Investigation of the Dynamical Behavior of a High-Power Laser Diode Subject to Stimulated Brillouin Scattering Optical Feedback

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Investigation of the dynamical behaviour of a high-power laser diode subject to stimulated Brillouin scattering optical feedback

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***Abstract*—In this work, we propose a new scheme of optical feedback using stimulated Brillouin scattering (SBS). A high-power laser diode emitting at 1450 nm stimulates Brillouin back-scattering in a 4km-long optical fibre and the back-scattered light is injected back into the laser diode for optical feedback. The experimental results with RF spectrum exhibit clearly the Brillouin frequency shift at 11.46 GHz. Although the frequency shift is very large, the laser diode subject to optical feedback using SBS shows abundant dynamics. RF spectrum maps are also established with respect to the laser drive current. The results are compared with the ones for conventional optical feedback and it is clearly shown that the dynamical behaviours for both the configurations are very different. The investigation with autocorrelation functions reveals that the time-delay signature vanishes completely using the SBS feedback scheme unlike the conventional feedback one.**

***Index Terms*—optical feedback, stimulated Brillouin scattering, chaotic laser**

I. Introduction

Optical feedback influence on properties of semiconductor lasers has been studied extensively since the early laser development in the 1970's. The main laser diode properties to be modified when subject to optical feedback are the threshold gain, the resonant frequency and the spectral linewidth[1], [2]. The dynamical behaviour of laser diodes shows different dynamical regimes, including chaotic regime[3]. Optical feedback can be achieved with a simple external mirror[4], [5]. There exist other configurations such as very-short caviry feedback[6], filtered optical feedback[7] and phase-conjugated optical feedback[8], [9]. Thanks to their high-complex dynamical behaviour, chaotic lasers have been used for number of applications such as chaos secure communications[10], [11], [12], chaotic lidar, chaotic radar[13], chaotic optical time-domain reflectometry[14], random number generation[15], reservoir computing[16], [17] and rogue wave generation[18], [19].

Recently, chaotic lasers have been used in the Brillouin scattering area such as suppression of stimulated Brillouin scattering (SBS) [20], Brillouin optical correlation-domain reflectometry and analysis [21] and dynamic Brillouin grating generation [22], [23]. SBS is an inelastic nonlinear scattering that occurs due to the interaction between the pump and Stokes fields through an acoustic wave. The scattered light is down-shifted in frequency because of the Brillouin grating. In a standard single-mode telecom optical fibre, Brillouin frequency shift (BFS) is typically around 11 GHz at 1550 nm [24].

One of the drawback of optical feedback laser diodes is the time-delay signature (TDS) due to the external cavity round-trip time. The TDS is an important key in secure chaos communications or in random-number generation. In order to enhance the security or the randomness of number generation, the TDS must be suppressed from chaotic signals. Some studies have shown that the TDS can be suppressed using post-signal processing such as self-interference[25], SBS [26], [27] or optical time-lens [28]. However, there is no optical feedback configuration to generate directly TDS-free signals from a laser diode.

In this letter, we propose a new optical feedback configuration using SBS in order to supress the TDS. As the Brillouin back-scattered light frequency is down-shifted by around 11 GHz, this configuration can be considered as frequency-shifted optical feedback configuration. Such a configuration has been studied mostly using an acousto-optic modulator[29], [30], never using BFS. Our new scheme also exploits random feedback from SBS which is considered as a random process. The random feedback is new and has never been reported. A high power laser diode is used for stimulating Brillouin scattering in a 4km-long fibre. Although chaotic behaviour of a laser diode reduces SBS significantly[20], the laser diode shows different dynamical behaviours by injecting back the stimulated Brillouin scattered light into the laser diode. The results will be compared with the ones in a conventional optical feedback (COF) in terms of L–I curves and radio-frequency (RF) spectra. A comparison will also be made using RF spectrum maps with respect to the laser drive current. Moreover, SBS occurs all along the fibre, rather than a distance-defined reflection. Hence, the optical feedback using SBS can be considered optical feedback using an infinite number of external mirrors. This feature gives a possibility of TDS suppression. For this purpose, we will also investigate autocorrelation functions.

