IEEE Photonics Journal
An IEEE Photonics Society Publication



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Volume 6, Number 2, April 2014

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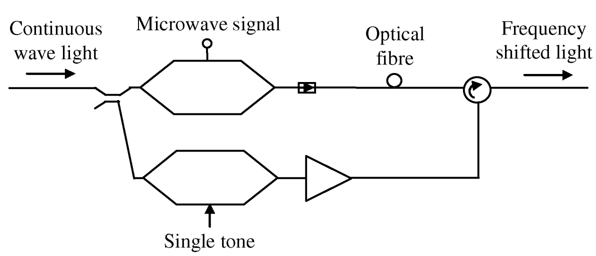


DOI: 10.1109/JPHOT.2014.2312921
1943-0655 

# All-Optical Frequency Shifter Based on Stimulated Brillouin Scattering in an Optical Fiber

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*DOI: 10.1109/JPHOT.2014.2312921*


Manuscript received February 16, 2014; revised March 15, 2014; accepted March 18, 2014. Date of publication March 20, 2014; date of current version April 7, 2014. This work was supported by the Australian Research Council. Corresponding author: E. H. W. Chan (e-mail: erwin.chan@sydney.edu.au).

**Abstract:** A new optical frequency shifter that can shift the light frequency in the microwave or millimeter-wave frequency range is presented. It is based on the use of stimulated Brillouin scattering gain and loss spectrums in an optical fiber to suppress one sideband of a double-sideband suppressed carrier modulation signal while amplifying the other sideband. The new optical frequency shifter only involves optical components and is capable of operating over a wide frequency range with low spurious generation and with tunable capabilities. It can be also used as a single-sideband suppressed carrier modulator. Experimental results demonstrate a 20 GHz frequency shift with a 25 dB signal-to-noise ratio and a widely tunable frequency shifting operation.

**Index Terms:** Optical frequency conversion, optical signal processing, optical fiber communication, optoelectronic devices.

## 1. Introduction

Microwave photonics offers the prospect of overcoming a range of challenging problems in the microwave field. Its key benefits, including the inherent speed and wideband nature, have led to diverse applications that have primarily targeted defense, fiber-radio and radioastronomy areas, for tackling issues of processing wideband fiber-fed distributed antenna signals, and for providing essential electromagnetic interference immunity [1]. Future systems require frequency shifting and modulation to microwave and millimeter wave frequencies with low spurious generation and with tunable capabilities, which is a difficult task using conventional approaches. Microwave photonic techniques can overcome these limitations to not only shift the light component from one optical frequency to another, but also to provide advanced modulation format capabilities such as single-sideband suppressed carrier (SSB-SC) modulation that is required in radio-over-fiber systems and long-haul optical fiber communication systems. Other applications, such as precision laser spectroscopy, quantum optics and optical measurements [2], require the frequency shifting operation and sometimes these applications require a large frequency shift of several GHz [3] or higher frequencies [4]. Therefore optical frequency shifters that can operate in the microwave frequency and even millimeter wave frequency range are needed.

Previous approaches to shift the light frequency have been principally based on acousto-optic techniques [5]. However, though this is an all-optical approach, it is well known that the acousto-optic

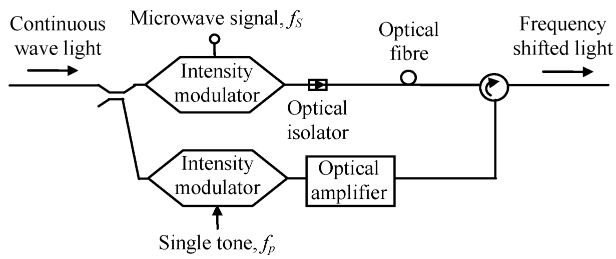


Fig. 1. New stimulated Brillouin scattering based optical frequency shifter topology.

effect imposes severe limitations by only permitting operation at low frequencies. Other techniques, such as the use of a dual-drive intensity modulator inside a Sagnac loop interferometer [6] and a dual-parallel Mach–Zehnder modulator (DPMZM) [7], require an electrical 90° hybrid coupler, and hence are not all-optical and are restricted especially for wide bandwidths by the limitations of the electrical coupler. The frequency shifter based on the Sagnac loop interferometer technique also generates high spurious frequency components, which limits the signal-to-noise ratio (SNR) to only around 10 dB. Here the SNR is defined as the ratio of the frequency shifted light amplitude to the dominant unwanted frequency component or noise amplitude. Recently a frequency shifter based on the use of a DPMZM with an active Y-branch optical intensity trimmer has been demonstrated to obtain 42 dB SNR but it requires five DC bias voltages into the modulator and the high-SNR frequency shift is only demonstrated at 8.6 GHz [8]. Techniques that do not rely on using electrical components to implement an optical frequency shifter have been reported [2], [9]. Although microwave and millimeter-wave frequency shifts have been demonstrated, these techniques have a relatively low SNR performance, e.g., the original optical carrier at the output of the frequency shifter presented in [9] is only 5 dB below the desired frequency shifted light. It is important to realize a frequency shifter that can operate over an ultra-wide frequency range of up to 100 GHz with low spurious generation and with tunable capabilities. To the best of our knowledge, no frequency shifter can achieve all these requirements.

