BRILLOUIN SELECTIVE SIDEBAND AMPLIFICATION OF MICROWAVE PHOTONIC SIGNALS

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ABSTRACT

We introduce a powerful Brillouin selective sideband amplification technique and demonstrate its application for achieving gain in photonic signal up- and down-conversions in microwave photonic systems.

Brillouin amplification in digital photonic systems has been extensively studied by many authors. Unfortunately, it has been proved to be impractical due to its narrow bandwidth and high spontaneous emission noise.[1,2] Perhaps because of such unsuccessful attempts in the digital domain, the application of Brillouin amplification in analog photonic systems was seldom investigated. In fact, the related Brillouin scattering is generally considered to be harmful and extensive efforts have been devoted to minimize its effect. We introduce a powerful selective sideband amplification scheme and demonstrate a an important application of this scheme in microwave photonic communication systems that fully exploit the advantages of Brillouin amplification and circumvent its disadvantages.

Stimulated Brillouin Scattering (SBS) is perhaps the most sensitive nonlinear optic effect in optical fibers with a threshold power as low as few milliwatts. If the input optical power in a photonic link exceeds the SBS threshold, the forward going optical signal will be scattered back due to its interaction with an acoustic grating ‘it generated via the eletrorestrictive effect, Consequently, the forward going signal at the output will saturate at some input power level.

Because the acoustic grating is moving in the direction of the pump light, the frequency of the backscattered light will be down shifted via the Doppler effect by $\nu_B = 2nv_a/\lambda_p$, where v_a is the velocity of the acoustic wave in the fiber, n is the refractive index of the fiber, and λ_p is the wavelength of the pump beam.

If a narrow-band seed signal with a frequency of VP – ν_B, where VP is the frequency of the pump laser, is injected into the fiber from the opposite end of the pump, the interaction of the seed signal with the pump will greatly enhance the induced acoustic grating, causing more backscattering of the pump into the seed and effectively amplifying the seed signal. In other words, the influence of the seed signal converts the spontaneous Brillouin scattering into a stimulated Brillouin scattering, at a pump power much below the SBS threshold, The stimulated backscattering light will add up in phase with the seed and greatly amplify the seed. This process is called Brillouin amplifications Because of its narrow bandwidth, Brillouin amplification was generally considered to be impractical for amplifying digital signals of much larger bandwidth. As will be discussed below, one may get around this limitation in many analog applications by using the concept of selective sideband amplification unique to Brillouin amplification.

The Concept of Selective Sideband Amplification

An optical signal may typically include an optical carrier and lower and upper modulation sidebands, with the sidebands much weaker than the carrier, as shown in Fig. la, The received signal in the photodetector is the beat between the carrier and the sidebands. If an optical amplifier, such as a semiconductor optical amplifier (SOA), an Er^+ doped fiber amplifier (EDFA), or a fiber Raman amplifier, is used to amplify the signal, both the strong carrier and the weak sidebands are amplified. This process is not efficient because much energy is needed to amplify the already strong carrier. In addition, the amplified strong carrier may saturate the amplifier, resulting in insufficient amplification of the weak sidebands, and it may also saturate the photodetector, further limiting the amplification of the information carrying sidebands.

Fig. la and Fig. lb together show the concept of Brillouin selective sideband amplification. The narrow bandwidth of Brillouin amplification is used to its advantage to selectively amplify one of the weak sidebands and leave the strong carrier unchanged. The RF (in this paper we use RF to label signals ranging from radio frequencies up to millimeter wave frequencies) signal in the photodetector will be the beat between the strong carrier and the amplified sideband. This way, we can dramatically increase the modulation index of the received RF signal and amplify it. In practice, one can either tune the frequency of the pump laser or the frequency of the signal laser so that one of the modulation sidebands coincides with the frequency of the Brillouin scattering and this sideband will be amplified. Such an amplification scheme is much more efficient than other optical amplification schemes because all Brillouin scattering energy from the pump laser goes into the desired weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided.

Fig. 1c is the experimental setup for demonstrating Brillouin selective sideband signal amplification of RF signals. In the experiment, a LiNB03 Mach-Zehnder modulator was used to modulate the optical carrier emitted by a signal laser (diode pumped YAG laser) at 1320 nm. The resulting optical signal is finally injected into the 12.8 km fiber from the opposite of the pump laser (also a diode pumped YAG laser). Isolators were used in front of the pump and signal lasers to prevent light from entering each other.