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II. Experimental setup

The schematic diagrams for conventional- and stimulated Brillouin back-scattering- optical feedback are illustrated in Fig. 1(a) and (b), respectively. It consists of a high-power laser diode (LD) of 3.1mm-long Fabry-Perot cavity, emitting at 1450 nm (3SP technologies). Such a laser diode is used to pump Raman fibres for Raman amplification. The laser temperature is set to 25°C and the maximum free-running laser power is 270 mW at a current of 1000 mA. The LD light is injected into a 4km-long single-mode fibre spool through two optical circulators (OC) and a coupler 90/10. The 90%-port of the coupler is used for injecting into the fibre and the power injected into the fibre is reduced to 140 mW at 1000 mA because of optical losses from the components. The other 10%-port is used for monitoring the laser output with a 12GHz photodetector (PD). In order to protect the PD, the monitoring power is attenuated to 1 mW at the maximum laser power through a variable optical attenuator (VOA). The PD output signal is visualised by a radio frequency (RF) spectrum analyser (26.5 GHz). The optical attenuation of the fibre spool at 1450 nm is around 1.2 dB (a linear attenuation of 0.3 dB/km). The isolator placed after the long fibre ensures unidirection, avoiding reflection from the fibre tip.

For COF, the isolator output is injected into the LD via VOA2 to adjust the optical feedback ratio, implementing a conventional closed-loop as depicted in Fig. 1(a). In this work, the feedback ratio is fixed to 0.1 % (−30 dB) and the round-trip time of the closed loop with the 4km long fibre is around 21 µs. It is also noted that it is incoherent optical feedback. According to Ref. [3] the distance of the optical feedback in semiconductor lasers does not affect Regime IV (chaotic regime). For SBS optical feedback (SBSOF), the back-scattered light of SBS occurred in the fibre is collected by Port 3 of OC2 and injected into the LD through Port 1 of OC1, setting up a SBS closed-loop configuration as shown in Fig. 1(b). To begin with, the optical feedback ratio with SBS is undefined as the back-scattering rate is unknown. When Port 1 of the OC1 is not connected, the setup is in an open-loop configuration.

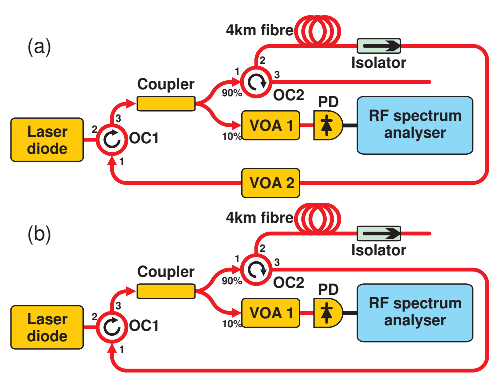

Fig. 1. Schematics of the experimental setup for (a) COF and (b) SBSOF. OC: optical circulator, VOA: variable optical attenuators, PD: photo-detector.

Hence, in this work, three configurations are considered:

1) Open-loop configuration: a free-running laser diode
2) COF configuration: 0.1% feedback in a ring cavity with a 4km-long fibre
3) SBSOF configuration: back-scattering cavity with unknown ratio

