

Ultra-narrow linewidth single longitudinal mode Brillouin fiber ring laser using highly nonlinear fiber

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Abstract

In this letter, we demonstrate a single longitudinal mode (SLM) Brillouin fiber laser by using highly nonlinear fiber (HNLF) as the nonlinear medium in which the stimulated Brillouin scattering effect takes place. The first Stokes line is generated at a threshold power of 18 dBm with a wavelength shift 0.08 nm from the Brillouin pump. The signal-to-noise ratio of the first Stokes line is measured to be ~58 dB. To the best of the authors' knowledge, this is the first report of a 0.7 kHz ultra-narrow linewidth of an SLM Brillouin fiber laser, using HNLF as the nonlinear medium, which features a simple cavity configuration.

1. Introduction

Narrow linewidth Brillouin fiber lasers (BFLs) applying low-phase noise and intensity noise are fast appearing as an ideal source for applications such as in coherent communications, high resolution spectroscopy and sensors [1, 2]. To meet these needs, however, there is an immediate requirement to develop laser systems with an extremely narrow linewidth [3–5], in particular single longitudinal mode (SLM) fiber lasers. Many approaches have been explored in the development of SLMs, and as a result of the extensive fiber cavity length, mode hoppings becomes a predominant issue. Mode-hopping can be reduced, as demonstrated by the use of fiber Bragg gratings (FBGs) and saturable absorbers (SAs) [6, 7]. Other approaches have also been demonstrated, such as that by Bernhardt *et al*, who reported an emission linewidth of 1.7 kHz using an approximately 1 cm long erbium-doped waveguide channel [3], while Wang *et al* realized an ultra-narrow linewidth of less than 2.0 kHz based on Rayleigh scattering in non-uniform optical fiber [4]. Recently also, a linewidth of less than 6.0 kHz linewidth has been reported in a

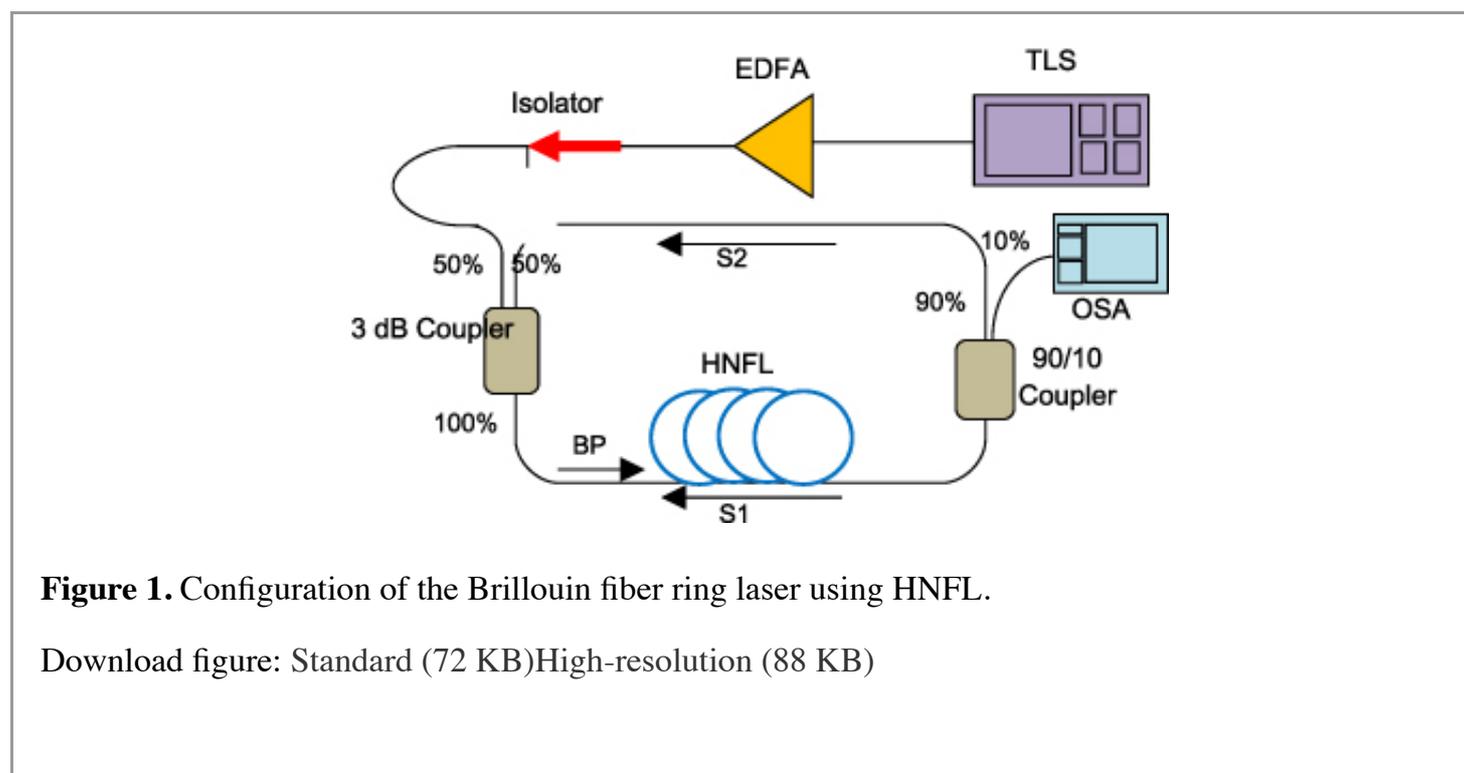
single-pass, single mode fiber (SMF) [5]. The magnitude of Stokes radiation for these lasers is generally several orders narrower than the pump laser.

