wavelength range, and then an optical microfibre coupler with a diameter of 3 μm was used for a fine wavelength measurement in the wavelength measurement system. The wavelength resolution of the improved system was measured using a high-resolution tunable laser (Agilent 81600 with a resolution of 0.1 pm and a low SSE ratio of 70 dB over an output wavelength range of 1520~1610 nm) as an input signal source, with a wavelength step changes of 1, 2, 3, 4 pm in the interval from 1520 nm to 1520.01 nm. The output power is collected by the power meters with a resolution of 0.001 dB which were controlled by a PC. If the microfibre coupler fails to reliably measure wavelengths located near the peak or valley of the transmission spectrum, thereafter the coupler can be heated to achieve a shift of the interference spectrum, as shown in Fig. 2b.

The measured ratio variation is shown in Fig. 6, which demonstrates that the improved measurement system is very capable of resolving wavelength changes smaller than 4 pm, verifying the claims made by the simulation presented earlier in this letter.

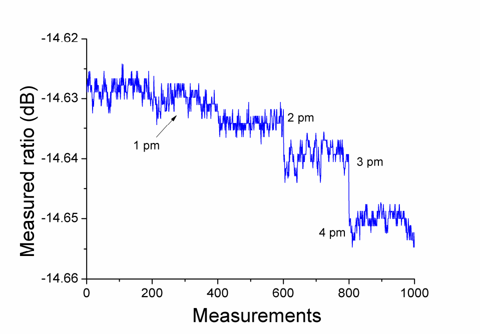

Fig. 6. Measured output ratio of the improved wavelength measurement system as the input wavelength shifts range from 1 to 4 pm; for each step change of the input wavelength the photodetectors are sampled 200 times.

V. CONCLUSION

In conclusion, the high temperature dependence of an optical microfibre coupler has been investigated experimentally. Used as the basis of a high temperature sensor, the temperature measurement sensitivity can reach up to 36.59 pm/^{o}C at a taper region outer diameter of 2.5 μm. An enhanced ratiometric wavelength measurement system based on two such microfibre couplers has also been proposed to improve the resolution of the system. 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.

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