III. Experimental results

First, L–I characteristics have been investigated in the open-loop, COF and SBS closed-loop configurations. Figure 2(a) traces L–I curves measured at the 10%-port of the coupler in the three configurations without VOA1 and PD. In the open-loop configuration, the laser threshold is measured as 155 mA (see the inset of the figure) and the power at 1000 mA is obtained as 19.6 mW from the L–I curve shown in the red curve of the figure (lowest curve). Note that the direct laser output power is measured as 270 mW, hence a factor of 14.2 must be taken into account to work out the real laser output power in the figure. The power measured just before injecting into the fibre spool is 140 mW at 1000 mA because of the components insertion losses. Therefore, a factor of 7.3 must be considered on the red curve to work out the real injection power. In the COF configuration, the laser threshold is reduced to 133 mA and the laser output power is increased to 20.6 mW at 1000 mA (green curve, uppermost curve). In the SBSOF configuration, the threshold is reduced to 147 mA as the blue curve (middle curve) indicates, but it is noticed that after 350 mA the laser output power in slightly increased. So the blue curve starts initially close to the red one, but goes close to the green one after 350 mA. The power is measured as 20.3 mW at 1000 mA in this case.

Figure 2(b) plots the power back-scattered from the 4km-long fibre, which is measured at port 3 of OC2. In the open-loop configuration, some irregular spikes are observed in the red curve. In fact, the free-running laser shows a broad spectrum as shown in Fig. 3(a) and its spectrum is very unstable. Theses spikes are suggested to be intermittent SBS due to this spectrum instability. The power of these spikes can go up to 20 mW. It is found that the base curve underneath spikes is not flat. Actually, the base curve appears like an L–I curve, measuring around 30 µW at 1000 mA. This back-scattered light is thought to be from Rayleigh scattering with a rate of −36.7 dB compared to the injection power. In the COF configuration, the back-scattered light is measured as only 32 µW at 1000 mA and the curve is similar to L–I curve as the green curve (lowest curve) manifests. As the laser outputs chaotic signal in this configuration, it is expected that no SBS is present[20] and the back-scattered light shown in the figure is thought to be as a result of Rayleigh scattering. The scattering rate is measured as −36.7 dB which is similar to the one in the open-loop configuration. In the SBSOF configuration, the back-scattered light is measured with another 90/10 coupler. Since the 10%-port is used for monitoring the back-scattered light power, the measured power represented in the blue curve of Fig. 2(b) has been multiplied by a factor of 10. As seen in the figure, the light increases significantly at around 306 mA unlike the other configurations. It is suggested that this current is the Brillouin threshold current for our setup. At this current, the laser output power in the red curve of

Fig. 2(a) is obtained as 3.77 mW. By multiplying the factor of 7.3, the power injected into the fibre is expected to be 27.5 mW which is considered as the Brillouin threshold power. It is clearly seen in the figure that the back-scattered power fluctuates strongly. As will be discussed later, SBSOF causes noise-like intensity fluctuations. In Fig. 2(b), the SBS light saturates to 450 µW as increasing the current. Therefore, SBSOF ratio is around −25 dB compared to the injection power. The reason for this saturation might come from the fact that as increasing the current, the noise-like fluctuation due to SBSOF becomes stronger, leading to preventing further SBS. Hence, the saturation power of 450 µW may be a trade-off between SBS and noise-like fluctuations in our setup. It is also noticed that the SBSOF ratio is 11.7 dB greater than that of the Rayleigh scattering rate. In summary, the parameters measured in the three configuration are shown in Tab.I:

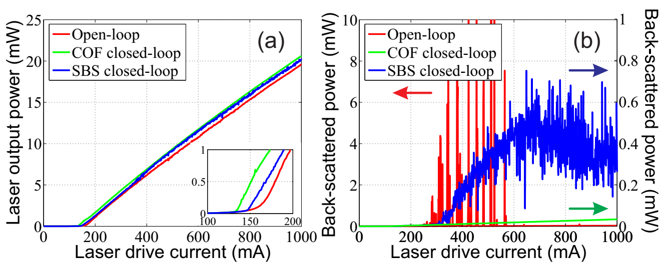

Fig. 2. (a) L–I curves measured at the 10%-port of the coupler and (b) back-scattered power measured at port 3 of OC2. See the left y-axis scale for the red curve and the right one for the green and blue curves as indicated with arrows. The inset of (a) is a zoom-in of the L–I curves near the thresholds.