Another interesting alternative would be to use highly nonlinear fibers (HNLFs). HNLFs are a very promising device for future photonics networks, as they can be easily interfaced with conventional single mode fibers and are able to maintain single mode operation while still retaining a high nonlinearity coefficient [8]. HNLFs are commonly used as a medium for supercontinuum light generation, Raman amplification, optical switching and optical sampling [9–11]. There are several advantages of HNLFs, such as higher index differences and smaller effective mode areas as compared to standard SMFs. As such only a short HNLF length is required to obtain nonlinearity characteristics similar to much longer conventional fibers. This allows for a compact BFL system to be realized that can generate an ultra-narrow linewidth SLM output.

In this work, an ultra-narrow linewidth SLM output is obtained from a BFL based on an HNLF as the nonlinear medium in which the stimulated Brillouin scattering (SBS) effect takes place. The first Stokes line is generated at the threshold power of 18 dBm with a wavelength shift 0.08 nm from the BP signal. The signal-to-noise ratio of the first Stokes line is measured to be ~58 dB. To the best of the authors' knowledge, this is the first report of a 0.7 kHz ultra-narrow linewidth of the SLM BFL by using HNLF as the nonlinear medium which features a simple cavity configuration.

2. Experimental setup

Figure 1 illustrates the experimental implementation of a BFL laser using HNLF as the nonlinear medium.



In order to produce a narrower Stokes linewidth, an all-fiber ring resonator setup is required. A tunable laser source (TLS) with the maximum output power of 13 dBm at 1550 nm (linewidth \approx 260.0 kHz) is injected into the EDFA to be amplified to an output power of about 26 dBm. This is then injected into the ring cavity through an optical isolator, which is connected to one of the 50% input ports of the 3 dB fused optical coupler. The optical isolator is used as a protection device in order to avoid any reflected signals that may damage the TLS. The 100% port of the coupler is connected to a 100 m HNLF which functions

as the medium for generating the Brillouin Stokes line while the other end is connected to the common port of a 90/10 coupler. Typically, a longer length of nonlinear medium is required to yield a narrower linewidth and the required spacing for SLM [12]. Using the HNLF, however, requires a short length and, as the HNLF can generally be wound into a very small diameter, thus a compact device can be realized [8]. The 90% port of the tap coupler is then connected to the remaining 50% port of the 3 dB coupler, thus completing the laser cavity. The 10% port of the 90/10 coupler is fed into an ANDO AQ6317C optical spectrum analyzer (OSA) with a resolution of 0.02 nm.

The generation of the Brillouin Stokes line takes place when the optical power of the BP signal exceeds the threshold power for yielding the first downshifted Stokes signal (S1). S1 then travels from the HNLF in the opposite direction to the BP signal, in a clockwise direction. A portion of S1 is tapped out at the 10% port of the fused coupler and the remaining 90% oscillates in the ring cavity so as to generate the second Stokes line (S2). This process continues as long as the signal power exceeds the threshold value of the subsequent Stokes generation [13]. For comparison purposes, the laser output is also measured using a high resolution APEX AP2051A OSA with a resolution of 0.16 pm. Measurements at a resolution this high have yet to be reported, and will allow for a very detailed analysis of the spectral form to be undertaken.