In this paper, we present a new optical frequency shifter structure. The concept is based on the use of the stimulated Brillouin scattering (SBS) gain spectrum to amplify one sideband of a double-sideband suppressed carrier (DSB-SC) modulation signal, and the SBS loss spectrum to suppress the other sideband. Since the proposed structure does not involve any electrical component and uses normal Mach–Zehnder modulators (MZMs), which can have 100 GHz bandwidth, it enables very high frequency shift well into the millimeter wave frequency range to be realized. The design of the system parameters to obtain a high SNR performance is presented. Experimental results are presented demonstrating the realization of a 20 GHz frequency shift with 25 dB SNR.

## 2. Stimulated Brillouin Scattering Based All-Optical Frequency Shifter

Fig. 1 shows the novel optical frequency shifter structure. It is based on an optical fiber for SBS together with two electro-optic Mach–Zehnder intensity modulators. SBS is a well-known effect in an optical fiber. The spectral performance of the SBS interaction is qualitatively summarized in Fig. 2 [10]. Two coupled effects appear. When a pump wave is launched into an optical fiber, a Brillouin gain spectrum centered at a frequency down-shifted by the Brillouin shift in the fiber is generated for a counter-propagating wave, shown dotted (Stokes wave) in Fig. 2(a), and the pump power depletes as it transfers energy to amplify the Stokes wave. Simultaneously, the counter-propagating wave induces a Brillouin loss spectrum centered at a frequency up-shifted by the Brillouin shift, which is shown in Fig. 2(b). Further details about the SBS gain and loss spectrum can be found in [10]. The characteristics of SBS, including its low threshold power and its simplicity of initiation, make it well suited to applications in microwave photonic signal processing. Early work on the technique of Brillouin selective side band amplification [11] has shown it to be a powerful approach for a range of microwave photonics applications, including microwave signal generation [12], up- and down-conversion of microwave signals [11], and phase-to-amplitude modulation

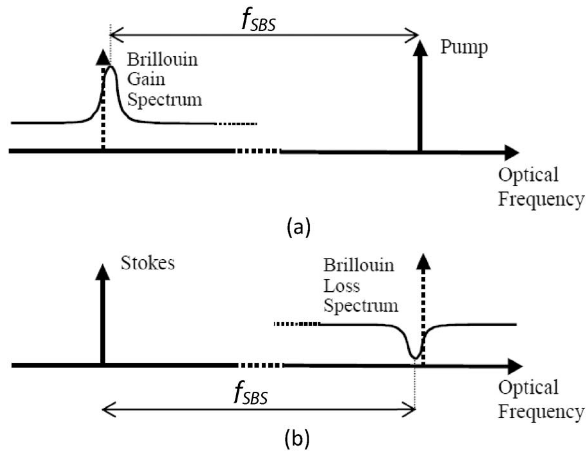


Fig. 2. Generation of (a) Brillouin gain spectrum and (b) Brillouin loss spectrum, due to the nonlinear SBS interaction between a pump wave and a Stokes wave.

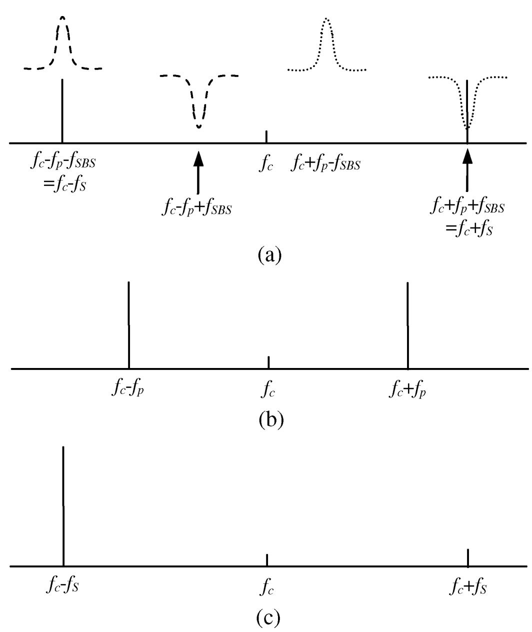


Fig. 3. (a) Spectrum of the DSB-SC modulation signal (the Stokes wave) into the optical fiber for the SBS process, and SBS gain and loss spectrums in the Stokes wave generated by the upper (dotted) and lower (dash) sideband of the pump. $f_c$ is the optical carrier frequency. (b) Spectrum of the pump wave into the optical fiber. (c) Output spectrum of the SBS based optical frequency shifter.

conversion [13]. Moreover, SBS is all-optical which means that it can operate and be tuned over extremely wide microwave and millimeter-wave bandwidths.