TABLE I
PARAMETERS MEASURED IN THE THREE CONFIGURATIONS.

Configuration	feedback ratio (dB)	threshold current (mA)	Output power (mW) at 1000 mA
Open-loop	N/A	155	19.6
COF	−30	133	20.6
SBSOF	−25	147	20.3

The reason for which only three configurations are considered is that these configurations are the most pertinent configurations in our work. The open-loop configuration is the case of a free-running laser. It is important to compare the results without and with feedback. The COF configuration is considered as a reference configuration in our work. In order to compare our new feedback configuration with the COF configuration, a feedback ratio of −30 dB has been chosen in the COF configuration because the feedback ratio from the SBS is around −25 dB at most.

Laser output spectra have also been measured in the three configurations. The measurements have been undertaken at the 10%-port of the coupler and the resolution of our optical spectrum analyser is 0.07 nm. The spectrum of the free-running laser is depicted in Fig. 3(a). It is broad and unstable. Actually, such a laser is used as a pump laser with a fibre Bragg grating for Raman amplifiers. The fibre Bragg grating acts as a filter and mirror for optical feedback, and allows stabilising the optical spectrum. In our setup, no fibre Bragg grating is used and the spectrum is unstable with noise. Nevertheless, SBS occurs intermittently as seen in Fig. 2(b). In the COF configuration, the laser spectrum changes radically to multimode spectrum as shown in Fig. 3(b). The spectrum is also stabilised without noise in the COF configuration. Figure 3(c) displays the spectrum of the SBSOF configuration and it is different to the spectra in Fig. 3(a) and (b). Although the spectrum of the free-running laser diode is broad and multimode emission-like, SBS still occurs with a small amount compared to the injected power according to the blue curve in Fig. 2(b). The spectrum appears very noisy because in the SBSOF case, the SBS stokes wave with BFS are added into the spectrum for each noise peak, leading to noisier spectrum.

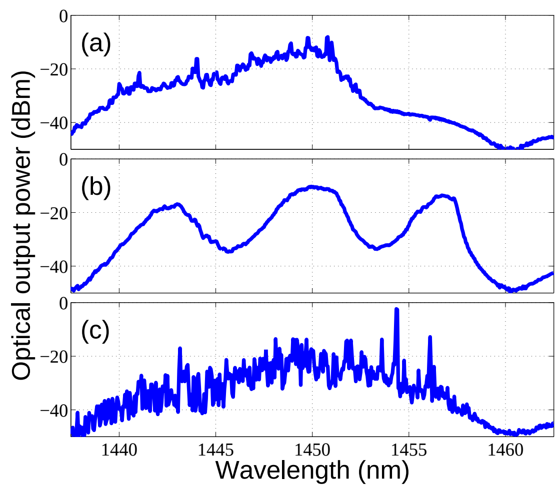

Fig. 3. Optial spectra measured at 1000 mA for (a) the open-loop configuration, (b) the COF closed-loop configuration with a feedback ratio of −30 dB and (c) the SBS closed-loop configurations.

In order to investigate the dynamical behaviour of the laser diode, we have measured RF spectra for the three configurations. Figure 4 depicts spectra measured at 1000 mA with a video bandwidth of 10 kHz in the SBS, COF closed-loop and open-loop configurations. In the open-loop configuration, the spectrum is almost the same as the noise floor of the system. But a peak at 14.41 GHz is observed in the spectrum. This peak appears to be the internal cavity frequency (side-mode) from the 3.1mm-long cavity of the LD. Despite of a small feedback ratio of −30 dB, the spectrum in the COF closed-loop configuration exhibits rich dynamics up to 16 GHz compared to the open-loop one. The peak at around 3 GHz results from the relaxation oscillation frequency of the laser diode. The side-mode at 14.41 GHz is also present. Figure 4(c) exhibits zoom-in spectra at 3 GHz. The red trace represents the spectrum of the open-loop noise floor. The blue trace indicates the spectrum for COF. The external cavity mode is clearly seen in the spectrum and the frequency is measured as 47 kHz due to the 4km-long fibre. Such external cavity frequencies are inevitably present in all feedback configurations. They are also clearly visible even in a very-short cavity of which the frequency is greater than the laser relaxation oscillation frequency[6]. On the other hand, the spectrum in the SBS closed-loop configuration appears very different to that in the COF one as shown in Fig. 4(b).

