Phase-to-Amplitude Modulation Conversion Using Brillouin Selective Sideband Amplification

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Abstract—We demonstrate an effective method for converting a phase modulated signal to an amplitude modulated signal by employing the powerful Brillouin selective sideband amplification technique. We further demonstrate several applications of this technique in various photonic systems, including microwave frequency multiplication, photonic microwave signal mixing with gain, microwave harmonic signal up-conversion, and coherent heterodyne signal detection.

Index Terms— Brillouin scattering, coherent detection, heterodyne, homodyne, microwave, microwave photonics, optical amplification, sidebands, signal mixing.

I. INTRODUCTION

EFFECTIVE and stable conversion of phase modulation (PM) to amplitude modulation (AM) is extremely important for a system employing phase modulation scheme. Almost all the phase to amplitude modulation conversion is accomplished by either the homodyne method in which a phase modulated optical carrier is made to beat with an unmodulated optical carrier of the same frequency, or the heterodyne method in which the phase modulated optical signal is made to beat with another optical carrier of a different frequency. A good example of the homodyne method is the Mach–Zehnder modulator in which an optical carrier is first split into two beams. One beam is then phase modulated and combines in the photodetector with the other beam to produce a corresponding amplitude modulation. However, such a conversion technique suffers not only a minimum of 3-dB optical loss, but also the bias drift problem.

In this letter, we introduce and demonstrate the novel concept of using Brillouin selective sideband amplification (BSSA) [1] to achieve effective PM-to-AM conversion. The converted amplitude modulation is extremely stable, immune to the fluctuations in the temperature and the fiber length. In addition, the conversion is also accompanied by an optical gain, resulting from the amplification of the desired sideband. Finally, this approach also provides many important new functions for lightwave communication systems.

II. THE CONCEPT OF BRILLOUIN PM TO AM CONVERSION

Fig. 1(a) is the experimental setup for demonstrating the concept of Brillouin PM to AM conversion. As shown in the figure, the optical carrier from the signal laser is first phase
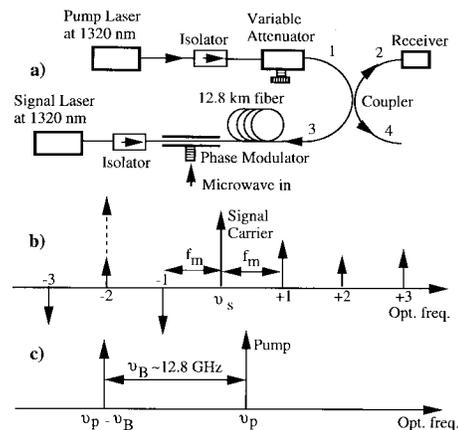
Fig. 1. (a) Experimental setup for demonstrating Brillouin phase to amplitude modulation. Both lasers are diode pumped YAG operating at 1320 nm. (b) A spectral diagram illustrating the phase and amplitude relationships between the optical carrier and the modulation sidebands of a phase modulated signal. (c) A spectral diagram showing the relationship between the frequencies of the pump laser and the Brillouin backscattered light. In our experiment, the Stocks frequency shift v_B is 12.8 GHz (not related to the 12.8-km fiber) and the threshold for the stimulated Brillouin scattering is 10 mW.

modulated by a microwave signal and then is transmitted through a 12.8-km fiber to the receiving end. The phase modulation of the optical carrier introduces many sidebands [2], each having a certain phase and amplitude relationship with the carrier and with each other, as shown in Fig. 1(b). Although in the optical receiver these sidebands beat with the carrier and beat with each other, they produce no amplitude modulations, because for each beat signal there always exists another beat signal which has the same amplitude and frequency but opposite phase. They cancel each other out perfectly.

