Investigation of thermal effects in a resonance condition of microfibre double-knot resonators as high-order filter

Somayeh Nodehi[1], *Waleed Soliman Mohammed*[2], *Harith Ahmad*[1], *Sulaiman Wadi Harun*[1,3]

[1]*Photonic Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[2]*Center of Research in Optoelectronics, Communication and Control Systems, School of Engineering, Bangkok University, Pathum Thani 12120, Thailand*
[3]*Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
E-mail: wsoliman@gmail.com

Published in Micro & Nano Letters; Received on 10th July 2015; Accepted on 22nd July 2015

Theoretical and experimental investigations are conducted into the thermal effect on resonance conditions of microfibre double-knot resonators. A double-knot microfibre resonator which utilises heat for optical path correction is introduced to increase the finesse. The proposed resonator consists of two knots with radii of 357.66 and 357.73 μm which are placed in series. Each individual knot has a finesse of 5 and an extinction ratio of 6 dB. When placed in series, the extinction ratio of the comb spectrum varies from 3.5 to 15 dB by controlling the resonance wavelength of both knots through optical correction. Optical path correction is implemented by placing a hot metal bar with a temperature of 30°C close to the smallest knot. This path resulted in a flat comb spectrum with a high extinction ration of 15 dB. The produced resonance has an unchanged free spectral range of 715 pm, a quality factor of 20 000, FWHD of 85 pm and a finesse of 9.5.

1. Introduction: Microfibre resonators have progressed as alternative and complementary elements of photonic integrated circuits in recent years. To date, a variety of microfibre resonators have been fabricated and introduced such as the microfibre ring [1–3], knot [4], racetrack ring-resonator based on two U-bent microfibres, coil [5–7] and Mach-Zehnder structures [8]. Among these resonators, the microfibre knot has found a very promising position because of its firm structure and easy manipulation compared with the others. The microfibre knot shows stable light coupling and supports single-mode operation readily. These characteristics have allowed this structure to be considered as modulators and converters [9, 10], time delay [11] and tunable lasers [12, 13]. Besides, it has functioned as a wide range of sensors for humidity, electricity currentsensing, temperature [14–17] and magnetic field sensors [18]. These sensors are based on the environmental effect on the resonance spectrum. Therefore, it is possible to take advantage of these effects to tune the resonance characteristics such as the extinction and suppression ratio, bandwidth and resonance wavelength, which can be applied to filters, lasers and modulators.

Temperature is one of the most applicable environment factors and any change in its range has a major influence on the output spectrum of microfibre resonators. Previously, a microfibre knot resonator (MKR) was demonstrated as a temperature sensor with a sensitivity of 0.27 nm/°C [19]. In another work [14], a microfibre loop resonator embedded in low refractive index polymer was demonstrated to exhibit a linear reduction of the extinction ratio against temperature at a rate of about 0.043 dB/°C. In 2007, an MKR was reported as an all fibre add-drop filter, while there are a few works that show the finesse of a microfibre knot or loop resonator spectrum will be dropped when the extinction ratio increases [20, 21]. In this Letter, a double microfibre knot is employed to improve both the finesse and the extinction ratio simultaneously. The same structure has been demonstrated for multi-point temperature sensing by taking advantage of the thermal effect on the structure [22]. However, in this Letter, the thermal effect is utilised to achieve a tunable high-order filter that improves the finesse and extinction ratio using the Vernier effect. It is found that the output comb filter of the proposed structure can be filtered by controlling the optical path length difference via a heating technique. This technique indicates that one can probably manipulate the spectrum as well as optimising the heating condition to maximise the finesse as well as the extinction ratio. Theoretical analysis is presented based on the transfer matrix to approximate the characteristics of the output comb.

2. Theory and discussion: This part focuses on the performance of the double-knot filter in comparison with the single knot one. The filter response of a filter can be expressed as [23]

$$H(K) = \frac{E_{\text{output}}(K)}{E_{\text{input}}(K)} \tag{1}$$

This describes how the filter output spectrum behaves away from the resonance wavelength. The output field for a single knot is

$$\begin{aligned} E_{\text{output}} &= E_{\text{input}}\left(\frac{-ik + \mathrm{e}^{-iKL}\mathrm{e}^{-\propto L/2}}{1 + ik\mathrm{e}^{-iKL}\mathrm{e}^{-\propto L/2}}\right) \\ &\cong \frac{1}{1 + ik\mathrm{e}^{-\propto L/2}(1 - iKL)} \end{aligned} \tag{2a}$$

