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Extraction of a single Stokes line from a Brillouin fibre laser using a silicon oxynitride microring filter

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Abstract

Extraction of a single channel Brillouin Stokes line generated by pumping a length of single mode fibre is demonstrated using a silicon oxynitride microring resonator. The high Q-factor microring resonator has a steep slope transmission profile with an extinction ratio of 20 dB and a free spectral range of 0.4 nm. Experimental results show that extraction of a single Brillouin Stokes line can be achieved with a side mode suppression ratio of more than 12 dB. Additionally, Brillouin Stokes line selection can be achieved by controlling the microring resonance wavelength by thermal tuning.

1. Introduction

Brillouin erbium doped fibre lasers (BEFLs) have been studied extensively for their capability to generate a comb of Stokes lines with spacing as narrow as 10 GHz, which is ideal for use as carriers in dense wavelength division multiplexing (DWDM) optical fibre communications systems [1–4]. Once generated, an individual Stokes line needs to be extracted to be modulated by the data signal. As the wavelength spacing between Brillouin Stokes lines is only 0.08 nm (10 GHz), their separation is challenging. Bulk optic Fabry–Perot filters having the required bandwidth are readily available; also, a fibre Bragg grating (FBG) with 3 dB rejection bandwidth of 5 GHz has been demonstrated with a grating length of 100 mm [5]. However, the former involves 'fibre–free space–fibre' coupling and is not suitable for on-chip integration, while the long grating length required for a narrowband FBG adds to the difficulty of fabrication and does not favour integration into a multifunctional planar waveguide platform. An arrayed-waveguide grating (AWG) with 10 GHz spacing would be ideal for on-chip Stokes signal (de)multiplexing. However, it requires a complex design, stringent fabrication requirements and a large footprint to achieve the required narrow channel spacing [6].

In contrast, microring resonators have been demonstrated to exhibit narrowband filtering capability. Silicon-based high index contrast microring resonators have been used as add-drop filters [7], bandpass filters and (de)multiplexers in DWDM systems [8, 9]. Application as a single wavelength microring mirror with a reflection full width at half maximum of 0.4 nm was also reported [10]. Microrings therefore seem to be a suitable solution for selecting a single line of the comb generated by a BEFL or, by using an array of rings, dividing and recombining the entire comb.

In this work, a narrowband filter based on a silicon oxynitride (SiON) microring resonator is used as a filter for single Brillouin Stokes signal extraction. The SiON microring resonator has a small footprint of 3×5 mm^2. Extraction of Brillouin Stokes signal is demonstrated with side mode suppression of ~12 dB. The microring resonator can be readily integrated into a photonics integrated chip (PIC) for multifunctional applications.

2. Experimental setup

The experimental setup of the Brillouin fibre laser with a microring filter is shown in figure 1. The BEFL is realized as a long linear cavity configuration by utilizing a pair of optical circulators connected at the end of both sides of the cavity [11]. A dispersion compensating module (DCM) with a dispersion value of −203 ps nm^{-1} is used to generate the multiwavelength Brillouin output comb through stimulated Brillouin scattering (SBS). A continuous wave tunable laser source (TLS) acts as the Brillouin pump (BP), which is amplified by a proprietary erbium doped fibre amplifier (EDFA), giving a maximum BP output power of 26.5 dBm (447 mW). The BP wavelength is set at 1550.25 nm. The amplified BP output from the EDFA is then injected into the cavity through a 3 dB coupler and then to an optical circulator (OC1). Port 3 of OC1 is connected to the DCM, followed by the second optical circulator OC2. Port 1 of OC1 is then connected to Port 2 of OC1 via the other input of the 3 dB coupler, thereby forming the 'mirror' of the cavity. On the other side of the cavity, Port 3 of OC2 is connected to its Port 1 through a 90:10 coupler to create the second 'mirror', thus completing the linear cavity of the multiwavelength Brillouin laser. The 10% port of the optical coupler serves as the output of the Brillouin laser. With the BP power injected at its maximum value of 26.5 dBm (447 mW), the average power at Port 2 of OC1 is measured to be approximately 24 dBm (251 mW). A variable optical attenuator is used to control the power level of the Brillouin output. Then the signal is coupled into the microring filter (inset of figure 1) and the output is connected to an optical spectrum analyser (Yokogawa AQ6370B) with a resolution of 0.01 nm for the measurement of the output spectrum.