3. Results and discussion

Figure 2 shows the obtained spectrum from the proposed fiber laser. The BP is set at an operating wavelength of 1550 nm, with a peak power of 26 dBm after EDFA amplification. The spectrum obtained using the OSA with the lower resolution is shown in figure 2(a). Using this OSA, four Brillouin Stokes lines are observed, which correspond to the second, fourth, sixth and eighth Stokes lines based on the configuration of the laser as shown in figure 1.

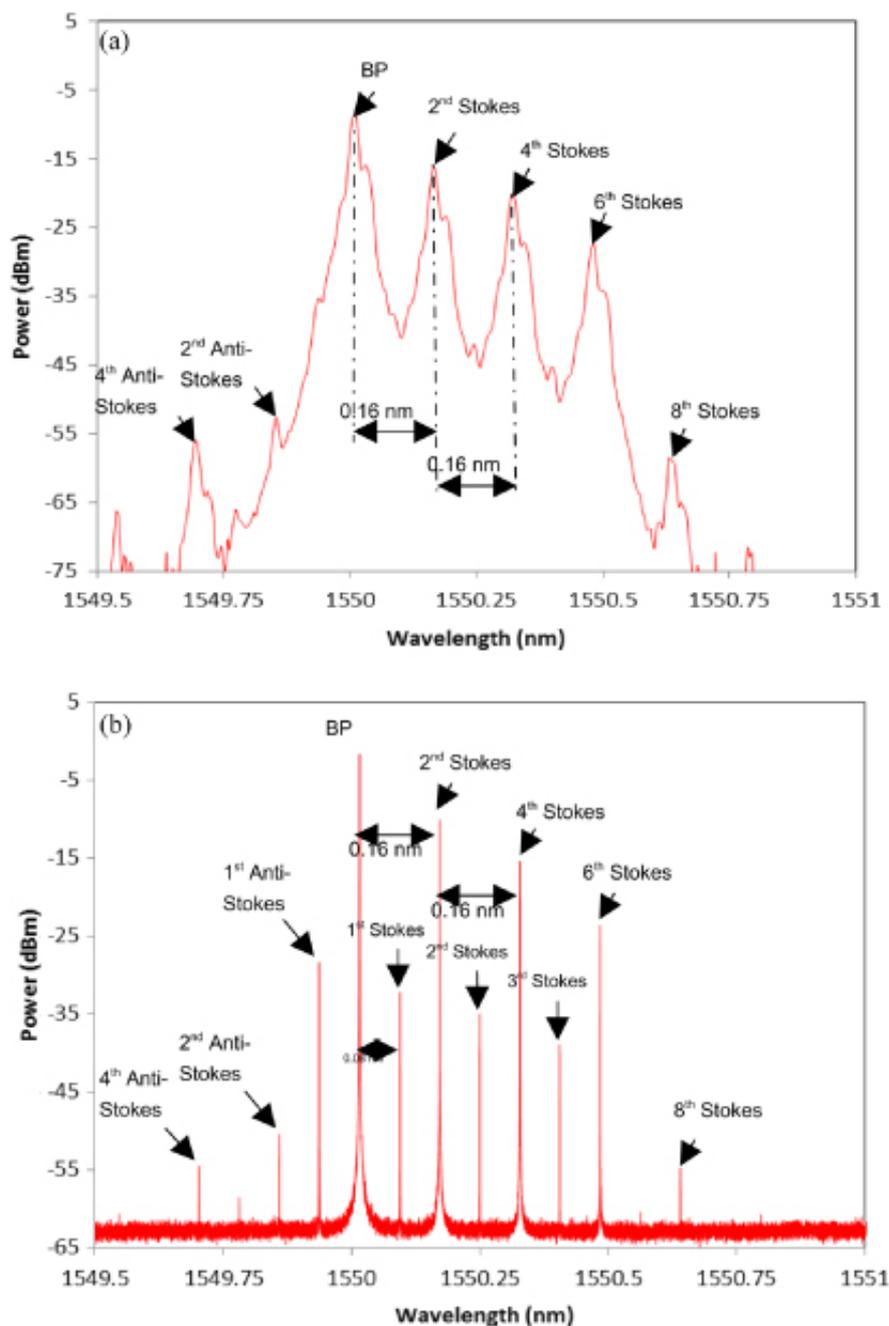


Figure 2. The output spectrum obtained at a BP power of ≈ 26 dBm (after amplification) at a BP wavelength of 1550 nm using the OSA with a resolution of (a) 0.02 nm and (b) 0.16 nm.