Fig. 2a and 2b are the experimental results demonstrating the Brillouin selective sideband amplification technique. In the figure, the broad peak (- 10 MHz) is the beat between the signal carrier and the Brillouin scattering, and it's width represents the Brillouin gain bandwidth. The clean narrow peak is the received RF signal or the beat of the signal carrier and the RF modulation sidebands. It is evident that when the lower sideband of the RF signal is aligned with the Brillouin scattering peak, it is amplified with a gain of more than 30 dB. When the Brillouin scattering peak is tuned away from the sideband, the amplification diminishes gradually.

The RF link gain (defined as the difference of the RF output power from the photodetector and the RF input power to the modulator in dB) as a function of RF input power is shown in Fig, 3a. With a pump power of only 12.23 mw, a small signal RF link gain of more than 20 dB at 5.5 GHz is achieved, As a comparison, the RF link loss without Brillouin selective sideband amplification is about -41 dB. This account for a total RF signal amplification of 61 dB.

Finally, Fig. 3b shows the RF signal gain versus optical pump power for different input RF power. It is evident that a substantial gain of the RF signals can be achieved even when the optical power is much less than the SBS threshold. At high pump powers, the gain also saturates. Part of the gain saturation may be due to the photodetector saturation.

*Properties of **Brillouin** Selective Sideband Amplification*

Our experimental results indicates that the Brillouin selective sideband amplification has the following properties. First, it is very efficient and requires very low pump power. A DFB laser with a few milliwatts output power is sufficient to achieve adequate signal amplification, Consequently it is much less expensive to implement than an EDFA or an SOA. Second, it has very narrow gain bandwidth which is advantageous for the efficient selective sideband amplification, however is disadvantageous for amplifying signals with wide bandwidths. Third, the gain of the weaker signal is generally higher, however this is accompanied by higher amplifier noise. The noise is due to the spontaneous Brillouin scattering of the pump laser. If the seed signal is sufficiently strong, the stimulated Brillouin scattering induced by the seed will dominant and deplete the energy that may otherwise be converted to noise (spontaneous Brillouin scattering). For an externally modulated link, we found experimentally that the amplifier noise is insignificant if the input RF signal is sufficiently strong to limit the RF gain to less than 30 dB. Finally, the gain saturates for large signals with a fast response time. As in an SOA, this fast gain saturation will generate intermodulation products and distort the signal. Despite many disadvantages, there are many applications in which the advantages of the Brillouin amplification can be fully utilized, while its limitations can be circumvented, such as in the example demonstrated below.

Photonic RF signal mixing with gain

The concept of photonic RF signal up- and down- conversion is very attractive because it has virtually infinite isolation between the local oscillator (LO), radio frequency (RF), and intermediate frequency (IF) ports. In addition, one step conversion from RF to IF or from IF to RF can be achieved no matter how large the IF and RF frequency different from each other. Photonic mixing has been demonstrated by many authors using two cascaded Mach-Zehnder electro-optic amplitude modulators. One of the modulators is driven by the LO and the other modulator is driven by the RF signal. The beating between the optical carrier and the RF modulation sidebands in the photodetector converts the signal back to electrical domain, while the beating between the LO modulation sidebands and the RF modulation sidebands in the photodetector produces the down and up converted signals. Because the LO sidebands are always much weaker than the optical carrier, the conversion process is always accompanied with a high loss.

As illustrated in Fig. 4a and Fig. 4b, using Brillouin amplification one can dramatically increase one of the LO modulation sidebands when it is aligned with the Brillouin frequency. In the illustration, the lower LO modulation sideband is amplified. Since the down converted signal involves the beat between the lower LO sideband and the lower RF sideband, amplifying the lower LO sideband will increase the down converted signal. Similarly, since the up-converted signal involves the beat between the lower LO sideband and the upper RF sideband, the amplification of the lower LO sideband will cause the up converted signal to be amplified. If the LO sideband is amplified to be larger than the carrier, the conversion will then experience a net gain.