$$K = \frac{2\pi n}{\lambda} \tag{2b}$$

Therefore, the response of a single knot is in the order of $1/K$ and the output port intensity behaves as $1/(1 + ik\mathrm{e}^{-\propto L/2}(1 - iKL))^2$ that follows the Lorentzian response which shows a sharper roll-off for higher orders. The filter response of the structure can be expressed based on the transfer matrix method [24] as

$$\begin{aligned} E_4 = &\left(\frac{-ik_a + \mathrm{e}^{-i(2\pi n/\lambda)L_a}\mathrm{e}^{-\propto L_a/2}}{1 + ik_a\mathrm{e}^{-i(2\pi n/\lambda)L_a}\mathrm{e}^{-\propto L_a/2}}\right) \\ &\left(\frac{-ik_b + \mathrm{e}^{-i(2\pi n/\lambda)L_b}\mathrm{e}^{-\propto L_b/2}}{1 + ik_b\mathrm{e}^{-i(2\pi n/\lambda)L_b}\mathrm{e}^{-\propto L_b/2}}\right)\mathrm{e}^{-i(2\pi n/\lambda)\Lambda}\mathrm{e}^{-\propto\Lambda}E_1 \end{aligned} \tag{3}$$

The field components E_1 and E_4 represent the input and the output fields, respectively. E_2 and E_3 are the field components inside the structure. Moreover, $k = \gamma k'$ and $k' = -i\sin \pi L_c/2L_\pi$. k_a and k_b are the coupling coefficients of microfibre segment 1 belonging to knot (a) and knot (b), respectively. k' is the coupling coefficient of the microfibre segment 2, whereas L_c and L_π are the physical coupling length and coupling length in order [25, 26]. γ in the above equation is the coupling loss. The exponential expression

doi: 10.1049/mnl.2015.0303

in (1) represents the round-trip loss of the light propagating through the knots while the constant ∝ is the loss coefficient. L_a and L_b are the round-trip lengths for knots (a) and (b), respectively (Fig. 1*a*). The constants λ, n and Λ are the operating wavelength of input light, the effective index of the microfibre and the length between the coupling regions of the two knots.

As shown in (3), the response of the structure is in the order of $1/K^2$. It has a sharper roll-off than a single knot. The interference between the individual knot's responses result in a flatter top compared with that which the single knot filter can obtain. Fig. 2*a* compares the simulation results of the double-knot structure spectrum (bold line) and a single knot spectrum (dashed line) filter. The Vernier effect obtains sharper roll-off when the number of resonators with similar resonance wavelength increases.

Fig. 1 illustrates the proposed resonator that consists of two cascaded knots in series as well as an optical microscopic image of the structure. The two knots are assembled based on a single tapered microfibre. First, a standard single-mode fibre is tapered adiabatically down to 8 µm of waist diameter by using the flame brushing method. Then it is cut in the middle into two parts where each part is used to fabricate the single knot. In the experiment, the knots are formed based on a traditional method of knitting a woolen or string, where one of the microfibre parts is looped around and two non-stick separated bars before a knot is formed by micro-manipulation. The two bars are then pressed close to each other to separate the sticky microfibre from the bars and then pulled up to form the knot. The second knot is formed based on the same technique using the other part of the microfibre. Both knots are then cascaded together by attaching and coupling two microfibre ends via van der Waals and electrostatic forces and denoted as knot (a) and knot (b). The radii of knot (a) and knot (b) are 357.66 and 357.73 µm, respectively. During the fabrication process, the transmission spectrum of the resonance structure is monitored by injecting amplified spontaneous emission light. This light comes from an erbium-doped fibre amplifier through the input port, whereas the output port is connected to the optical spectrum analyser. The environment was controlled during the fabrication process and the measurement through vibration control and keeping a constant temperature.