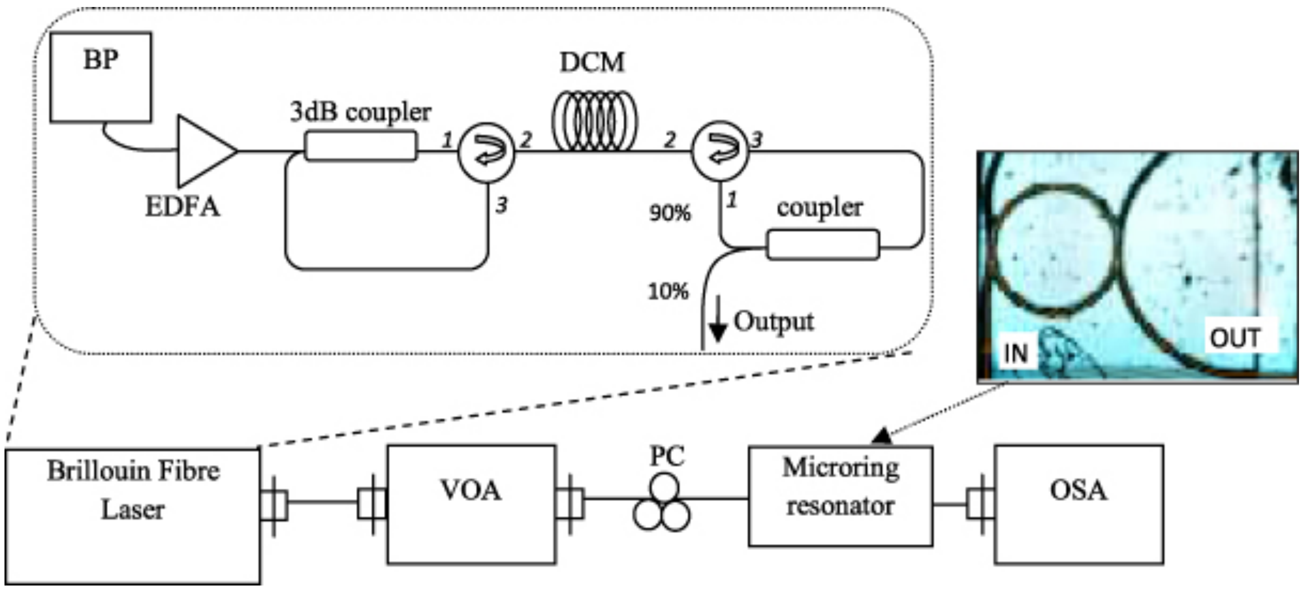

Figure 1. Experimental setup of a proposed Brillouin Stokes signal extraction: BP, Brillouin pump; VOA, variable optical attenuator; EDFA, erbium-doped fibre amplifier; DCM, dispersion-compensating module; PC, polarization controller; OSA, optical spectrum analyser). A micrograph of the microring resonator is shown in the inset.

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A silicon oxynitride (SiON) microring resonator was used as the narrow bandpass filter. Details of the SiON waveguide fabrication process can be found in [12]. The refractive index of the SiON film deposited using plasma enhanced chemical vapour deposition (PECVD) is 1.513. The film was deposited on a silicon substrate with a 15 µm thick thermal oxide layer as an under cladding buffer. Waveguides are defined through reactive ion etching (RIE) followed by deposition of a borophosphosilicate glass (BPSG) layer as the over cladding. The refractive index contrast is 4.5%. As the microring resonator is polarization dependent, a polarization controller is placed between the VOA and microring filter to control the polarization of light before it enters the microring filter. The input and output ports of the microring resonator are at 90° as shown in the inset of figure 1.

3. Results and discussion

The spectral transmission of the microring filter at different temperatures is shown in figure 2.

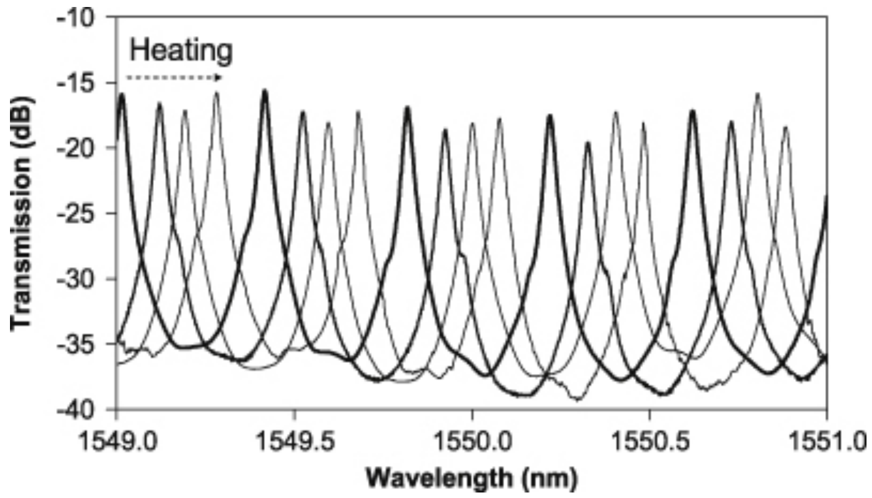

Figure 2. Transmission profile of the microring filter at different temperatures.