It is important to notice that the Brillouin amplification assisted signal mixing described above is independent of the bandwidth of the RF signal in spite of the narrow bandwidth of the Brillouin amplification. This is because only the single tone LO sideband band is being amplified. Therefore, using Brillouin amplification for signal mixing can avoid the shortfall of its narrow amplification bandwidth. Although it is possible to amplify the RF signal sideband instead of LO to achieve the same IF amplification, the signal bandwidth will be limited by the Brillouin amplification bandwidth. It should also be noticed that because only one of the LO sidebands (a single tone) is amplified, the intermodulation distortion from the gain saturation can be avoided. Finally, unlike in a digital fiber optic system in which the optical signal power is generally too weak for the simulated emission process to dominate, the strong optical power in the LO sideband of the RF photonic system will effectively saturate the Brillouin gain and greatly suppress the spontaneous emission noise. In short, all the shortcomings of the Brillouin amplification (narrow gain bandwidth, nonlinearity from gain saturation, and high spontaneous emssion noise) can be avoided with the approach above.

We peformed two experiments to demonstrate photonic mixing with Brillouin gain. The setup for the first experiment is similar to Fig, 1c. The modulator used in the experiment has two independent RF input ports with a mutual isolation of over 40 dB. An LO signal at a level of 4.83 dBm at 5,18 GHz was injected into one of the port and an RF signal of -5 dBm at 5.5873 GHz was injected into the other port. The modulator was biased at 50% of the transmission peak, Without the Brillouin amplification, the total optical power at the detector is 0.314 mW, the received LO is -40 dBm, and the received RF is -52 dBm. At an optical pump power of 12.112 mW, the Brillouin amplification increased the total optical power at the detector to 2.61 mW and increased the LO power to -15 dBm. The received down converted signal is -40 dBm and the up converted signal is -42 dBm, resulted in a down-conversion gain of 12 dB and up-conversion gain of 10 dB. The spectra of the amplified LO, down converted signal and up converted signal are shown in Fig. 4c and Fig. 4d. Similar results were also obtained in the second experiments with two cascaded Mach-Zehnder modulators.

In summary, we have demonstrated the powerful scheme of Brillouin selective sideband amplification. Such an amplification scheme is much more efficient than any other optical amplification schemes because all Brillouin scattering energy from the pump laser only goes into the desired weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided. Using the Brillouin selective amplification technique, we obtained a net link gain of 20 dB for an externally modulated photonic link at 5 GHz with an optical power of only 2.61 mW in the photodetector. We also demonstrated broadband photonic signal up- and down-conversion with 12 dB gain by using this scheme. This demonstration makes photonic mixing readily applicable without having to employ high power lasers and high power photodetectors.

Using the concept of Brillouin selective sideband amplification, we also demonstrated efficient phase modulation to amplitude modulation conversion, RF frequency multiplication, RF frequency comb generation, harmonic RF signal up conversion, and an all optical opto-electronic oscillator.[6] We further demonstrated RF signal up- and down- conversions using two phase modulators, therefore eliminating the bias drift and loss associated with the Mach-Zehnder modulators.

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Fig. 1 a) The typical spectrum of an RF signal imposed on an optical carrier. b) The spectrum diagram showing the frequencies of the pump and the brillouin scattering. When the frequency of one of the sidebands coincides with the frequency of the Brillouin scattering, it will be amplified. c) The experimental setup for demonstrating Brillouin selective sideband amplification.

Fig. 2 Experimental results demonstrating Brillouin selective sideband amplification. a) Pump is tuned to be aligned with a signal sideband. An RF gain of 31.5 dB is observed. b) The pump laser is tuned two gain bandwidths away and the RF gain decreased to 3 dB. The frequency span of the measurement is 100 MHz and the noise bandwidth is 1 MHz. The input RF signal is at 5.43 GHz with a power of -2.17 dBm.

Fig. 3. a) RF link gain as a function of RF input power to the modulator. A small signal link gain of 20 dB was obtained with only 2.61 mW optical power in the photodetector. The gain decreases at high input RF power levels. The optical pump power in the experiment is 12.23 mW. b) The gain of RF signals vs. optical pump power for different RF input powers to the modulator. Substantial RF gain was obtained even when the pump power is much lower than the SBS threshold level of 10 mW. Note that the gain saturates at high optical pump powers.