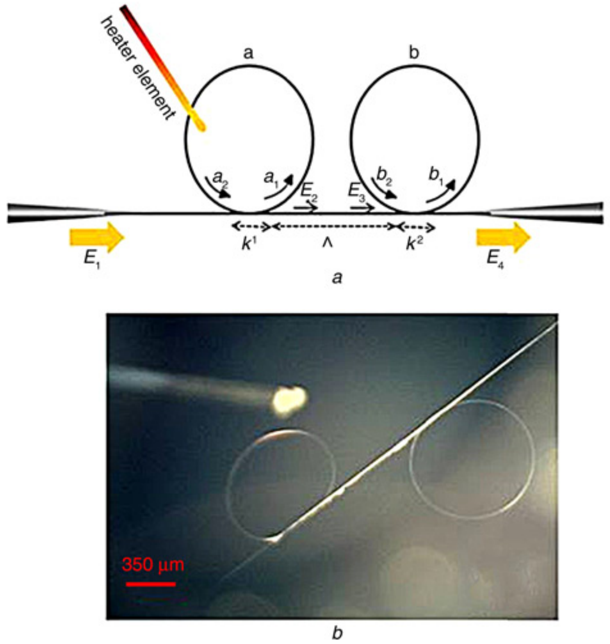

Figure 1 *L_a and L_b are round-trip lengths for knots (a) and (b), respectively*
a Schematic diagram of proposed microfibre cascaded knots structure
b Microscopic image of proposed setup for optical path correction

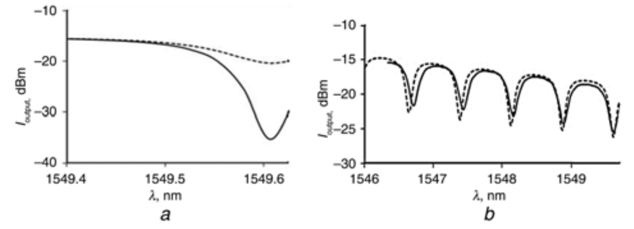

Figure 2 *Simulation results of the double-knot structure spectrum (bold line) and single knot spectrum (dashed line) filter*
a Simulation result of output spectrum for a single-knot (dashed line) and double-knot structure (bold line)
b Simulation and experimental curves fittings of the output comb spectrum for the knot with a ring radius of 357.66 µm

At the coupling region of the knot resonator, the microfibre is represented by segment 1 and segment 2; segment 1 represents the ingoing and outgoing lights and segment 2 the light energy exchange between the two segments.

3. Experiment and results: Fig. 2*b* shows the output spectrum of the fabricated knots before and after assembling them separately. The theoretical investigation curve is also included in Fig. 2*b* as shown by a dashed line for comparison. Fig. 2*b* demonstrates the output spectrum of knot (a) with the ring radius of 357.66 µm. The spectrum in this Figure is monitored separately by attaching another microfibre at the output end of the knot (a) before it was assembled with the second knot. On the basis of the experimental spectrum (solid line) analysis, the quality factor ($\lambda_0/\Delta\lambda$) of the knot is calculated to be about 11 000, while the free spectral range (FSR), full-wave half maximum (FWHM), finesse and extinction ratio are obtained at about 715 pm, 137 pm, 5 and 6 dB, respectively. The best-fit curve is obtained at the coupling coefficient of 0.7. Sequentially, combining the two knots in series with a distance Λ, estimated to be 2000 µm, a new comb filter with a complex spectrum is obtained at the output (Fig. 3*a*). In which of two attenuated wavelengths are excited at peak of each ripple of that comb of single knot. As can be clearly seen from Fig. 3*a*, the extinction ratio has diminished from 6 to about 3.5 dB compared with the extinction ratio at the single knot. This is due to the slight mismatch in the radii of the knots of about ∼70 nm, which corresponds to a significant phase difference between the two spectrums.

To overcome the radii mismatching, this Letter proposes a method that provides a simple solution for optical path correction by heating up a small section from the loop of the smallest knots by placing a hot metallic wire close to the loop with a pitch of ∼60 µm. As shown in Fig. 3*b*, this eliminates the attenuated wavelengths at the peak of the output comb filter of the double-knot structure, showing a flat comb filter with a high extinction ratio of about 15 dB. Such filtering indicates that a proper optical path correction has been made. According to Fig. 3*b*, a significant change in the

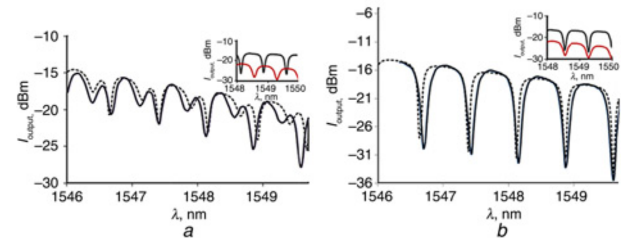

Figure 3 *Simulation and experimental curves fittings of output comb spectrum for*
a Structure before heating
b After heating

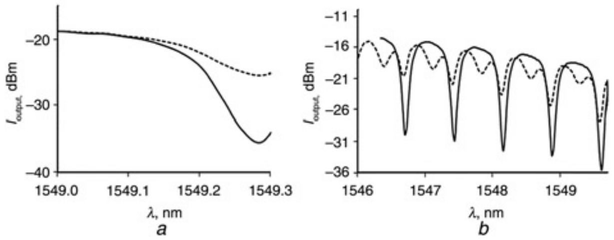

Figure 4 *Spectrum tuning*
a Experimental result of output spectrum for a single-knot (dashed line) and double-knot structure (bold line)
b Experimental curves of output spectrum for cascaded knot structures before heating (dashed line) and after heating (bold line)

output spectrum of the structure after heating knot (a) can be clearly observed. As a result of the temperature increase of the metallic wire from the room temperature of 28–30°C, the round-trip length of knot (a) extended to few nanometres.