With reference to Fig. 1, the continuous wave light from the optical source is split into two paths via an optical coupler, both of which contain an electro-optic intensity modulator biased at the minimum transmission point. The outputs of the modulators have two sidebands with the optical carrier being suppressed. The top modulator is driven by a microwave signal with the frequency $f_S$ equal to the desired frequency shift. The bottom modulator is driven by a single tone with the frequency $f_p$ equal to the difference between the desired frequency shift and the SBS frequency $f_{SBS}$ of the optical fiber used for the SBS process. The optical frequency components into the optical fiber are shown in Fig. 3(a) and (b). The DSB-SC modulation signal after the top and bottom modulator is referred to as the Stokes and pump wave for the SBS process respectively. The amplitude of the pump wave can be controlled by the optical amplifier after the bottom modulator. The optical amplifier can be avoided by using a high power optical source and designing the optical coupler coupling ratio. The pump wave launches into the optical fiber in an opposite direction to the Stokes wave via an optical circulator. This generates two sets of SBS gain and loss spectrums in the Stokes wave, as shown in Fig. 3(a). The upper sideband (USB) in the Stokes wave is suppressed by the SBS loss spectrum. The lower sideband (LSB) in the Stokes wave is amplified by the SBS gain spectrum. This results in the output optical spectrum shown in Fig. 3(c). This shows that after passing through the SBS based optical frequency shifter, the frequency of the laser light is downshifted by the frequency of the microwave signal $f_S$ that drives the top electro-optic intensity modulator, and thus it realizes the frequency shifting operation. The amplitude of the frequency shifted light and the unwanted spurious signals can be controlled by the system parameters such as the modulation index and the pump power.

It can be seen from Fig. 1 that the structure involves an optical fiber and two normal Mach–Zehnder intensity modulators that can have 100 GHz bandwidth [14]; hence the new structure is capable of attaining up to 100 GHz frequency shift. Note that, unlike many reported frequency shifting techniques, the optical frequency shifter shown in Fig. 1 does not require any electrical components, and it enables tunability over a wide frequency range by controlling the microwave signal and the single tone frequencies. The lowest frequency shift of the SBS based optical frequency shifter is limited by the onset of overlapping of the SBS gain and loss spectra, which is determined by the Brillouin linewidth and is typically 10 to 50 MHz depending on the medium used for the SBS process. Therefore the separation between the SBS gain and loss spectra needs to be at least 100 MHz. This sets the lower frequency limit of the SBS based optical frequency shifter to be around 50 MHz. Regarding the shape of the SBS gain spectrum, it has a Lorentzian shape in the low gain limit and becomes Gaussian in the high gain limit [15]. In both cases, the spectrum is not flat, however for the frequency shifting operation this non-flat gain spectrum does not affect the performance of the proposed scheme as the light to be frequency shifted has a single frequency and the linewidth of the telecommunication-type lasers is less than a few MHz, which is a decade less than the SBS gain spectrum width.

## 3. Analysis and Discussion

Assuming the top modulator shown in Fig. 1 is driven by a sinusoidal signal with the frequency $f_S$ and that it is biased at the minimum transmission point for the frequency shifting operation, and also assuming the optical coupler in Fig. 1 has a 50% coupling ratio, the spectrum of the Stokes wave into the optical fiber can be written as

$$S_{Stokes,in}(\omega) = \frac{1}{2} P_o t_{ff} \left[\cos^2 A \cdot J_0^2(B_1) \cdot \delta(\omega + \omega_c) + \sin^2 A \cdot J_1^2(B_1) \cdot \delta(\omega + (\omega_c \pm \omega_S))\right] \tag{1}$$

where $P_o$ is the continuous wave light power into the SBS based optical frequency shifter, $t_{ff}$ is the modulator insertion loss, $\omega_c$ and $\omega_S$ are the angular frequency of the optical carrier and the microwave signal into the top modulator respectively, $J_m(\mathrm{x})$ is the Bessel function of $m$th order of first kind

$$A = \frac{\pi}{2}\left(\frac{1}{2} + \frac{\varepsilon}{2}\right) \tag{2}$$

$$\varepsilon = 1 - \frac{4}{\pi} \tan^{-1} \frac{1}{\sqrt{ext}} \tag{3}$$

where $ext$ is the modulator extinction ratio in dB, $B_1$ in (1) is given by

$$B_1 = \frac{\pi}{2} \varepsilon V_S \tag{4}$$

where $V_S$ is the voltage of the microwave signal into the top modulator. Equation (1) shows that the amplitude of the optical carrier in the Stokes wave reduces as the modulator extinction ratio increases. Assuming the bottom modulator shown in Fig. 1 is driven by a sinusoidal signal with the frequency $f_p$ and that it is biased at the minimum transmission point, the spectrum of the pump wave into the optical fiber can be written as