Fig. 4 Experimental result demonstrating amplified photonic signal up- and down-conversion. a) Spectrum of down converted signal. b) Spectrum of up converted signal. The LO and RF frequencies are 5.18 and 5.5873 GHz respectively.

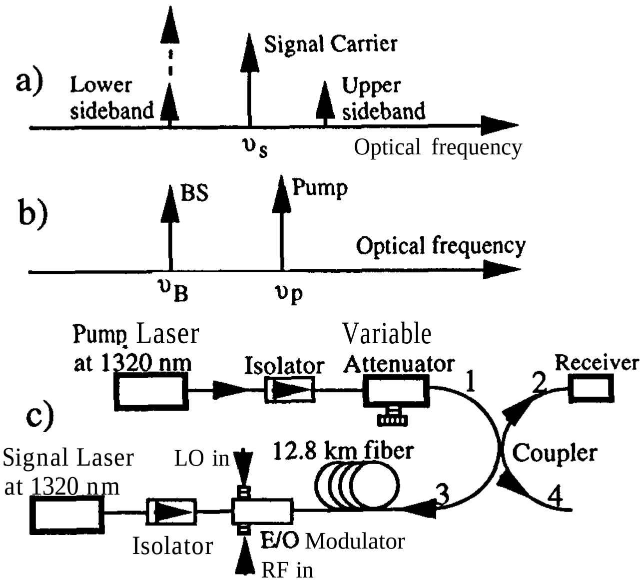

Fig. 1

Yao, "Brillouin selective sideband amplification"

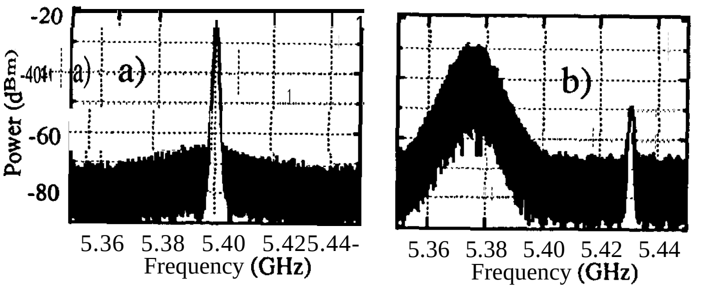

Fig. 2

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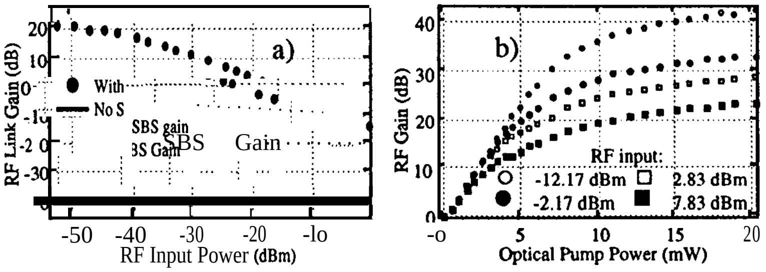

Fig. 3

Yao, "**Brillouin** selective sideband amplification”

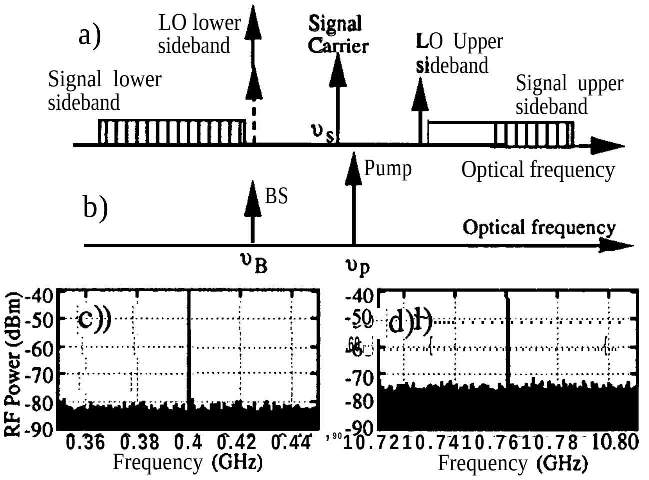

Fig. 4

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