Fig. 3*b* shows the best-fit curve (dashed line) from the experimental result using a fitting coupling coefficient of 0.7 for both knots. The simulation for the single knot and the structure is based on (2a) and (3) in order. Figs. 3*a* and *b* both show a sub-plot from two individual knots (a) and (b) spectra which demonstrates when those are out-of-phase and in-phase lead to the spectrum in Figs. 3*a* and *b* in order. On the basis of the calculations, the resonance characteristics of the structure have been changed where the quality factor increased to 20 000, with reducing in FWHD of 85 pm, and thus, improve the finesse to 9.5 as well as increasing the extinction ratio to 15 dB. There is an obvious difference between the calculations and experimental results because of the approximation in estimating the coupling length in each knot. Moreover, there might be slight error while measuring the actual radii of the two knots. Regardless of the slight difference between the simulation and experiment, the proposed method of optical path correction shows that the extinction ratio can be significantly improved by keeping both resonators in phase.

The same approach can also be used for spectrum manipulation using thermal effects. Thermal effect can help to tune the characteristics of the output spectrum and possibly to eliminate unwanted attenuated wavelengths and enhance some other parts of the spectrum. It is shown in Fig. 4*a* that the double-knot structure (bold line) obtains a sharper roll-off than that of a single knot (dashed line) filter due to the Vernier effect, where the finesse increases to about two times that of a single knot. Spectrum tuning is shown in Fig. 4*b* when the knots are out-of-phase (before heating) and when the optical temperature is applied to bring the two resonances in phase as shown by the solid line.

4. Conclusion: A double-knot microfibre resonator has been successfully fabricated using a flame brushing technique. It consists of two similar knots with radii of 357.66 and 357.73 µm with an almost similar individual resonance characteristics of (FSR = 715 pm, quality factor ∼11 000, FWHM = 137 pm, finesse = 5 and extinction ratio = 6 dB). In the proposed structure, the two knots are combined in series with a distance between two coupling regions of 2000 µm. The smallest knot is slightly heated to change its path length to be matched with the second knot resonator's path length. Consequently, the output spectrum transforms to a new comb spectrum with an improved quality factor and extinction ratio of 20 000 and 15 dB, respectively. In this work, it has been found that using the thermal effect helps to tune the characteristics of the output spectrum. Such tuning is very useful for different applications specially at filtering and in fibre laser. Manipulation of the spectrum opens up a way to transfer a multi-knots spectrum to a single knot with high quality.