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The fibre-to-fibre insertion loss is less than 17 dB, which is mainly due to the non-optimized fibre–waveguide coupling. The microring diameter is ~1.21 mm, which produces a free spectral range (FSR) of 0.4 nm (50 GHz). At room temperature, peak transmission occurs at wavelengths of 1549.02, 1549.42, 1549.82, 1550.22 and 1550.62 nm. The transmission spectrum has an extinction ratio of ~20 dB and a 3 dB transmission bandwidth of 0.026 nm (3.2 GHz). The resonance frequency can be controlled and shifted by changing the microring temperature by using, for example, a resistance heating pad. The resonant wavelength can be easily controlled with a precision as high as 1 pm. Figure 2 shows four responses which are shifted by 0.08 nm, corresponding to temperatures of 25, 31, 36 and 41 °C.

Figure 3 shows the output spectrum of the Brillouin fibre laser. The wavelength of the Brillouin pump is set at 1550.25 nm which coincides with the peak transmission wavelength of the microring filter. The power level of the Brillouin pump and its three adjacent Stokes lines are −29.80, −30.45, −31.27 and −32.50 dBm. The 3 dB spectral width of the Brillouin pump and its Stokes signals is about 0.04 nm.

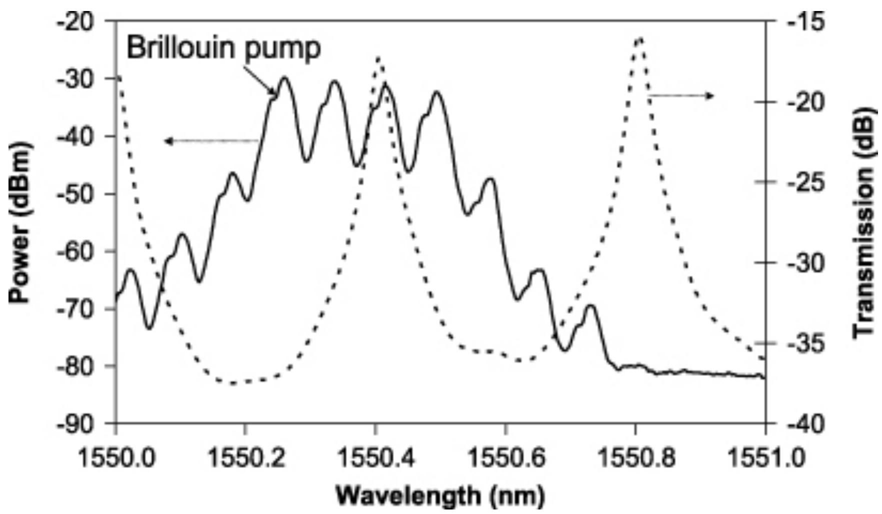

Figure 3. Brillouin fibre laser spectrum with the Brillouin pump and three adjacent Stokes with a

similar power level. The transmission profile of the microring filter thermally tuned to overlap with the second Stokes line is shown.

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The filtered Brillouin signal is shown in figure 4. Figure 4(a) shows the extraction of the Brillouin pump. Mode suppression can be observed after the microring filter, with a suppression ratio of more than 12 dB. The 3 dB spectral width of the Brillouin pump is also observed to be reduced to 0.026 nm, which corresponds to the transmission bandwidth of the microring filter. Selection of the Stokes signals of the Brillouin fibre laser is achieved by controlling the temperature of the microring filter, and the spectral profile of individual Stokes signals after filtering is shown in figures 4(b)–(d). Likewise, a side mode suppression of more than 12 dB and spectral narrowing are observed for all the measured Stokes signals.