$$S_{pump,in}(\omega) = \frac{1}{2} P_o t_{ff} G\left[\cos^2 A \cdot J_0^2(B_2) \cdot \delta(\omega + \omega_c) + \sin^2 A \cdot J_1^2(B_2) \cdot \delta\left(\omega + (\omega_c \pm \omega_p)\right)\right] \tag{5}$$

where $G$ is the gain of the optical amplifier after the bottom modulator, $\omega_p = 2\pi f_p$ is the angular frequency of the single tone into the bottom modulator, $B_2$ is given by

$$B_2 = \frac{\pi}{2} \varepsilon V_p \tag{6}$$

where $V_p$ is the voltage of the single tone into the bottom modulator. The spectrum at the output of the SBS based optical frequency shifter can be obtained from (1) and (5), and can be written as

$$\begin{aligned} S_{out}(\omega) = \frac{1}{2} P_o t_{ff} \Big[ &\cos^2 A \cdot J_0^2(B_1) \cdot e^{-\alpha L} \delta(\omega + \omega_c) + \sin^2 A \cdot J_1^2(B_1) \cdot e^{-\alpha L} g_B \delta(\omega + \omega_c - \omega_S) \\ &+ \sin^2 A \cdot J_1^2(B_1) \cdot e^{-\alpha L} \frac{1}{g_B} \delta(\omega + \omega_c + \omega_S) + N_{SBS,c}(\omega) + N_{SBS,l}(\omega) \\ &+ N_{SBS,u}(\omega) + \left\{\cos^2 A \cdot J_0^2(B_2) \cdot \delta(\omega + \omega_c) + \sin^2 A \cdot J_1^2(B_2) \cdot \delta(\omega + \omega_c - \omega_p)\right. \\ &\left.+ \sin^2 A \cdot J_1^2(B_2) \cdot \delta(\omega + \omega_c + \omega_p)\right\} \times G\left\{\frac{S_c}{2}\left(1 - e^{-2\alpha L}\right)\right\} \Big] \end{aligned} \tag{7}$$

where $\alpha$ is the fiber loss coefficient, $L$ is the length of the optical fiber used for the SBS process, $g_B$ is the peak Brillouin gain coefficient [10], $N_{SBS,c}(\omega)$, $N_{SBS,l}(\omega)$ and $N_{SBS,u}(\omega)$ are the SBS noise generated by the carrier, the LSB and the USB of the pump respectively, and $S_c$ is the recapture factor, which determines the amount of scattered power that is recaptured and guided backwards [16].

The second term in (7) is the frequency shifted light; the other terms in the equation are either the spurious frequency components or the SBS noise, which limit the frequency shifter SNR. The first term in (7) is the carrier in the Stokes wave passed through the optical fiber. The presence of this term is because practical modulators have limited extinction ratio, hence the optical carrier cannot be fully eliminated at the modulator output even if the modulator is biased at the minimum transmission point. The third term is the USB of the Stokes wave, which is attenuated by both the fiber loss and the SBS loss spectrum. Since the SBS gain can be $>$ 30 dB and the amount of signal attenuation by the SBS loss spectrum is the same as the amount of signal amplification by the SBS gain spectrum, the amplitude difference between the upper and the lower sideband of the Stokes wave at the fiber output can be $>$ 60 dB. However, this requires a high pump power, which results in high Rayleigh backscattering pump power that limits the SNR. The fourth, fifth and sixth term in (7) are the noise generated by the SBS process. As for the Stokes wave, the pump wave comprises three frequency components: namely the two modulation sidebands and the suppressed optical carrier. Each of these three frequency components can generate an SBS noise centered at the SBS gain spectrum and the SBS loss spectrum. The noise components present at the SBS loss spectrums can be neglected as they are much smaller than that present at the SBS gain spectrums [10]. The last three terms in (7) are due to the Rayleigh backscattering of the pump wave.

In order for the SBS based optical frequency shifter to have a high SNR performance, a high extinction ratio modulator is required. The sidebands at the output of the top modulator need to have high amplitude in order to maximize the frequency shifted light amplitude. This can be achieved by designing the modulation index to be 1.84 according to (7). Large suppression in the unwanted USB of the Stokes wave is obtained by using a high pump power, which creates a high-rejection-level loss spectrum in the Stokes wave. A high-power pump can be obtained by designing the modulation index of the single tone to be 1.84 and by using a high-gain optical amplifier.