The spectrum manifests abundant dynamics in low and high frequency bands and appears noisy. As the optical spectrum in the SBSOF configuration (See Fig. 3(c)) is noisy due to BFS at each noisy peak, the RF spectrum also appears noisy. In Fig. 4(d), the blue trace corresponds to the spectrum for SBSOF and no external cavity frequencies are observed unlike that in the COF configuration. This result is promising for the TDS suppression. It is also seen from the figure that the BFS is present at 11.46 GHz which corresponds to the one calculated with the theory. This is a clear evidence of the presence of SBS in the system. The Brillouin gain spectrum linewidth is measured as 30 MHz. It is also clearly noticed that the side-mode is shifted from 14.41 GHz to 15 GHz because of SBSOF.

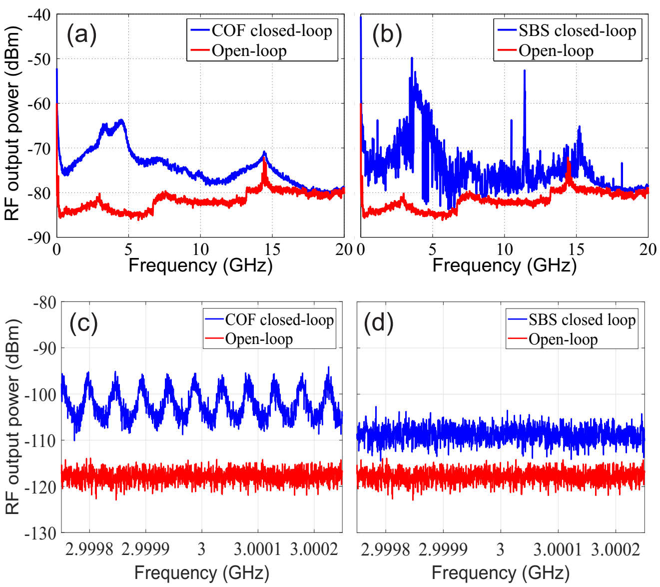

Fig. 4. RF spectra measured at 1000 mA for (a) the COF closed-loop configuration and (b) SBS closed-loop configuration. For comparison, an RF spectrum for the open-loop configuration is also plotted in each figure. The y-axis scale of (b) is the same as the one in (a). (c) and (d) are the zoom-in spectra at a centre-frequency of 3 GHz with a span of 500 kHz for the three configations. An averaging of 10 has been performed in order to reveal the external-cavity frequency clearly. The y-axis scale of (d) is the same as the one in (c).