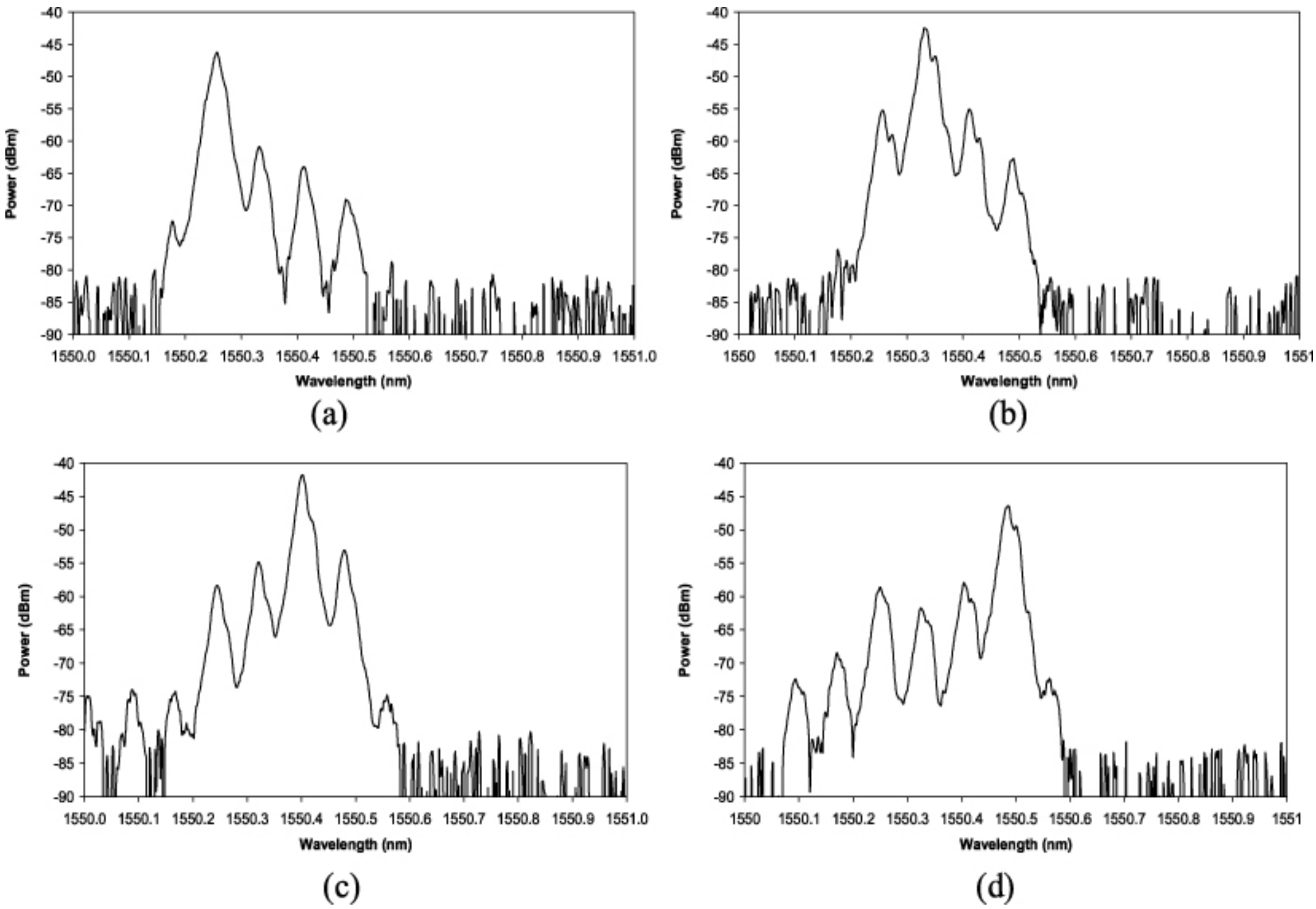

Figure 4. Brillouin fibre spectra after the microring filter with the extraction of (a) the Brillouin pump and (b)–(d) the first, second and third Stokes lines, respectively.

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Extraction of individual Stokes lines of a Brillouin fibre laser using a microring filter is achievable using a high index contrast waveguide material such as SiON. The transmission bandwidth of the mirroring filter is smaller than that of the generated Brillouin Stokes lines, resulting in narrower Stokes lines after filtering. However, this narrowing of the filtered lines should not have a significant deteriorating effect on the signal. The mirroring filter spacing of 50 GHz can be changed by controlling the microring radius. The microring filter has a temperature response of ~16 pm $°C^{-1}$ which is similar to that of a fibre laser. This relatively high temperature response also enables the selection of Brillouin Stokes lines by thermal tuning. The present side mode suppression ratio of ~12 dB can be improved by improving the *Q*-factor of the microring resonator, or cascading multiple microring resonators to achieve a higher extinction ratio. However, the improvement in mode selection quality should be balanced by the trade-off of insertion loss of the filter as a whole.

4. Conclusion

In this work, extraction of a single channel Brillouin Stokes line from a comb generated by a Brillouin fibre laser has been achieved using a SiON microring resonator. Individual extraction of the Brillouin pump and adjacent Stokes channels has been demonstrated using a 50 GHz microring resonator with narrow transmission band and a side mode suppression ratio of more than 12 dB. In addition, selection of Brillouin Stokes lines is possible using thermal tuning. A higher suppression ratio can be achieved by improving the *Q*-factor of the microring, as well as using a microring array. Current spacing of 50 GHz can also be customized by varying the microring radius to achieve larger filter spacing. The use of an on-chip narrowband filter will provide additional functions to the integrated optics and allows the comb spectrum from the Brillouin fibre laser to be used as a signal source in a DWDM network system.

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