Harmonic signal generation and frequency upconversion using selective sideband Brillouin amplification in single-mode fiber

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Harmonic signal generation and frequency upconversion at millimeter-wave bands are experimentally demonstrated by using selective sideband Brillouin amplification induced by stimulated Brillouin scattering in a single-mode fiber. The harmonic signals and frequency upconverted signals are simultaneously generated by the beating of optical sidebands, one of which is Brillouin amplified. By using this method, we successfully demonstrate generation of third-harmonic millimeter waves at 32.55 GHz with f_{LO} of 10.85 GHz and upconversion of 10 Mbps quadrature-shift keyed data at f_{IF} of 1.55 GHz into a 30 GHz band with more than 17 dB RF power gain. © 2007 Optical Society of America

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Signal generation and frequency upconversion realized with an optical method are key functions in radio-over-fiber systems, where radio signals are optically transmitted between central and base stations [1,2]. Particularly, it is attractive to use harmonic signals for realizing functions at millimeter-wave bands, because expensive electrical and optical components for millimeter waves can be replaced by relatively cheaper ones operating at lower frequency bands.

In realizing harmonic signal generation and frequency upconversion, selective sideband Brillouin amplification (SSBA) induced by stimulated Brillouin scattering (SBS) in an optical fiber can be a promising candidate since it can provide high RF power gain for the generated harmonic signals by amplification of the desired optical sideband [3–6]. In addition, several experimental methods for SBS generation without using additional pump sources have been reported for optical signal processing [7–9], optical sensing [10], and Brillouin amplification analysis [11].

In this Letter, we demonstrate harmonic signal generation and frequency upconversion at millimeter-wave bands using SSBA induced in a 10 km long single-mode fiber (SMF) without additional pump sources. In our method, harmonics of local oscillator (LO) and upconverted signals are obtained by the beating of optical sidebands, separated by the desired frequency for Brillouin amplification. By using this method, we successfully demonstrate generation of third-harmonic millimeter waves at 32.55 GHz with f_{LO} of 10.85 GHz and upconversion of 10 Mbps quadrature-shift keyed (QPSK) data at 1.55 GHz f_{IF} into a 30 GHz band with more than 17 dB RF power gain.

Figure 1 shows the experimental setup for demonstration of harmonic signal generation and harmonic frequency upconversion based on SSBA, along with the expected optical or RF spectra at different locations. As shown in the figure, the optical carrier at 1551.35 nm is provided by a tunable laser source (TLS) and amplified by an Er-doped fiber amplifier (EDFA). The amplified optical carrier is divided into two arms by an optical coupler. In the upper arm, 1% of the amplified optical carrier is modulated by a Mach–Zehnder Modulator (MZM, 3 dB bandwidth of about 8 GHz) with LO signal at the Brillouin frequency (f_{LO}=10.85 GHz) as well as 10 Mbps QPSK data carried at intermediate frequency (IF) of 1.55 GHz. In the experiment, large power LO (24 dBm) and IF (16 dBm) signals are supplied to a MZM so that many high-order optical sidebands are generated due to MZM nonlinearity [12]. Theses optical signals are launched into a 10 km long SMF [point (A)].

The optical carrier coupled into the lower arm is injected into the SMF from the opposite direction via an optical circulator and induces SSBA within the

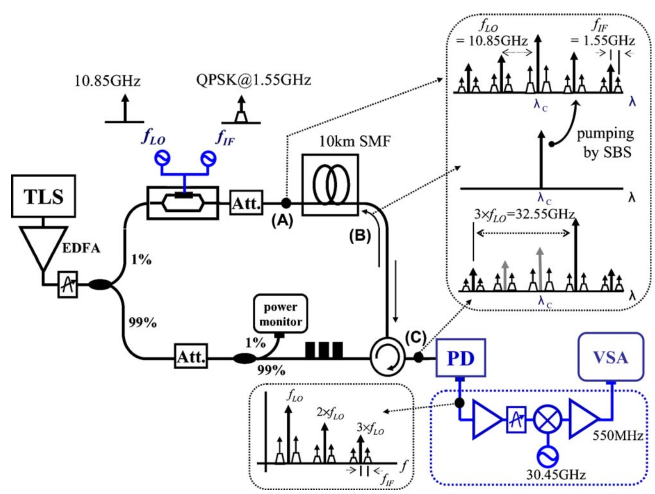

Fig. 1. (Color online) Experimental setup for demonstration of harmonic signal generation and harmonic frequency upconversion based on SSBA. Abbreviations are defined in text.