RF spectrum mapping is also undertaken by scanning the laser drive current from 0 mA to 1000 mA at every 5 mA. Figure 5 presents the RF spectrum maps for COF and SBSOF. The map in the COF configuration with a feedback ratio of −30 dB (Fig. 5(a)) manifests very abundant dynamics. In the map, the side-mode is seen at 14.41 GHz and the relaxation oscillation frequency can also be seen as increasing the current. The spectrum in the SBSOF configuration as shown in Fig. 5(b) appears very different to that in the COF one. The relaxation oscillation frequency is clearly visible in the spectrum and this frequency tends toward 2.7 GHz as increasing the laser drive current. In fact, the clear appearance of the relaxation oscillation frequency is attributed to the Ralyleigh scattering from the long fibre. Moreover, the relaxation oscillation frequency starts appearing from 190 mA whilst SBS starts from 306 mA. So it is found that Rayleigh scattering occurs in the fibre before SBS. In Fig. 5(b), the BFS is clearly seen from 306 mA at 11.46 GHz. As the SBS starts from this current, the peak at 15 GHz and the other at 3.6 GHz also start emerging at the same time. Besides, the internal cavity frequency is shifted from 14.41 GHz to 15 GHz as seen in Fig. 4(b). Despite of the presence of Rayleigh scattering, these peaks are a clear evidence of the strong contribution of SBS. In addition, the SBSOF ratio is −25 dB whereas the Rayleigh scattering rate is −36.7 dB. As SBS is stronger than Rayleigh scattering in the fibre, this noise-like dynamics of the laser mainly originate from SBS. As increasing the current, the spectrum become broader and its power goes higher, leading to stronger power fluctuations. As discussed above, the SBS power saturation is caused by the competition between the strong fluctuation and SBS. So the saturation power of 450 µW is a trade-off between them. We have also carried out another mapping in a COF configuration with a feedback ratio of −36 dB which is similar to the Rayleigh scattering rate. But in Fig. 5(c) only the relaxation oscillation frequency and the side-mode at 14.41 GHz are observed. Therefore it is confirmed that the complex laser dynamics shown in Fig. 5(b) are strongly attributed to SBS. In the COF configuration, the spectrum can slightly be flattened at 1000 mA with a strong feedback (> −20 dB). However, in the SBSOF configuration, we have not observed any flattening of spectrum. It is suggested that this is because of the weak SBS power. Further experiment is needed to investigate this aspect by amplifying the SBSOF.

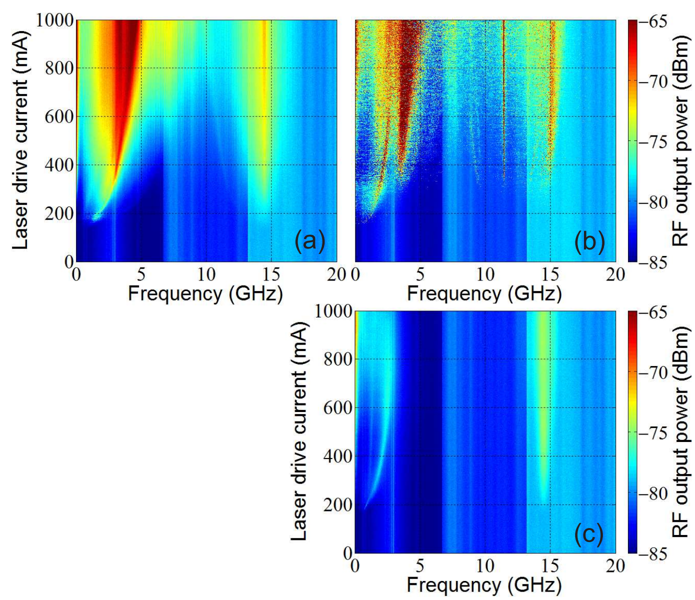

Fig. 5. RF spectrum maps for (a) conventional optical feedback with −30 dB, (b) stimulated Brillouin scattering optical feedback and (c) conventional optical feedback with −36 dB. The y-axis scale of (b) is the same as the one in (a) and the colour-coded scale for RF power in (b) is shared with (a).

