Precise Optical Frequency Shifting Using Stimulated Brillouin Scattering in Optical Fibers

Gourav Prateek Sharma[1,2], Stefan Preußler[1], and Thomas Schneider[1]

***Abstract*—We propose a precise method for optical frequency shifting with high signal to noise ratio based on stimulated Brillouin scattering (SBS). The lower sideband of the intensity modulated signal is amplified by the SBS. Also, polarization properties of the SBS are used to further suppress the other sideband and carrier. In addition, the pump wave is locked to the sideband by using software, or lock-in control method. The optical signal can be shifted by 16 GHz with a switching speed of 7 GHz/s. The frequency shifts obtained using our method are very precise because of the high quality radio frequency generator (RFG) used for the intensity-modulation. Dependent on the type, these RFGs can be adjusted in the milli-Hertz range.**

***Index Terms*—frequency shifting, single sideband modulation, stimulated Brillouin scattering**

I. Introduction

IN the past few years, there has been a lot of interest in the development of widely tunable and efficient optical frequency shifters [1], [2]. Optical frequency shifters are very important for true time delay beam steering in frequency domain continuous wave (FMCW) radars for precise range and velocity measurements [3]–[5]. Conventional systems require frequency ramps in the lower GHz range with sweep times in the ms range. Thereby a precise setting of the frequency resolution in the mHz range is necessary. Moreover, frequency shifters that can provide shifts of several GHz are useful in high-resolution laser spectroscopy [6]. A precise frequency shifter is also important for the heterodyne detection of the measurement beam in laser vibrometry [7].

Previously, many methods have been proposed to realize optical frequency shifting. One approach is to use a dual-drive Mach–Zehnder intensity modulator, where two sets of electrodes are fed with modulating signals which have to be orthogonal to each other [8]. For this approach, an electrical $\pi/2$ hybrid coupler is required, which limits a wide-band operation of the frequency shifter. Another approach is to use narrow-band optical filters, such as a fiber Bragg grating (FBG) [9], to attenuate one sideband of a dual-sideband suppressed-carrier (DSB-SC) signal and allow the other sideband to pass. However, with the relatively wide pass band of FBGs it is difficult to attenuate one sideband without affecting the other. Alternatively, an acousto-optic modulator can be used to shift the frequency, but only in a very small range [2]. The tuning speed in all previous mentioned approaches depends directly on the speed of the utilized radio frequency generator that specifies the frequency shift.

In this letter, we present an all-optical method for optical frequency shifting based on stimulated Brillouin scattering in a standard single mode fiber (SSMF). The basic idea is to amplify one of the sidebands of an intensity modulated wave and suppress the other sideband and the carrier. A fast and simple tuning can be achieved by a change of the sinusoidal frequency applied to the intensity modulator. In contrast to other methods [10], [11], here the polarization pulling properties of stimulated Brillouin scattering (polarization pulling assisted stimulated Brillouin scattering, PPA-SBS) are exploited to suppress the unwanted sideband and the carrier effectively [12]. This leads to a remarkable enhancement of the performance in respect to the overall SNR (ratio of amplified sideband power to un-amplified sideband power). Additionally, for a fast and reliable frequency tuning an automatic locking of the pump wave to the sideband is necessary. This is done by regulating the pump current (and therefore the pump frequency) with two approaches, i.e. a computer program and a lock-in control. The shifter is found to have a SNR of 48 dB and a frequency tuning range from 0-16 GHz with a tuning speed of 7 GHz/s. Methods for a possible further enhancement of the performance are discussed as well.

II. Theory and Principle

Due to its relatively small threshold [13], SBS is a very common non-linear effect in optical fibers. SBS arises from the interaction between a pump wave, a weak counter-propagating Stokes wave and an acoustic wave [14], [15]. The interaction results in the coupling of power from the forward propagating pump wave to the backward propagating Stokes wave, which is frequency downshifted to the pump wave at 1550 nm by the Brillouin shift of $f_{SBS} \sim 11$ GHz in SSMF. Furthermore, narrow bandwidth Brillouin amplification is accompanied by polarization properties [12], [16], wherein the state of polarization (SOP) of the counter-propagating Stokes wave is drawn towards the SOP of the pump wave. The principle of operation of SBS based frequency shifter is explained next.