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The Stokes lines generated span from 1550.17 to 1550.65 nm, with the spacing between each consecutive Stokes line being approximately 0.16 nm in the wavelength domain or 20 GHz in the frequency domain.

Figure 2(b) on the other hand shows the output spectrum taken from the high resolution OSA. It is very interesting to note that under the higher resolution, the spectrum obtained indicates the presence of the odd Stokes line, particularly the first to third Stokes lines at wavelengths of approximately 1550.08, 1550.25 and 1550.41 nm respectively. Indications of higher-ordered odd Stokes lines are also observed,

though the powers of these peaks are low enough that they blend in with the noise floor. From this observation it can be deduced that, even though the above-described ring configuration should only allow for double-spaced Stokes outputs, in reality both even and odd Stokes lines propagate in both directions in the laser cavity. In this regard, previous reports of double-spaced Brillouin fiber lasers such as those in [14–16] may be misleading, although this would have resulted from the limited resolution of the OSAs used, as opposed to a misinterpretation of data.

Figure 3(a) shows the output spectrum taken from the OSA with a resolution of 0.02 nm, while figure 3(b) shows the same spectrum obtained when using the OSA with a resolution of 0.16 pm taken at a signal power of 18 dBm after being amplified by the EDFA with a TLS output of -13 dBm. The threshold power for the first Stokes generation is about 18 dBm, as can be seen from figure 3(a), which implies that lower powers than this value do not generate any Stokes signals. From figure 3(a), it is observed that the output powers of the BP and the first Stokes line are about -28 and -8 dBm respectively, with a wavelength spacing of 0.08 nm between the BP signal and the first Stokes line, which is not distinct. Using the 0.16 pm OSA, as shown in figure 3(b), the spacing between the BP and the first Stokes line is well defined, giving a spacing of about 0.08 nm, with an output power of about -24 dBm and -3 dBm respectively.