We have also investigated auto-correlation functions from timetraces for both the configurations. The autocorrelation function is used for analysing dynamical signals and allows revealing any periodicity in the signal. The value of 1 in the ACF means that it is completely correlated at that time shift. Timetraces are recorded at the 10%-port of the coupler at 1000 mA by the PD and a 15GHz digital oscilloscope with 4 million data points in a window of 100 µs. So the sampling rate is 40 GS/s which is enough to pick up any high frequency fluctuation. The autocorrelation function used in this work is defined in Ref. [28] and plotted in Fig. 6. In the figure, the autocorrelation functions for COF and SBSOF display a very sharp form and they are in fact decorrelated within 1 ns. However, in Fig. 6(a), the autocorrelation function for COF reveals another sharp peak at 21.1 µs. This peak is the time-delay signature which corresponds to the external cavity frequency of 47 kHz. On the other hand, the autocorrelation function for SBSOF in Fig. 6(b) does not manifest such a signature. We have verified that there is no peak neither at around 42.2 µs in the SBSOF configuration. Hence, it is evident that SBS contributes to the suppression of the time-delay signature. By comparing to Refs.[25], [26], [27], [28], it is clearly shown from the figure that the TDS is successfully suppressed in our new configuration. It is noticed from the figure that the sidelobe base is slightly thicker than that of Fig. 6(a). This is due to the BFS at 11.46 GHz which can easily be filtered out by a low-pass filter.

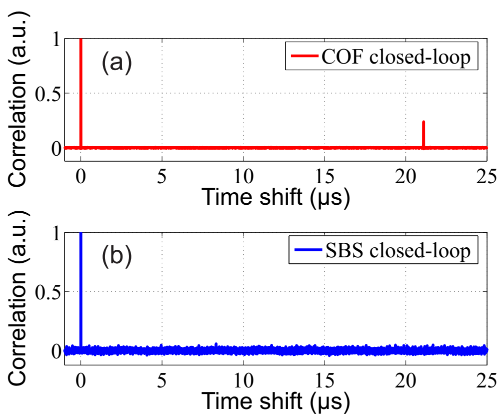

Fig. 6. Autocorrelation functions calculated from a timetrace of 4 million data points over 100 µs (a) for COF and (b) for SBSOF.

IV. Conclusions

In conclusion, we have investigated the dynamical behaviour of the laser diode subject to stimulated Brillouin scattering optical feedback (SBSOF). The Brillouin back-scattered light from a 4km-long fibre is injected into the laser diode for optical feedback. The RF spectrum results clearly indicate the Brillouin frequency shift at 11.46 GHz which is a clear evidence of the presence of stimulated Brillouin scattering (SBS). Such a shift of 11.46 GHz is a very large shift for optical feedback laser diodes. The frequency shift used in frequency-shifted feedback is implemented by an acousto-optic modulator which provides in general a frequency shift of few 100 MHz. Hence, the frequency shift of 11.46 GHz is much greater than frequency shifts obtained by acousto-optic modulators. Despite of such a very large frequency shift, the laser diode with SBSOF shows abundant dynamics. Moreover, the SBS rate is around -25 dB which is 11.7 dB stronger than the Rayleigh scattering rate. As such, this is a clear indication that such complex dynamics originate from SBS rather than Rayleigh scattering. The RF spectrum maps confirm that the optical feedback using SBS strongly contributes to complex dynamical behaviours of the laser diode. By comparing qualitatively with the one for conventional optical feedback (COF), it is clearly seen that the spectral aspect is different for both the feedback configuration. In the SBSOF configuration, the time-delay signature is also successfully suppressed as seen in the autocorrelation function investigation unlike that in the COF configuration.

As Brillouin scattering is described as a random process, SBS provides random feedback which also allows generating complex dynamical behaviours. In the fundamental point of view, this is the first study showing complex dynamical behaviours in a laser diode subject to random feedback via SBS. The signals obtained from random SBSOF are expected to be stochastic. Further study is being carried out to determine the randomness of the signals by studying Lyapunov exponents and Kolmogorov entropy.

In the engineering application point of view, our new random feedback scheme which allows vanishing the time-delay signature is promising in the engineering applications such as enhancing the randomness in random number generation or the security in secure chaos communications. Compared to the other works which uses post-signal processing[25], [26], [27], [28], our configuration is the first configuration of random feedback which allows generating complex signals directly without the presence of the time-delay signature, not suppressing it by any post-signal processing. It can also be used for sensing application as in sensing application with chaotic lasers.

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