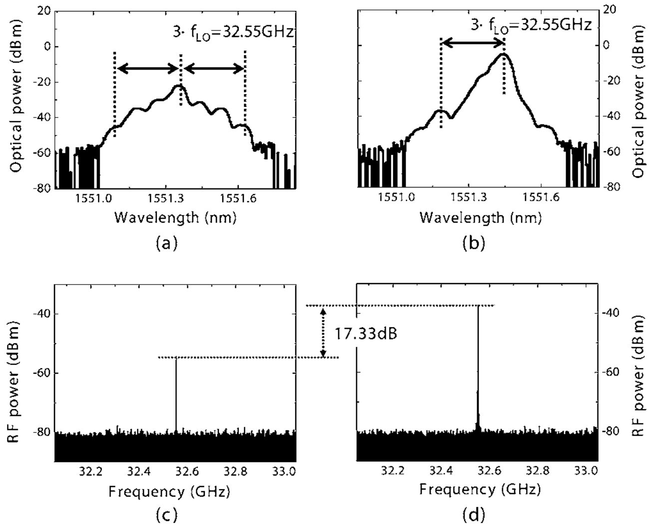

Fig. 2. Measured optical and RF spectra (a), (c) without SSBA and (b), (d) with SSBA induced by 8 dBm optical pumping in a 10 km long SMF.

SMF [(point (B)]. The power and polarization of the injected signals are adjusted by an optical attenuator (Att.) and a polarization controller, respectively. As can be seen in Fig. 1, the pump and modulator output signal counterpropagate in the SMF and interact with each other, resulting in amplification of the first sideband located at a longer wavelength by SSBA, which results in the optical spectrum shown for point (C). When these signals are detected by a photodetector (PD), harmonic signal generation and frequency upconversion is performed as shown in the figure. Since we are interested in millimeter wave applications of our scheme, we focus our investigation at 32.55 GHz, the third harmonic of f_{LO}, which is produced by the beating of the amplified sideband with the second sideband at a shorter wavelength from the optical carrier.

Figures 2(a) and 2(c) show measured optical and RF spectra without a SMF for generation of SSBA. Figures 2(b) and 2(d) show measured spectra with an 8 dBm optical pump in a 10 km long SMF. Both optical spectra were measured at point (C). For RF spectrum measurement, a low-noise amplifier (LNA) having 18 dB RF gain was used after photodetection. Figure 2(b) clearly shows that the first optical sideband located at a longer wavelength from the optical carrier was amplified by SSBA, although the resolution (0.07 nm) of the optical spectrum analyzer was not high enough to distinguish each sideband. In addition, due to asymmetric peak powers for sidebands involved in beating, no signal fading problem induced by fiber dispersion is expected when these signals are transmitted over dispersive fiber [4].

As can be seen from Figs. 2(c) and 2(d), SSBA provides RF power gain for the desired harmonic signal. With an 8 dBm optical pump in a 10 km long SMF, 17.33 dB RF power gain was achieved. Figure 3 shows the measured RF power gain at different pump powers. Although RF power gain drastically increases with the optical pump power, the optical pump power should be lower than the SBS threshold

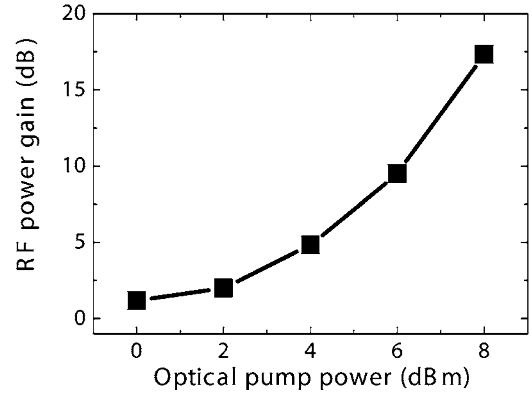

Fig. 3. Measured RF power gain according to the optical pump power.