1) SBS Based Frequency Shifting: The concept of SBS based frequency shifting is based on the selective amplification of an intensity modulated signal by SBS amplification. The output wave of a distributed feedback (DFB) laser diode with a center wavelength in the C-band of optical telecommunications (around 1550 nm) is intensity modulated in a Mach–Zehnder intensity modulator with a sinusoidal wave of frequency f_m. The resulting frequency shift between the carrier and the

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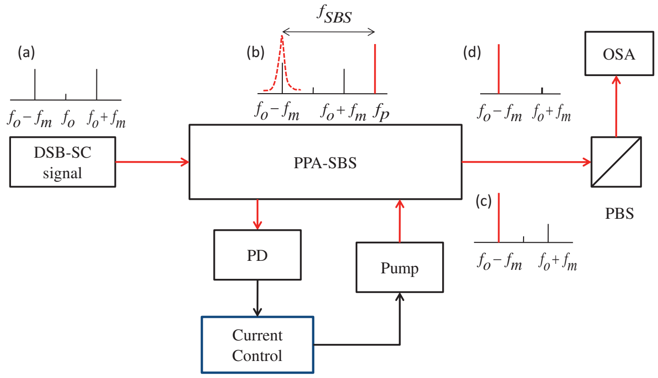

Fig. 1. Block diagram showing the basic idea behind the SBS based optical frequency shifter. (a) Spectrum of the input DSB-SC signal. (b) Frequency spectrum showing the Brillouin amplification of the lower sideband (LSB). (c) Spectrum at the output of the PPA-SBS. (d) Spectrum at the output of the PBS. DSB-SC: dual-sideband suppressed-carrier, PPA-SBS: polarization pulling assisted-SBS, PD: photodiode, PBS: polarization beam splitter, OSA: optical spectrum analyzer.

sidebands is very precise and reliable due to the high quality of common radio frequency generators. By adjusting the power of the modulating signal, SOP of input wave, and the bias voltage of the modulator, the carrier is suppressed in the maximum possible way, as shown in Fig. 1(a). The DSB-SC signal, with two sidebands at $f_o \pm f_m$ enters from the left and travels in forward direction in the PPA-SBS block. The PPA-SBS block consists of a SSMF which acts as the Brillouin gain medium and two circulators in order to separate the forward from the backward propagating waves. The pump wave of frequency f_p traveling in counter-propagating direction causes Brillouin amplification of the lower sideband of the DSB-SC signal at $f_o - f_m$ inside the PPA-SBS block as shown in Fig 1(b). The frequency of the pump wave is regulated by a control mechanism, discussed in the next section. At the output of the PPA-SBS block, the lower sideband is amplified by SBS. The upper sideband (USB) and the carrier only suffer propagation loss as illustrated in Fig. 1(c). However since the polarization properties of SBS were utilized, the SOP of the lower sideband is drawn towards the polarization of the pump wave. Thus, as shown in Fig. 1(d), by utilizing a polarization filter, such as a polarization beam splitter (PBS), the upper sideband and the carrier are effectively suppressed.

2) Pump Current Regulation: In order to enable a stable operation and a fast, precise and reliable tuning, the frequency of the pump has to be locked such that it causes a maximum amplification of the lower sideband of the DSB-SC signal. The pump frequency is controlled by regulating the current of the pump laser diode. The laser diode current is regulated by two mechanisms, either by using a software or by a Pound–Drever–Hall (PDH) method [17]. The Brillouin amplification results in a transfer of power from the pump wave to the frequency downshifted Stokes signal [14]. The maximum power transfer takes place when the Stokes signal is at the center of the gain-bandwidth caused by SBS in the fiber. Thus, the basic idea of both methods is to use the depletion of the pump power caused by SBS in the optical fiber as the measurement signal in order to regulate the frequency of the pump laser.

The pump wave entering the PPA-SBS block in Fig.1 causes an amplification of the Stokes signal and the residual pump power propagates to the photodiode (PD). The PD converts this signal to a voltage. This voltage has a minimum when the lower sideband of the Stokes signal is exactly at the center of the Brillouin gain-bandwidth region. The current control block then adjusts the pump current according to the voltage signal at its input. If there is a change of the frequency of the Stokes signal, the current control block adjusts the pump current to a new value.

For the software control method, the current control block is a program written in LabView. It is essentially an infinite loop, which repetitively reads the PD voltage output, searches for the minimum and regulates the pump current accordingly. Although the pump frequency regulation by software is very simple, it is quite slow. Moreover, if the frequency of the Stokes wave is changed too fast, the controller does have no time to adjust to a new value. Thus, the sideband frequency leaves the gain-bandwidth region and the pump current cannot be regulated. We have measured a maximum tuning speed of just 100 MHz/s.

To overcome the disadvantages of the software control method, a lock-in control method inspired by the PDH technique, which is used to stabilize lasers [17], is adopted. For the original PDH stabilization, the reflection from a Fabry–Perot cavity is used to tune the frequency of a laser to match the resonance condition of the cavity [17]. Here, the pump depletion characteristics of SBS are used to tune the laser in order to enable a maximum power transfer from the pump wave to the Stokes signal. Instead of a separate PID circuit for the PDH technique a lock-in amplifier is used [18].