As an example, assuming the optical fiber used for the SBS process has a typical SBS frequency of 11 GHz, and that the frequency shift is designed to be 40 GHz, this requires the frequency of the single

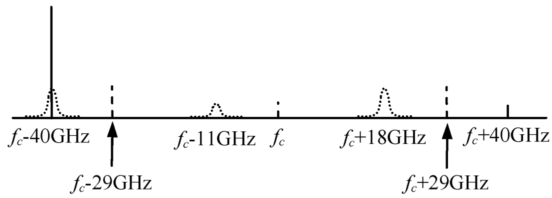


Fig. 4. Output spectrum of the stimulated Brillouin scattering based optical frequency shifter, comprising the Stokes wave (solid), the SBS noise (dotted) and the Rayleigh backscattering of the pump (dash).

tone into the modulator to be 29 GHz. Fig. 4 shows the frequency shifted light together with the spurious frequency components and the noise at the output of the frequency shifter. The amplitude of the frequency shifted light, the spurious frequency components and the noise are dependent on the system parameters such as the modulator extinction ratio, the optical source power, the optical amplifier gain, the amplitude of the microwave signal and the single tone into the modulator, and the length of the optical fiber used for the SBS process. These system parameters need to be optimized in order to obtain a high SNR performance. To do this, first, high extinction ratio modulators are needed in order to minimize the amplitude of the optical carrier in the Stokes wave, the SBS noise generated by the pump wave carrier and the Rayleigh backscattering of the optical carrier in the pump wave, which correspond to the first, fourth and seventh term in (7). Next, the amplitude of the microwave signal and the single tone into the modulators can be designed according to (1) and (5) to obtain high-amplitude DSB-SC modulation signals for the Stokes and pump wave into the optical fiber respectively. Then the optical source power can be adjusted to control the amplitudes of the two sidebands in the Stokes wave, which need to be high so that the output frequency shifted light has high amplitude. However, if the two sidebands in the Stokes wave have very high amplitudes then a very high pump power, which is obtainable by controlling the optical amplifier gain, is required to attenuate the USB and to amplify the LSB of the Stokes wave. This leads to the generation of high Rayleigh backscattering components, which limits the frequency shifter SNR performance.

The length of the fiber used for the SBS process also affects the frequency shifter SNR. It can be seen from (7) that the power of the Rayleigh backscattering pump wave is proportional to $1 - e^{-2\alpha L}$. This means that the amount of Rayleigh backscattering pump power is small when a short fiber is used for the SBS process. However, a higher pump power is required when using a shorter fiber, in order to obtain the required SBS gain and loss to amplify and attenuate the lower and upper sideband of the Stokes wave respectively. This leads to a large Rayleigh backscattering pump wave, reducing the optical frequency shifter SNR.

The operation of the new SBS based optical frequency shifter was simulated using VPItransmission Maker simulator [17]. A laser source having 0 dBm output power was used, together with two minimum-biased Mach–Zehnder intensity modulators with 30 dB extinction ratio and a single mode fiber with 11 GHz SBS frequency. The amplitudes of the microwave signal and the single tone into the modulators were set to obtain two high-amplitude DSB-SC modulation signals for the Stokes and pump waves. The power of the pump wave was adjusted by controlling the gain of the optical amplifier. Fig. 5 shows the simulated output spectrum of the SBS based optical frequency shifter designed to obtain a 40 GHz frequency shifting operation. It can be seen from the figure that the frequency shifter SNR is 33.8 dB when using a 1 km long single mode fiber. Using a short fiber has the advantage that the lower fiber loss results in a higher power for the output frequency shifted light. However, a high optical amplifier gain of 23.8 dB was required to amplify the pump wave for the SBS process.

The SBS based frequency shifter structure shown in Fig. 1 can be used for SSB-SC modulation. This has the advantage of high frequency operation as the structure does not require any electrical components. The maximum operating frequency is only limited by the normal electro-optic Mach–Zehnder intensity modulator operating frequency, which can be large. The bandwidth of this SBS based SSB-SC modulator is determined by the Brillouin linewidth, which is typically range from 10 MHz to 50 MHz dependent on the medium used for the SBS process. Techniques such as phase

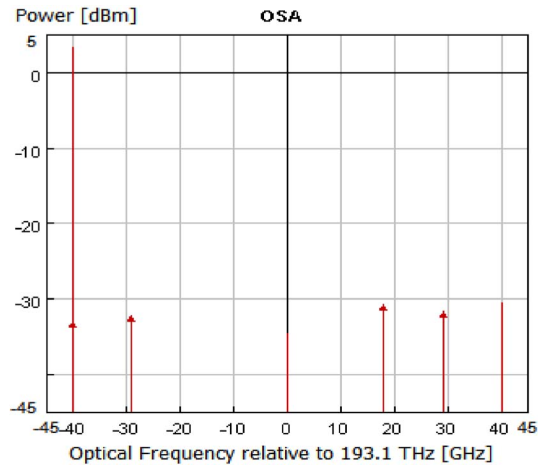


Fig. 5. VPI simulated stimulated Brillouin scattering based optical frequency shifter output spectrum.