References

[1] Jung Y.M., Brambilla G., Murugan G.S., *et al.*: 'Optical racetrack ring-resonator based on two U-bent microfibers', *Appl. Phys. Lett.*, 2011, **98**, (2)
[2] Lee T., Broderick N.G.R., Brambilla G.: 'Resonantly enhanced third harmonic generation in microfiber loop resonators', *J. Opt. Soc. Am. B*, 2013, **30**, (3), pp. 505–511
[3] Sumetsky M., Dulashko Y., Fini J.M., *et al.*: 'The microfiber loop resonator: theory, experiment, and application', *J. Lightwave Technol.*, 2006, **24**, (1), pp. 242–250
[4] Xu Y.P., Ren L.Y., Liang J., *et al.*: 'A simple, polymer-microfiber-assisted approach to fabricating the silica microfiber knot resonator', *Opt. Commun.*, 2014, **321**, pp. 157–161
[5] Hsieh Y.C., Peng T.S., Wang L.A.: 'Millimeter-sized microfiber coil resonators with enhanced quality factors by increasing coil numbers', *IEEE Photonics Technol. Lett.*, 2012, **24**, (7), pp. 569–571
[6] Jasim A.A., Lim K.S., Muhammad M.Z., *et al.*: 'Transmission characteristic of multi-turn microfiber coil resonator', *Opt. Laser Technol.*, 2012, **44**, (6), pp. 1791–1795
[7] Xu F., Horak P., Brambilla G.: 'Optical microfiber coil resonator refractometric sensor (vol 15, pg 7888, 2007)', *Opt. Express*, 2007, **15**, (15), p. 9385
[8] Tan Y.Z., Sun L.P., Jin L., *et al.*: 'Microfiber Mach-Zehnder interferometer based on long period grating for sensing applications', *Opt. Express*, 2013, **21**, (1), pp. 154–164
[9] Zhang X.L., Belal M., Chen G.Y., *et al.*: 'Compact optical microfiber phase modulator', *Opt. Lett.*, 2012, **37**, (3), pp. 320–322
[10] Zhang Y., Xu E.M., Huang D.X., *et al.*: 'All-optical format conversion from RZ to NRZ utilizing microfiber resonator', *IEEE Photonics Technol. Lett.*, 2009, **21**, (17), pp. 1202–1204
[11] Xu Y.P., Ren L.Y., Ma C.J., *et al.*: 'Wide-bandwidth zero-dispersion slow light in MKRs with a two-ring parallel connection structure based on an analogue of electromagnetically induced transparency', *J. Mod. Opt.*, 2014, **61**, (13), pp. 1109–1114
[12] Liu M., Liu H., Zheng X.W., *et al.*: 'Demonstration of multiwavelength erbium-doped fiber laser based on a microfiber knot resonator', *IEEE Photonics Technol. Lett.*, 2014, **26**, (14), pp. 1387–1390
[13] Sulaiman A., Harun S.W., Ahmad F., *et al.*: 'Tunable laser generation with erbium-doped microfiber knot resonator', *Laser Phys.*, 2012, **22**, (3), pp. 588–591
[14] Lim K.S., Harun S.W., Damanhuri S.S.A., *et al.*: 'Current sensor based on microfiber knot resonator', *Sens. Actuators A, Phys.*, 2011, **167**, (1), pp. 60–62
[15] Wu Y., Zhang T.H., Rao Y.J., *et al.*: 'Miniature interferometric humidity sensors based on silica/polymer microfiber knot resonators', *Sens. Actuators B, Chem.*, 2011, **155**, (1), pp. 258–263
[16] Yang H.J., Wang S.S., Wang X., *et al.*: 'Temperature sensing in seawater based on microfiber knot resonator', *Sensors Basel*, 2014, **14**, (10), pp. 18515–18525
[17] Gouveia M.A., Pellegrini P.E.S., dos Santos J.S., *et al.*: 'Analysis of immersed silica optical microfiber knot resonator and its application as a moisture sensor', *Appl. Opt.*, 2014, **53**, (31), pp. 7454–7461
[18] Li X.L., Ding H.: 'Temperature insensitive magnetic field sensor based on ferrofluid clad microfiber resonator', *IEEE Photonic Technol. Lett.*, 2014, **26**, (24), pp. 2426–2429
[19] Zeng X., Wu Y., Hou C.L., *et al.*: 'A temperature sensor based on optical microfiber knot resonator', *Opt. Commun.*, 2009, **282**, (18), pp. 3817–3819
[20] Sumetsky M., Dulashko Y., Fini J.M., *et al.*: 'Optical microfiber loop resonator', *Appl. Phys. Lett.*, 2005, **86**, (16)
[21] Jiang X.D., Chen Y., Vienne G., *et al.*: 'All-fiber add-drop filters based on microfiber knot resonators', *Opt. Lett.*, 2007, **32**, (12), pp. 1710–1712
[22] Wu Y., Jia L., Zhang T.H., *et al.*: 'Microscopic multi-point temperature sensing based on microfiber double-knot resonators', *Opt. Commun.*, 2012, **285**, (8), pp. 2218–2222
[23] Madsen C.K., Zhao Z.H.: 'Optical filter design and analysis' (John Wiley & Sons, New York, 1999)
[24] Yariv A., Xu Y., Lee R.K., *et al.*: 'Coupled-resonator optical waveguide: a proposal and analysis', *Opt. Lett.*, 1999, **24**, (11), pp. 711–713
[25] McKinnon W.R., Xu D.X., Storey C., *et al.*: 'Extracting coupling and loss coefficients from a ring resonator', *Opt. Express*, 2009, **17**, (21), pp. 18971–18982
[26] Delage A., Xu D.X., McKinnon R.W., *et al.*: 'Wavelength-dependent model of a ring resonator sensor excited by a directional coupler', *J. Lightwave Technol.*, 2009, **27**, (9), pp. 1172–1180

doi: 10.1049/mnl.2015.0303