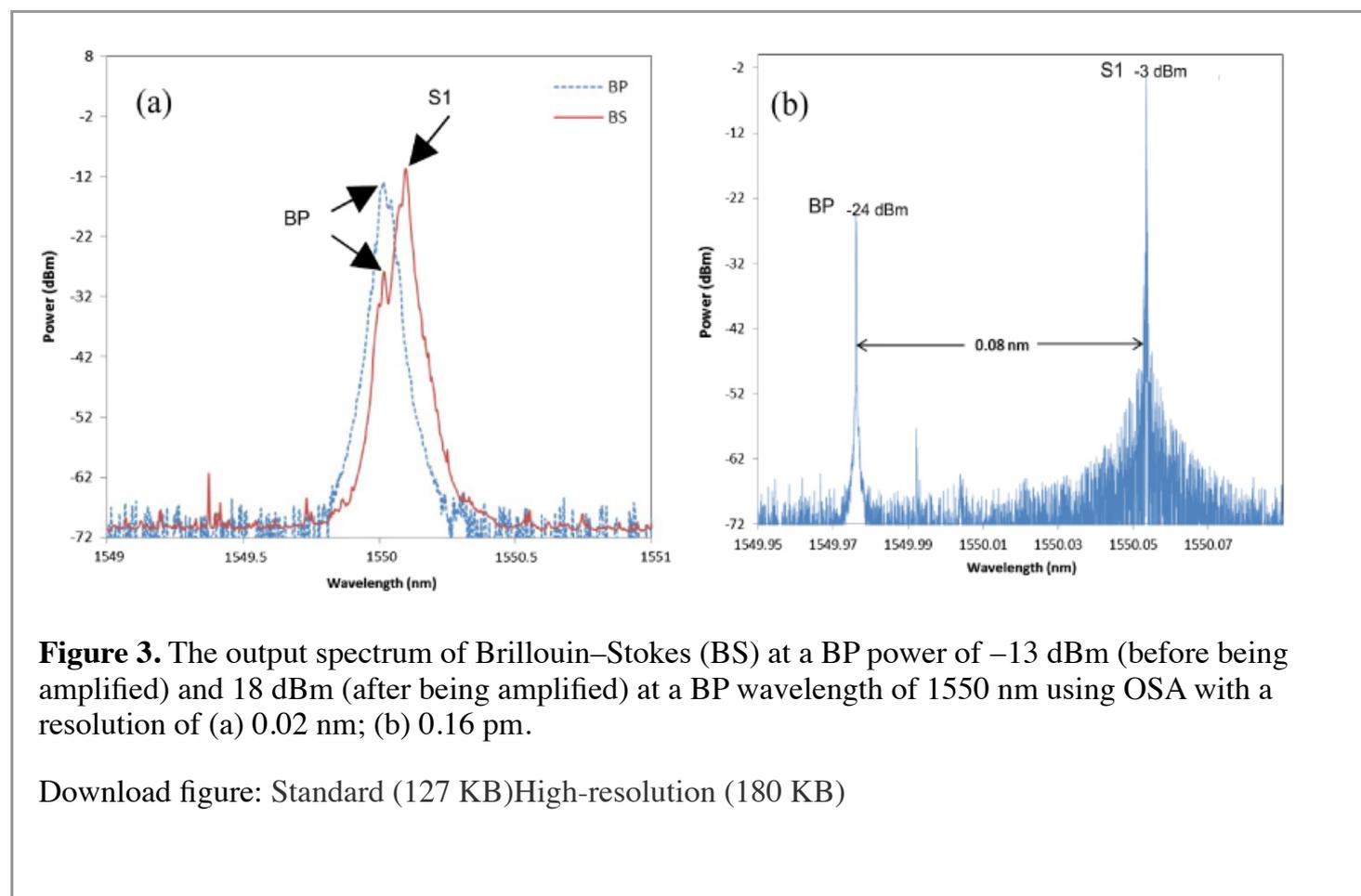


Figure 3. The output spectrum of Brillouin–Stokes (BS) at a BP power of -13 dBm (before being amplified) and 18 dBm (after being amplified) at a BP wavelength of 1550 nm using OSA with a resolution of (a) 0.02 nm; (b) 0.16 pm.

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The output wavelength is tunable within the range of between 1540 and 1570 nm by simply varying the wavelength of the TLS since no gain media is adopted in the cavity [5]. The signal-to-noise ratio of the first Stokes line is about 58 dB, as measured, and this has not been highlighted in any other works. Further increase of the BP power will result in more Stokes lines being generated, as can be seen from figure 2.

Since the interest of this work is to generate SLM ultra-narrow linewidth output, therefore the BP signal needs to be filtered off at the output. A Fabry–Perot filter (FP-filter) is used in this setup, which would

transmit the first Stokes line while suppressing the BP signal. Figure 4 shows the output spectrum of the single line of an ultra-narrow linewidth output after the suppression of the BP signal, whereby the inset shows the spectrum of the FP-filter. The output power of the BP signal is suppressed by about 29 dB, which results in a remaining BP signal with a low output power of about -53 dBm. By a proper choice or having a better filtering system, with a higher extinction ratio, this BP signal can be totally eliminated.