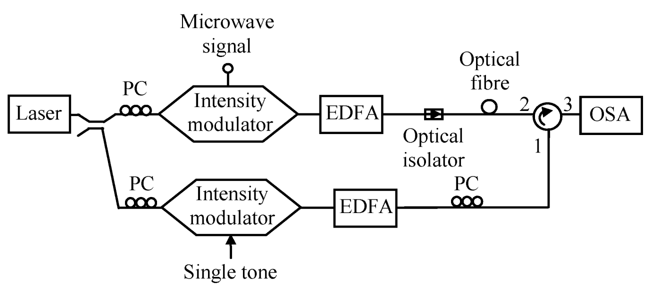


Fig. 6. Experimental setup of the stimulated Brillouin scattering based optical frequency shifter.

modulation [18] and direct modulation [19] have been developed to increase the Brillouin linewidth to GHz frequencies. Recently a Brillouin gain bandwidth of 25 GHz in an optical fiber has been demonstrated [20]. These techniques can be used to increase the bandwidth of the SBS based SSB-SC modulator.

## 4. Experimental Results

An experiment was set up, as shown in Fig. 6, to verify the proof of principle of the SBS based optical frequency shifter. The optical source was a wavelength tunable laser operated at 1550 nm. The laser had a narrow linewidth of less than 500 kHz. The continuous wave light at the laser output was equally split into two paths by a 50% coupling ratio optical coupler. The electro-optic intensity modulators used in the experiment had around 25 dB extinction ratio, and a 3 dB bandwidth of 10 GHz and 20 GHz. They were biased at the minimum transmission point. The 10 GHz and 20 GHz bandwidth modulators were located in the bottom and top path, and were driven by the pump frequency and the frequency shift microwave frequency signal, respectively, to obtain two DSB-SC modulation signals. The powers of these driving signals were designed to maximize the amplitudes of the DSB-SC modulation signals at the modulator outputs. The amplitudes of the two modulation sidebands for the pump and Stokes waves were controlled by the erbium-doped fiber amplifiers (EDFAs) at the modulator outputs. A 25 km long single mode fiber was used as the Brillouin medium. It had an SBS frequency of 10.53 GHz at 1550 nm. The relative state of the polarization between the pump and the Stokes wave was controlled using a polarization controller (PC) at Port 1 of the optical circulator, which was adjusted to maximize the output frequency shifted

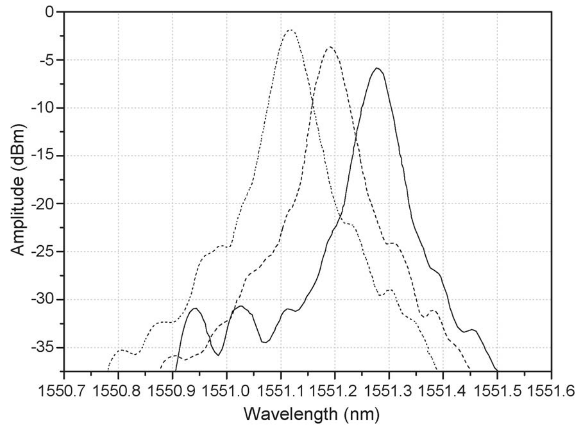


Fig. 7. Measured output spectrum of the stimulated Brillouin scattering based optical frequency shifter before (dotted) and after 10 GHz (dashed) and 20 GHz (solid) frequency shift.

light amplitude. The frequency shifted light was measured at Port 3 of the optical circulator using an optical spectrum analyzer (OSA).

First, a 20 GHz frequency shift was realized by applying a microwave signal with 20 GHz frequency into the top modulator and a single tone with the frequency of 9.47 GHz corresponding to the difference between the microwave signal frequency and the SBS frequency of the optical fiber used in the experiment, to the bottom modulator, as shown in Fig. 6. This generated 20 GHz and 9.47 GHz DSB-SC modulated optical signals acting as the Stokes and pump wave respectively for the SBS process. The amount of gain introduced by the SBS process was measured. The experimental result showed that the USB (in wavelength) of the 20 GHz modulated optical signal can be amplified by 19 dB after proper adjustment of the polarization controller and by using a high-power pump wave. Theoretically the amount of loss generated by the SBS process is the same as the gain. However, this could not be observed in the experiment due to the limited resolution of the OSA used in the experiment and the presence of the small unwanted spurious signals and noise. It was found from the experiment that, with this amount of amplification, the noise generated by the SBS process was high, which degraded the system SNR. In order to maximize the SBS based optical frequency shifter SNR, the gains of the EDFAs after the modulators were optimized. The laser light spectra before and after 20 GHz frequency shift are shown in Fig. 7. Note that the horizontal axis on the OSA display is in wavelength. Therefore a downshift in frequency corresponds to an upshift in wavelength. Three spurious peaks can be seen in the 20 GHz frequency shifted light spectrum. The spurious peak at 1550.94 nm is the unwanted sideband in the Stokes wave. The spurious peak at 1551.02 nm is the Rayleigh backscattering of one of the pump sidebands. The spurious peak at around 1551.11 nm comprises three components: the carrier in the Stokes wave, the Rayleigh backscattering of the pump wave carrier, and the SBS noise spectrum generated by the USB (in frequency) of the pump wave, which is 1 GHz away from the original optical carrier frequency and it cannot be resolved by the OSA that has a limited resolution bandwidth of 0.05 nm. The amplitudes of the three spurious peaks shown in Fig. 7 are dependent on the Stokes and pump wave powers, which are in turn dependent on the EDFA gains. It was found from the experiment that the amplitudes of the frequency shifted light and the spurious peaks are related to each other. For example increasing the pump power can increase the frequency shifted light amplitude and suppress the amplitude of the spurious peak at 1550.94 nm but this will increase the amplitude of the spurious peak at 1551.02 nm due to the increase of the Rayleigh backscattering of the pump wave and the increase of the SBS noise at around the original carrier frequency. It can be seen from Fig. 7 that the SBS based optical frequency shifter has 25 dB SNR. The figure also shows 10 GHz optical frequency shift, which was obtained by applying a 10 GHz microwave signal into the top modulator and 530 MHz single tone into the bottom modulator. Different optical frequency shifts from 2 to 20 GHz were obtained, by controlling the frequencies of the