Inside the lock-in amplifier, the detected signal at the PD is mixed with a reference frequency of the lock-in amplifier and passed through a low pass filter. The output of the filter is used to regulate the current fed to the pump laser diode. Therefore, the lock-in adjusts the pump wave frequency to the maximum power depletion in the PPA-SBS block and therefore results in a maximum amplification of the LSB. In the experimental setup, as the current control block in Fig. 1, a lock-in amplifier was used. The output of the pump laser diode was phase modulated with a frequency generated by the lock-in amplifier.

III. Experimental Setup and Results

The experimental setup to demonstrate the SBS based frequency shifter is shown in Fig. 2. The DSB-SC signal is generated by modulating the output of LD1 using an MZM intensity modulator in the carrier suppressed regime. The pump wave is generated by the laser diode LD2.

For the locking of the pump wave to the sideband, LD2 is phase modulated with a sinusoidal frequency of 5 MHz derived from a lock-in amplifier. With 5 MHz, the modulation frequency is well below the gain bandwidth of SBS. Thus, this modulation does not generate additional SBS gains [19]. The SBS gain bandwidth is the convolution between the natural SBS bandwidth in the medium and the bandwidth of the

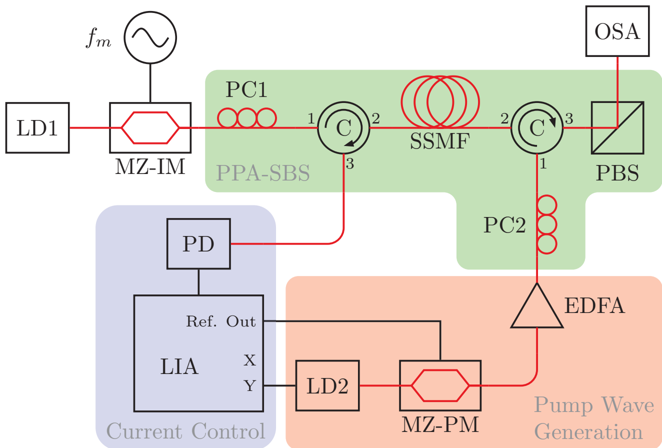

Fig. 2. Experimental setup of SBS based frequency shifter with pump current (or frequency) control. LD: laser diode, MZ-IM: Mach–Zehnder intensity modulator, PD: photodiode, LIA: lock-in amplifier, PC: polarization controller, C: circulator, SSMF: standard single-mode fiber, MZ-PM: Mach-Zehnder phase modulator, EDFA: erbium doped fiber amplifier, PBS: polarization beam splitter, OSA: optical spectrum analyzer.

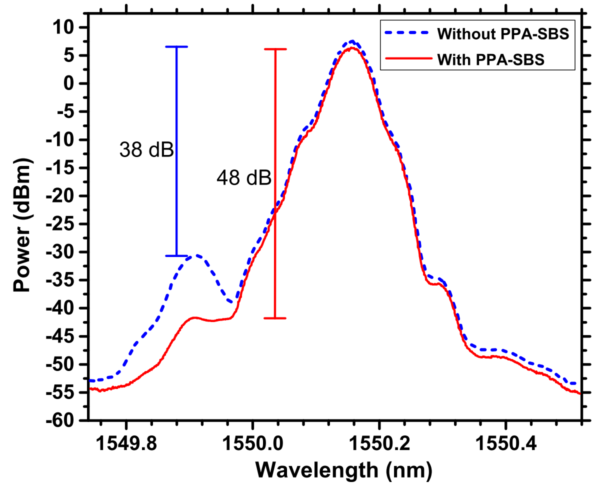

Fig. 3. Output spectrum of the optical frequency shifter showing the effect of PPA-SBS.

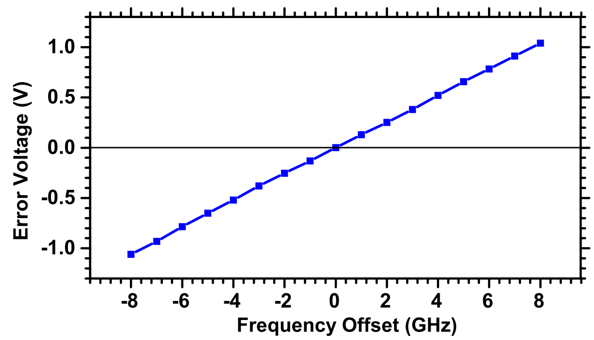

Fig. 4. Variation of the error signal produced by lock-in amplifier.