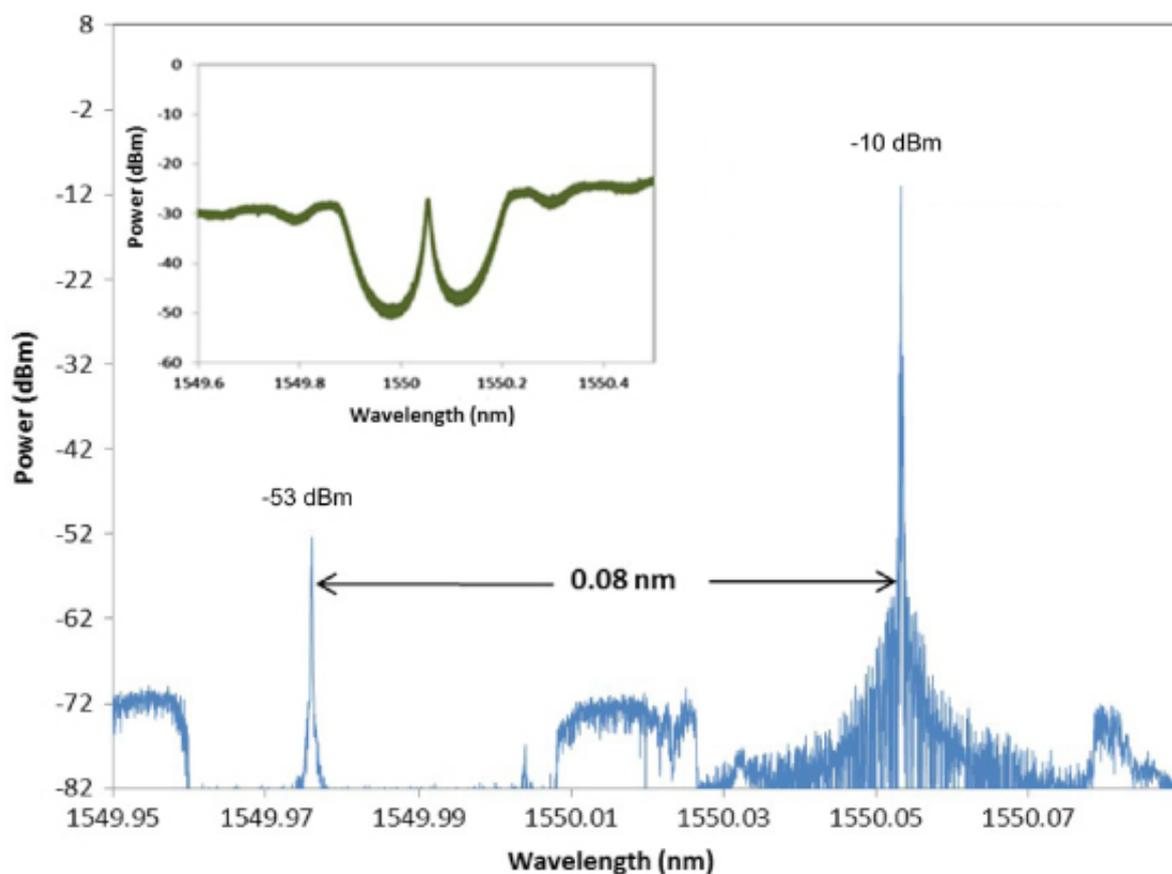


Figure 4. The output spectrum after filtration by a Fabry–Perot filter (inset: the spectrum of the FP filter).

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It is also observed that the output power of the first Stokes line decreases by about 8 dB as compared to that seen in the spectrum without using the filter, and this can be improved by having a filter with better transmittivity at this wavelength.

Figures 5(a) and (b) show the linewidth measurement of the BP signal and the SLM Brillouin fiber laser respectively. The two spectra are obtained independently using the self-heterodyne technique. A delayed self-heterodyne detection technique [17, 18] is used for the linewidth measurement since it could not be measured directly from the OSA due to its resolution of only 20 MHz or 0.16 pm. The beat tone produced is displayed at a frequency shift of 80 MHz which is broadened by the laser linewidth. An Anritsu MS2667C radio frequency spectrum analyzer (RFSAs) is used to measure the linewidth of laser output through a high speed Agilent 83440C photo-detector.