Amplitude modulation will result if this perfect balance is broken, and this can be accomplished by using the BSSA technique [1]. As shown in Fig. 1(a), a pump beam is injected into the optical fiber from the opposite end of the signal laser and induces, via the electrorestrictive effect, an acoustic grating moving in the direction of the pump beam along the fiber. Part of the pump beam is then scattered backward by this moving grating and produces a frequency down-shifted (due to the Doppler effect) light beam propagating in the direction of the signal laser [3], [4], as shown in Fig. 1(c). By tuning the frequency of either the pump laser, the signal laser, or both, the frequency of the backscattered light can be made to coincide with one of the phase modulation sidebands of the signal laser. The interaction of this sideband, the grating, and the pump will further enhance the induced acoustic grating, causing
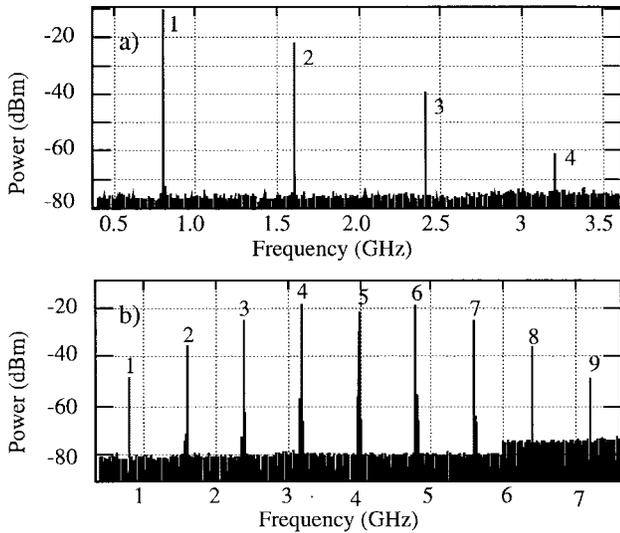
Fig. 2. (a) The received RF spectrum of a phase modulated signal when the −1 sideband is amplified by Brillouin amplification. The RF input to the modulator has a frequency of 0.8 GHz and a power of 10.83 dBm. The first, second, third, and fourth peaks are mainly from the amplified −1 sideband beating with the carrier, the +1-, +2-, and +3-order sidebands, respectively. (b) The received RF spectrum of the same phase modulated signal when −5 sideband is amplified. The RF input to the modulator has a frequency of 0.8 GHz and a power of 20 dBm. The peaks labeled 1–9 are the results of the amplified −5 RF sideband beating with −4, −3, −2, −1, carrier, +1-, +2-, +3-, and +4-order RF sidebands respectively. An RF filter can be used to select any one of the beating signals. The spectral resolution of the measurements in (a) and (b) are 100 and 30 kHz, respectively, and the pump power for both (a) and (b) is 11.5 mW.

more backscattering of the pump and greatly amplifying the sideband. The amplification of this modulation sideband will break the perfect amplitude balance of sidebands of a phase modulation and cause the phase modulation to convert to an amplitude modulation.

In a demonstration, a microwave signal was used to drive a phase modulator and the output from a photodetector was connected to an RF spectrum analyzer. Without the Brillouin pump, no RF signal was observed. When the pump was turned on and its frequency was aligned with the −1 order sidebands, a strong signal similar to that of Fig. 2(a) was detected by the spectrum analyzer, indicating an effective phase modulation to amplitude modulation conversion.

III. APPLICATIONS

A. Frequency Multiplication

The Brillouin PM-to-AM conversion can be used to achieve photonic frequency multiplication using a phase modulator. As shown in Fig. 1(b) and (c), one may selectively amplify a higher order sideband and obtain beat frequencies which are multiples of the frequency of the RF driving signal. Fig. 2(a) and (b) show the received RF spectrum when the −1-order sideband and −5-order sideband were amplified respectively. It is evident from Fig. 2(b) that frequency components as large as nine times the frequency of the driving signal were efficiently generated. Note that the phase modulator used has a specified bandwidth of only 0.5 GHz. However, with the aid of the selective Brillouin amplification, it generated

frequencies as high as 7 GHz. In the same way, we expect that a common 10-GHz modulator can be used to obtain signals exceeding 100 GHz, especially when it is combined with the harmonic carrier generation technique of [5]. This efficient Brillouin frequency multiplication is, therefore, very useful for generating millimeter wave signals without the need for using expensive high-speed modulators, high-frequency sources, and over driving the modulator.