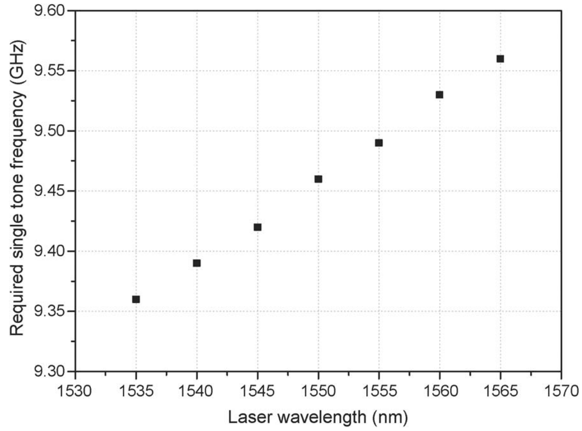


Fig. 8. Measured required single tone frequency into the bottom modulator in order to obtain 20 GHz frequency shift versus the laser wavelength.

microwave signal and the single tone, demonstrating the SBS based optical frequency shifter can realize a widely tunable frequency shifting operation. Regarding the efficiency of the SBS based optical frequency shifter, it can be seen from Fig. 7 that there is 1.7 dB and 3.8 dB loss for 10 GHz and 20 GHz frequency shift respectively. This small loss can be compensated by using an optical amplifier after the frequency shifter. Note that Fig. 7 also shows that the frequency shifted light amplitude reduces as the frequency shift increases. This is because the modulator switching voltage increases as the frequency increases, which reduces the modulation sideband amplitude. Nevertheless an optical amplifier can be used at the frequency shifter output to amplify the frequency shifted light amplitude. The spectrum of the SBS gain was also measured by tuning the frequency of the microwave signal into the top modulator at around 18 GHz for example, while the single tone frequency into the bottom modulator was fixed at 7.47 GHz, and measuring the corresponding frequency shifted light power on the OSA. The 3 dB bandwidth of the SBS gain spectrum was measured to be 32 MHz.

In order to demonstrate that the SBS based optical frequency shifter has the ability to operate at different input laser wavelengths, the wavelength of the laser source was tuned over a wide range from 1535 nm to 1565 nm together with the single tone frequency into the bottom modulator to realize the 20 GHz frequency shifting operation. The reason for changing the single tone frequency is that the SBS gain and loss spectrum frequencies are slightly dependent on the wavelength of the pump light. Fig. 8 shows the single tone frequencies required to obtain 20 GHz frequency shift for different laser wavelengths. In all cases, around 25 dB SNR were obtained demonstrating that the SBS based optical frequency shifter is capable of operating at different laser wavelengths.

## 5. Conclusion

A new optical frequency shifter that involves only optical components, and has the ability to realize microwave/millimeter-wave frequency shift, has been presented. It is based on using two minimum-biased Mach–Zehnder intensity modulators to generate two DSB-SC modulation signals for the pump and Stokes waves, and an optical fiber for the SBS process. The SBS gain and loss spectrums generated by the pump wave amplify and attenuate the lower and upper sidebands of the Stokes wave respectively, to implement the frequency shifting operation. By means of a detailed analysis of spurious components at the output of the frequency shifter, the design of the system parameters to minimize the spurious components in order to obtain a high SNR performance has been presented. The new SBS based optical frequency shifter has been verified using VPI photonic simulation software, and experimental results have demonstrated a 20 GHz frequency shift with 25 dB SNR and a widely tunable 2 to 20 GHz frequency shifting operation.