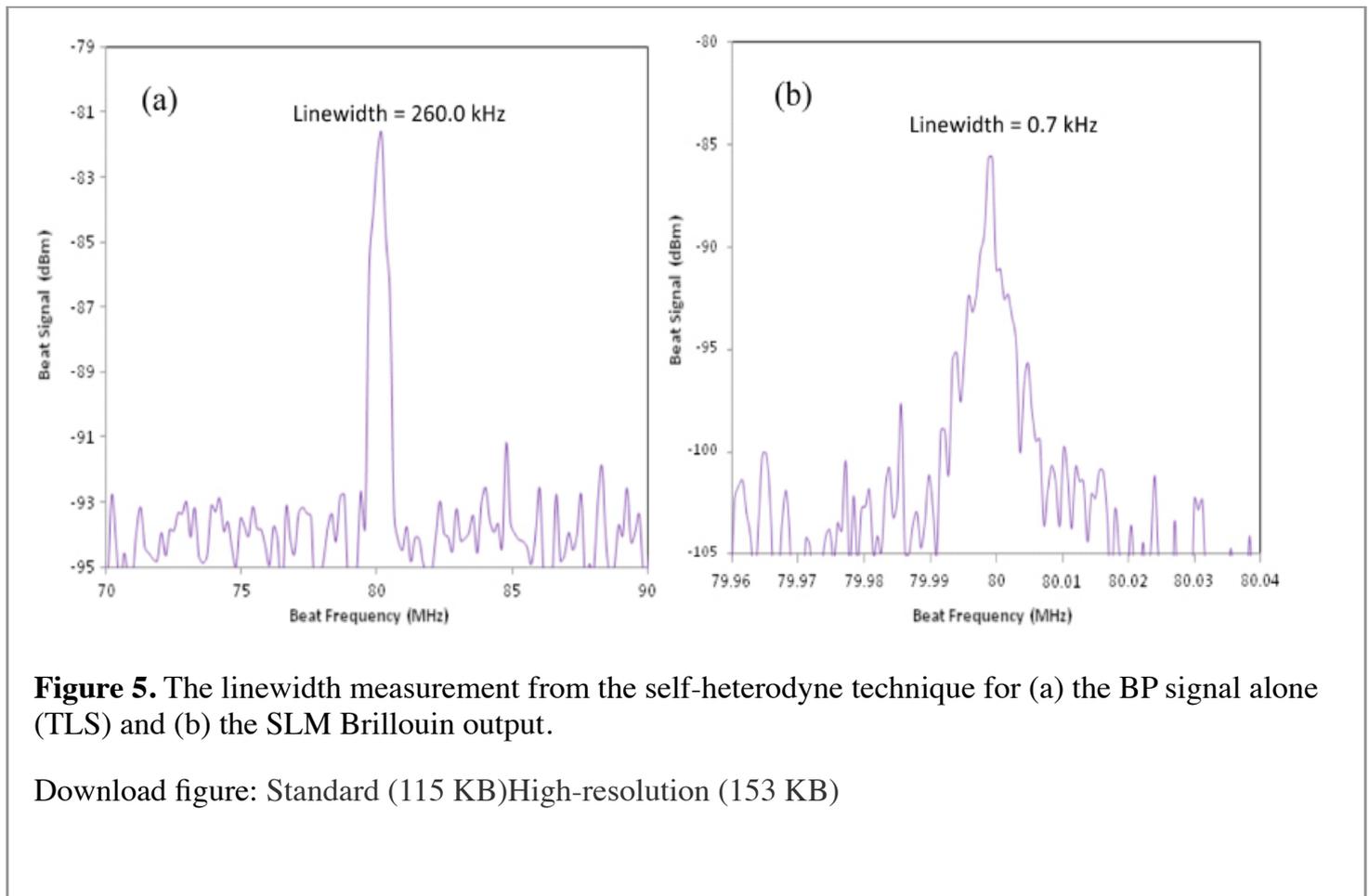


Figure 5. The linewidth measurement from the self-heterodyne technique for (a) the BP signal alone (TLS) and (b) the SLM Brillouin output.

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The linewidth of BP as shown in figure 5(a) is 260.0 kHz, whereas the linewidth of the SLM Brillouin fiber laser is 0.7 kHz taken at the 3 dB point. The correlation between the Stokes linewidth, $\Delta\nu_{\text{Stokes}}$ and the BP linewidth, $\Delta\nu_{\text{pump}}$, as given in [17, 19], can be written as:

$$\Delta\nu_{\text{Stokes}} = \frac{\Delta\nu_{\text{pump}}}{\left(1 + \frac{\pi \Delta\nu_{\text{B}}}{-c \ln \frac{R}{nL}}\right)} \quad (1)$$

where $\Delta\nu_{\text{B}}$ is the Brillouin gain bandwidth, L is the cavity length, R is the coupling ratio and c is the velocity of light in a vacuum, while n is the refractive index of the fibre. From the equation, the estimated linewidth of the proposed SLM Brillouin laser output is 0.65 kHz, which agrees well with the measurement of 0.7 kHz. This is, to the best of the authors' knowledge, the narrowest Brillouin linewidth measured using the self-heterodyne technique in comparison with other reports [1, 5, 20].

4. Conclusion

An SLM BFL with an ultra-narrow linewidth of 0.7 kHz is demonstrated using a HNLf. A threshold power of 18 dBm was obtained at the first Stokes line with a wavelength spacing of 0.08 nm from the BP signal. The signal-to-noise ratio of the first Stokes line is measured to be ~ 58 dB. To the best of the authors' knowledge, this is the first report of a 0.7 kHz ultra-narrow linewidth of the SLM BFL using HNLf as the nonlinear medium.

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