It is important to note that the total received optical power for Fig. 2(a) and (b) at the photodetector was 0.55 mW without BSSA, and 3.46 and 1.85 mW, respectively, with the amplification, resulting in the amplified sideband much stronger than the carrier of the signal. The corresponding modulation depths for the two cases are about 74% and 92%, respectively. For Fig. 2, the pump power entering the 12.8-km fiber was 11.5 mW, slightly higher than the stimulated Brillouin scattering (SBS) threshold of 10 mW. Our other experiments also demonstrated that effective PM-to-AM conversion can be achieved with a pump power much lower (∼3 mW) than the SBS threshold. A close to 100% modulation can be achieved by adjusting the pump power so that the amplified sideband and the carrier have about the same power.

B. Signal Mixing and Harmonic Signal Up-Conversion

In a separate letter [1], we reported using the concept of BSSA to achieving signal up and down conversion with gain using two amplitude modulators. With the technique of Brillouin PM-to-AM conversion described above, the signal mixing can even be achieved with two-phase modulators, as shown in Fig. 3(a) and (b). If the local oscillator (LO) lower sideband is amplified by BSSA, the beat between the amplified LO sideband and the signal's lower sideband produces an amplified down converted signal. Similarly, the amplified LO lower sideband beating with the signal's upper sideband produces an up-converted signal.

The same concept can be extended to achieve harmonic signal up-conversion if a higher order LO sideband is amplified, as shown in Fig. 3(c) and (d) in which the −2 LO sideband is amplified. The amplified LO sideband beating with the upper and lower signal sidebands up-converts the signal to the harmonic of the LO frequency. We demonstrated this harmonic signal up-conversion with two low-frequency phase modulators (0.5-GHz bandwidth) and the results are shown in Fig. 3(e). With the amplification of the −5-order sideband of the 0.8-GHz LO modulation, the 0.1-GHz signal is up-converted to 6.4 GHz, a 64 times signal up-conversion. We again expect that with a 10-GHz modulator and 10-GHz LO source, one can easily up-convert a low-frequency signal to 100 GHz and beyond, especially when this technique is combined with that demonstrated by Sun et al. [5].

One may notice that in Fig. 3(e) that the harmonics of the signal are also up-converted (the peaks u and v corresponds to the harmonics of the signal, while peaks x and y corresponds to the signal itself). The reason for the signal and its harmonics to be up-converted around each peak in Fig. 3(e) is because each LO sideband is also modulated by the second-phase modulator in Fig. 3(a). If the arrangement of Fig. 3(b) is used, the up-
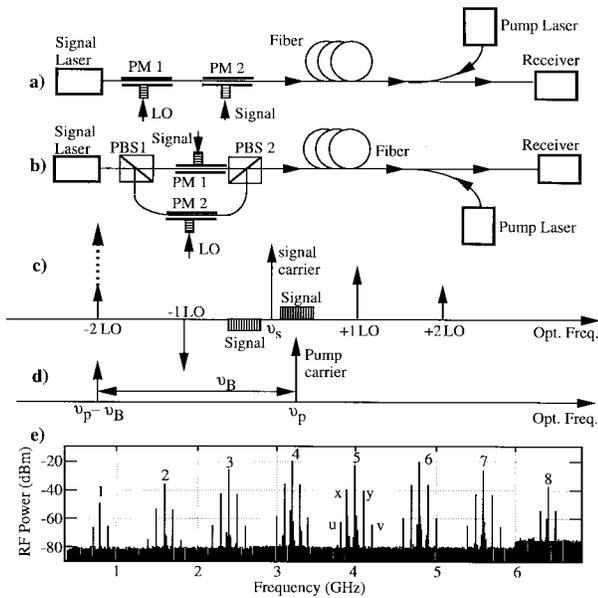
Fig. 3.   (a) An arrangement for photonic signal mixing and harmonic signal up-conversion with two cascaded phase modulators. (b) An alternative arrangement with two paralleled phase modulators. In the drawing, PBS stands for polarization beamsplitter. (c) Spectrum diagram illustrating various LO and signal sidebands. (d) Spectrum of Brillouin scattering. (e) Experimental result showing the effectiveness of the harmonic signal up-conversion with the arrangement of (a). The LO driving the first modulator has a frequency of 0.8 GHz and a power of 21 dBm while the signal driving the second modulator has a frequency of 0.1 GHz and a power of −1.83 dBm. The received optical power at the photodetector is 1.72 mW with the amplification and 0.55 mW without the amplification. The optical pump power into the fiber is 11.5 mW. As indicated in (c), the signal is up-converted to as high as 6.4 GHz with an LO of only 0.8 GHz. The peaks labeled 1–8 are the results of the amplified −5-order LO sideband beating with −4, −3, −2, −1, carrier, +1-, +2-, and +3-order LO sidebands, respectively.