modulating signal. Since the natural SBS bandwidth is around 10-30 MHz, the broadening of the SBS gain bandwidth will be small and it does not affect the operation of the system. The pump wave is amplified to 11 dBm using an EDFA. The EDFA is adjusted to the constant power mode so that the pump wave has always the same power independent of the output power from LD2. The polarization controllers PC1 and PC2 are used to set the polarization of the pump and Stokes signals in accordance with the PBS before they interact in an SSMF with a length of 50 km. Depending on the position of signal wave LSB in the gain-Bandwidth region caused by the pump wave, the two side-bands of the pump wave at $f_p \pm 5$ MHz experience different amount of depletion while propagating through the fiber. The LSB or upper sideband (USB) of the pump wave will be more depleted if the signal wave LSB falls in the gain region generated by pump wave LSB (or USB). At the PD, two beat signals, which are produced by beating of two unequal sidebands with the carrier interfere with each other to produce a sinusoidal signal with a frequency of 5 MHz. This signal is fed to the lock-in amplifier where it is mixed with the reference signal and filtered with the built-in low pass filter of time constant 0.1 ms. The output of the lock-in amplifier is the error signal used to regulate the pump current. Even rather low signal wave powers down to -25 dBm can cause sufficient amount of pump power depletion which can be detected by the lock-in amplifier.

The output of the shifter is observed at an optical spectrum analyzer (OSA) after passing through a polarization beam splitter (PBS). The output spectrum of the frequency shifted signal obtained at the OSA for a modulation frequency of 16 GHz is shown in Fig. 3. The blue dashed line shows the measured signal without using the polarization properties of the SBS and the red solid line shows the signal after the suppression of all unwanted components in the PBS. As can be seen, with PPA-SBS the SNR of the frequency shifter is improved by about 10 dB.

To demonstrate the tunability of the frequency shifter, the frequency of the modulating signal is varied for ± 8 GHz around 8 GHz at a rate of 7 MHz/ms. During the scanning interval, the pump wave is locked to the LSB of the Stokes wave resulting in depletion of the pump wave and the amplification as well as the error signal is monitored continuously. For faster tuning speeds the pump laser lock is lost. Fig. 4 shows the variation of the error voltage produced by the lock-in amplifier. The output spectrum obtained for three different modulation frequencies is shown in Fig. 5.

In Fig. 5, due to limited resolution of OSA, the residual USB can only be seen in the red solid line at 1549.90 nm. Nevertheless, the amplified sideband to suppressed sideband ratio is around 48 dB for the full range of scanning. The overall stability of the frequency shifter depends on the independent laser that carries the signal. Environmental drifts of the system, e.g. temperature and therefore a shift of f_{SBS} are compensated by the pump laser diode locking itself. In general, this technique should enable a stability of the shifted frequency in the range of some kHz [20]. On the other hand the tuning speed of the proposed method is limited by the electronic parts, e.g. lock-in amplifier, laser diode controller and the radio frequency generator. Compared to other methods similar tuning speed is

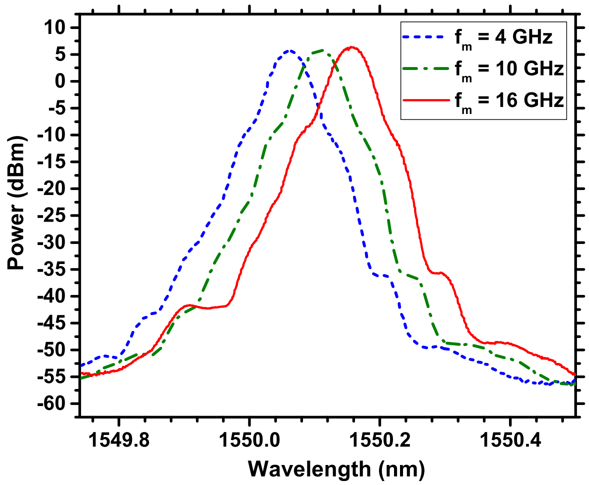

Fig. 5. Output spectrum obtained for different modulation frequencies.

achieved, which can be easily enhanced by using different control electronics or analog circuits. However, the frequency resolution as well as the SNR is superior.

IV. Conclusion

In conclusion, an all-optical frequency shifter based on SBS with a frequency tuning range from 0-16 GHz with pump current regulation is presented. The SBS gain spectrum is used to amplify the LSB of a DSB-SC signal. The use of polarization dependent amplification of the LSB by SBS results in an improvement of the SNR from 38 dB to 48 dB. The regulation of the pump current is done by a computer program and a lock-in control method. With the lock-in control method, the instantaneous frequency of the output signal can be tuned with a maximum rate of 7 GHz/s. The tuning range is restricted by the bandwidth of the used modulator. Thus, the tuning range can be easily expanded by the use of a higher bandwidth modulator, whereas the tuning speed might be possibly enhanced by the incorporation of an analog circuit.

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