[6]. In our experiment, the measured SBS threshold power was slightly larger than 10 dBm.

For the demonstration of harmonic frequency upconversion, both 10 Mbps QPSK data at f_{IF} of 1.55 GHz and f_{LO} were applied to a MZM. The upconverted signal was evaluated with a vector signal analyzer (VSA) after photodetection and electrical downconversion using an external mixer and a 30.45 GHz LO as shown in Fig. 1. Figure 4(a) shows the RF spectrum of the upconverted lower sideband (LSB) signal with SSBA induced by an 8 dBm optical pump in a 10 km long SMF, and Fig. 4(b) shows that of the downconverted signals. The increased noise floors shown in Fig. 4(a) are due to the external mixer's (HP11970A) connection to the spectrum analyzer (HP8563E) for the measurement of 30 GHz bands as well as the LNA. Figures 5(a) and 5(b) show the eye diagrams for a demodulated 10 Mbps QPSK signal without SSBA (no SMF for generation of SSBA) and with SSBA induced by an 8 dBm optical pump in a 10 km long SMF, respectively. The measured error vector magnitude (EVM) was about 24% [Fig. 5(a)] and 12% [Fig. 5(b)]. EVM gets better with SSBA because the system performance is limited by noises produced in receiver electrical components rather than SSB noises when the pump power is less than the SBS threshold power.

We have experimentally demonstrated harmonic signal generation and harmonic frequency upconversion based on SSBA induced by SBS in a 10 km long SMF. The proposed scheme can produce high RF power gain for harmonic signals without using a high-speed modulator. Using this proposed method,

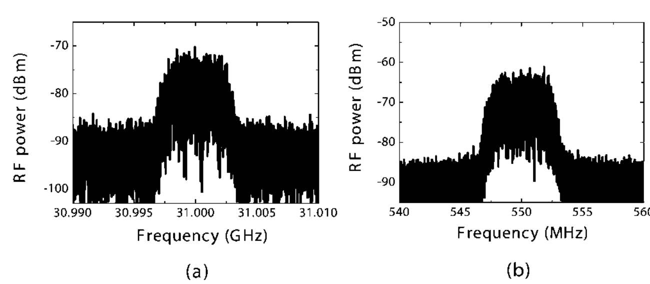

Fig. 4. Measured RF spectra of (a) upconverted and (b) downconverted LSB signals of 10 Mbps QPSK data with SSBA induced by an 8 dBm optical pump in a 10 km long SMF.

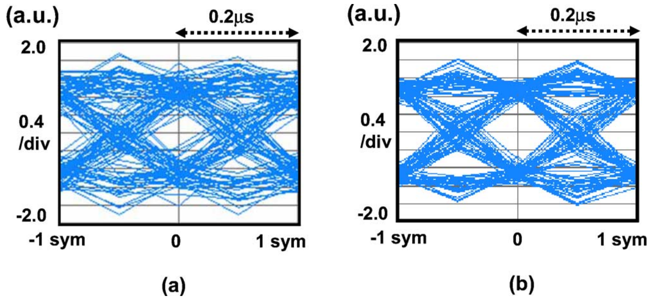

Fig. 5. (Color online) Measured eye diagrams for a demodulated 10 Mbps QPSK signal (a) without and (b) with SSBA induced by an 8 dBm optical pump in a 10 km long SMF.

we successfully generated millimeter waves corresponding to the third-harmonic (32.55 GHz) component of $f_{LO}=10.85$ GHz. In addition, we achieved harmonic upconversion of 10 Mbps QPSK data carried at 1.55 GHz into a 30 GHz band with more than 17 dB RF power gain.

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