## References

[1] R. A. Minasian, E. H. W. Chan, and X. Yi, “Microwave photonic signal processing,” *Opt. Exp.*, vol. 21, no. 19, pp. 22 918–22 936, Sep. 2013.
[2] H. Murata, M. Anjiki, and Y. Okamura, “Optical suppressed-carrier single side-band modulator/optical frequency shifter utilizing three-branch waveguide interferometer and polarization-reversed structure,” in *Proc. 36th Eur. Microw. Conf.*, 2006, pp. 609–611.
[3] F. B. J. Buchkremer, R. Dumke, C. Buggle, G. Birkl, and W. Ertmer, “Low-cost setup for generation of 3 GHz frequency difference phase-locked laser light,” *Rev. Sci. Instrum.*, vol. 71, no. 9, pp. 3306–3308, Sep. 2000.
[4] S. Hisatake, K. Hattori, and T. Nagatsuma, “Continuous operation of a Bragg diffraction type electrooptic frequency shifter at 16 GHz with 65% efficiency,” *Adv. Opt. Technol.*, vol. 2012, pp. 676785-1–676785-6, 2012.
[5] M. G. Gazalet, M. Ravez, F. Haine, C. Bruneel, and E. Bridoux, “Acousto-optic low-frequency shifter,” *App. Opt.*, vol. 33, no. 7, pp. 1293–1298, Mar. 1994.
[6] M. Y. Frankel and R. D. Esman, “Optical single-sideband suppressed-carrier modulator for wide-band signal processing,” *J. Lightw. Technol.*, vol. 16, no. 5, pp. 859–863, May 1998.
[7] S. Shimotsu, S. Oikawa, T. Saitou, N. Mitsugi, K. Kubodera, T. Kawanishi, and M. Izutsu, “Single side-band modulation performance of a $LiNbO_3$ integrated modulator consisting of four-phase modulator waveguides,” *IEEE Photon. Technol. Lett.*, vol. 13, no. 4, pp. 364–366, Apr. 2001.
[8] Y. Ogiso, Y. Tsuchiya, S. Shinada, S. Nakajima, T. Kawanishi, and H. Nakajima, “High extinction-ratio integrated Mach–Zehnder modulator with active Y-branch for optical SSB signal generation,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 12, pp. 941–943, Jun. 2010.
[9] W. Chujo, T. Hanasaka, M. Naganuma, and T. Yoneyama, “A 60-GHz optical frequency shifter using coupled inverted slot lines,” *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 12, pp. 2280–2286, Dec. 1999.
[10] A. Loayssa, D. Benito, and M. J. Garde, “Applications of optical carrier Brillouin processing to microwave photonics,” *Opt. Fiber Technol* , vol. 8, no. 1, pp. 24–42, Jan. 2002.
[11] X. S. Yao, “Brillouin selective sideband amplification of microwave photonic signals,” *IEEE Photon. Tech. Lett.*, vol. 10, no. 1, pp. 138–140, Jan. 1998.
[12] X. S. Yao, “High-quality microwave signal generation by use of Brillouin scattering in optical fibers,” *Opt. Lett.*, vol. 22, no. 17, pp. 1329–1331, Sep. 1997.
[13] X. S. Yao, “Phase-to-amplitude modulation conversion using Brillouin selective sideband amplification,” *IEEE Photon. Tech. Lett.*, vol. 10, no. 2, pp. 264–266, Feb. 1998.
[14] H. Huang, S. R. Nuccio, Y. Yue, J. Y. Yang, Y. Ren, C. Wei, G. Yu, R. Dinu, D. Parekh, C. J. C. Hasnain, and A. E. Willner, “Broadband modulation performance of 100-GHz EO polymer MZMs,” *J. Lightw. Technol.*, vol. 30, no. 23, pp. 3647–3652, Dec. 2012.
[15] A. Villafranca and J. A. Lazaro, “Stimulated Brillouin scattering gain profile characterization by interaction between two narrow-linewidth optical sources,” *Opt. Exp.*, vol. 13, no. 10, pp. 7336–7341, Sep. 2005.
[16] M. Artiglia, M. A. Locaputo, and C. Ruocchio, “Backscattering recapture factor measurements using optical continuous wave reflectometry,” in *Proc. 28th ECOC*, 2002, pp. 1–2.
[17] VPItransmissionMaker photonic simulator. [Online]. Available: www.VPIsystems.com
[18] T. Tanemura, Y. Takushima, and K. Kikuchi, “Narrowband optical filter, with a variable transmission spectrum, using stimulated Brillouin scattering in optical fiber,” *Opt. Lett.*, vol. 27, no. 17, pp. 1552–1554, Sep. 2002.
[19] A. Zadok, A. Eyal, and M. Tur, “Gigahertz-wide optically reconfigurable filters using stimulated Brillouin scattering,” *J. Lightw. Technol.*, vol. 25, no. 8, pp. 2168–2174, Aug. 2007.
[20] K. Y. Song and K. Hotate, “25 GHz bandwidth Brillouin slow light in optical fibers,” *Opt. Lett.*, vol. 32, no. 3, pp. 217–219, Feb. 2007.