converted signal will only be around peak 5, assuming −5 LO order is amplified.

C. Phase Locking in Coherent Heterodyne Systems

In a coherent homodyne or heterodyne communication link [9], a strong local oscillator is generally placed in front of the receiver to interfere with a phase modulated optical signal. The interference converts the phase modulation into an amplitude modulated signal. Since the local oscillator is much stronger than the original optical carrier of the signal, the receiving sensitivity will be greatly improved. In order for the system to work properly, typically the signal and the LO laser must be phase locked.

Looking from a different viewpoint, the photonic mixing configuration of Fig. 3(a) and (b) is essentially a coherent heterodyne system with the advantage that there is no need to phase lock the LO laser to the signal laser. Instead of directly sending the LO laser signal into the photodetector like in a common heterodyne system, here the LO laser [the pump laser in Fig. 3(a) and (b)] is sent toward the signal laser. Tuning the frequency of the LO laser to one of the LO modulation sidebands, the sideband will be greatly amplified by the LO laser via the Brillouin amplification process. The amplified LO modulation sideband then goes into the detector and beats with the signal sidebands. The phase and frequency of the amplified LO sideband are derived from the signal laser and

therefore are automatically locked to the signal laser, with a stability determined by the electrical LO driving signal. On the other hand, most of the power of the amplified sideband comes from the LO laser.

In other words, because BSSA produces a signal proportional to the intensity of the pump (magnitude squared of the pump field), the phase fluctuation of the pump is not an issue. On the other hand, the relative frequency drift of the pump and the signal lasers will cause the Brillouin gain profile to shift in frequency. In order to achieve a stable PM-to-AM conversion, the relative frequency drift of the pump laser and the signal laser must be confined to be within the Brillouin gain bandwidth, about 10 MHz. This is a much easier task in practice than having to directly phase lock the LO and signal lasers, as in a conventional heterodyne system [6].

IV.   SUMMARY

We have demonstrated the conversion of phase modulation to amplitude modulation using Brillouin selective sideband amplification (BSSA) so that one can use lower loss and less expensive phase modulators to replace conventional Mach–Zehnder modulators in many photonic systems, including the Brillouin optoelectronic oscillator [7]. Such a replacement not only results in much higher link gain, but also eliminates the bias drift associated with biasing the Mach–Zehnder modulators. In addition, we showed that the BSSA technique can also turn a phase modulator into an efficient photonic frequency multiplier with large multiplication factors, without having to over drive the modulator or to use high power lasers. Furthermore, we demonstrated using two optical phase modulators to achieve signal down/up-conversion with gain. Finally, we showed that this signal down/up-conversion scheme provides a novel and simple solution for the difficult laser frequency and phase locking problem in coherent optical communication systems.

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