Harmonic Millimeter Wave Generation and Frequency Up-Conversion Using Optical Injection Locking and Brillouin Selective Sideband Amplification *

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Harmonic millimeter wave (mm-wave) generation and frequency up-conversion are experimentally demonstrated using optical injection locking and Brillouin selective sideband amplification (BSSA) induced by stimulated Brillouin scattering in a 10-km single-mode fiber. By using this method, we successfully generate third-harmonic mm-wave at 27 GHz (f_{LO} = 9 GHz) with single sideband (SSB) modulation and up-convert the 2 GHz intermediate frequency signal into the mm-wave band with single mode modulation of the SSB modes. In addition, the mm-wave carrier obtains more than 23 dB power gain due to the BSSA. The transmission experiments show that the generated mm-wave and up-converted signals indicate strong immunity against the chromatic dispersion of the fibers.

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The mm-wave carrier generation and intermediate frequency (IF) signal up-conversion realized with the optical method for radio-over-fiber (RoF) systems are currently being investigated by many researchers due to demands of mm-wave bands used in future communication systems, especially in wireless local area networks (WLANs) applications. Optical down-link signals are generated from the central station (CS) and are transmitted to the antenna base stations (BSs). In the base stations, mm-wave signals, which are converted from the optical down-link signals, are transmitted to the mobile stations (MSs). Since the use of single sideband (SSB) signals as optical mm-wave generators is desirable to avoid the dispersion-induced power deviation of the generated mm-wave carrier, different heterodyne methods have been demonstrated.[1−6] IF signal up-conversion can be carried out by direct[4] or external[5] modulation of the two SSB modes. However, the modulation of the two SSB modes generates four IF modulation sidebands beside the two SSB modes, as shown in Fig. 1(a). The fiber dispersion results in walk-off among the relative phase of the four sidebands. Two unwanted beat signals, which are induced from the four IF modulation sidebands at the photodetector (PD), interfere with the carrier signal from the SSB modes. These unwanted components also lead to the power deviation of the mm-wave carrier due to the fiber chromatic dispersion. Additionally, the four IF modulation sidebands result in power deviations of the up-converted IF signals in the same way.[4]

In this Letter, we experimentally demonstrate an approach to generate the third-harmonic mm-wave carrier at 27 GHz with f_{LO} of 9 GHz and up-convert the IF signal (f_{IF} = 2 GHz) into the mm-wave band with single mode modulation of the SSB modes, which can overcome the dispersion-induced power deviation.

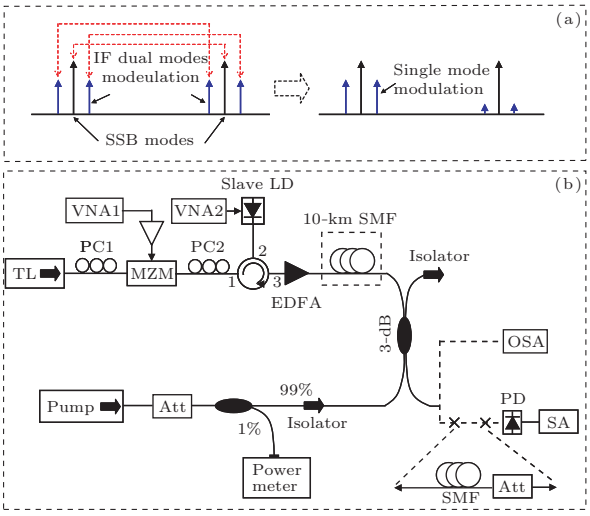


Fig. 1. (a) Schematic diagram of IF dual modes modulation and single mode modulation; (b) experimental setup.

Figure 1(b) shows the experimental setup. The output of an external cavity tunable laser (TL, Agilent 81949A) with inner isolator was modulated by a 40-GHz Mach-Zehnder intensity modulator (MZM)

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driven by a local oscillator (LO) from a vector network analyzer (VNA1, Agilent 8722ET). Large power LO of 21 dBm at 9 GHz was supplied to the MZM so that many high-order optical sidebands were generated due to the MZM nonlinearity as shown in Fig. 2(b). The output of the MZM was injected into a 1550 nm distributed feedback (DFB) laser (Fig. 2(a)), through a three-port optical circulator. The biased current of the DFB laser was 28.5 mA ($= 1.9I_{\rm th}$). The laser was frequency stabilized using thermoelectric cooler and output power of 326 μW at the wavelength of 1546.7 nm. The DFB laser was injection locked to the carrier (−12 dBm) of the modulated light as shown in Fig. 2(c). Additionally, the optical carrier and sidebands injected into the slave laser cavity beat within the active region, which created a series of harmonic mm-waves in the active region. These mm-waves caused the modulation of the slave laser. Hence the slave laser emitted modulation sidebands in Fig. 2(c).[8] However, the modulation efficiency was much lower. Thus, the carrier power was much larger than its sidebands. The resulting optical signals were finally injected into a 10-km single-mode fiber (SMF) through an Er^{+3}-doped fiber amplifier (EDFA).

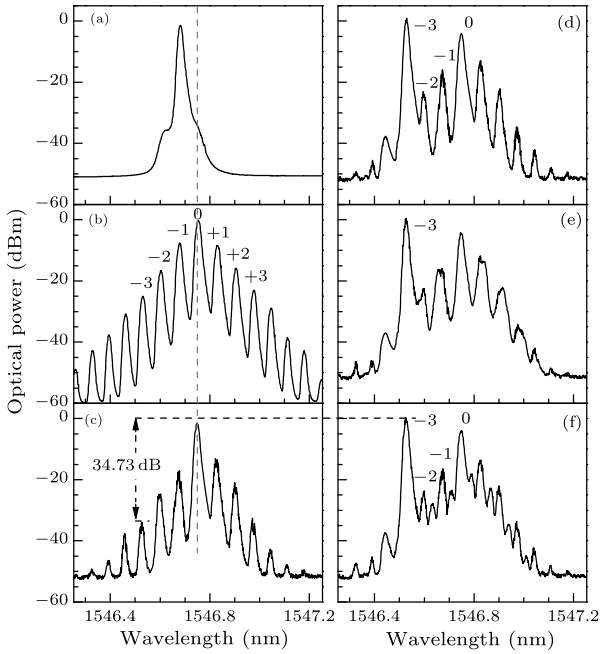


Fig. 2. Measured optical spectra of (a) free-running slave laser, (b) modulated master laser, (c) injection locked slave laser without 10-km SMF, (d) injection locked slave laser with BSSA of the -3rd LO-sideband in a 10-km SMF, (e) 2-GHz direct modulation of the injection locked slave laser with BSSA, and (f) 5-GHz direct modulation of the injection locked slave laser with BSSA (spectra (a) and (b) are also measured after the EDFA and 3-dB coupler in Fig. 1(b)).

SSB modulation can be obtained by filtering out one of the sidebands[1] or using an SSB modulator.[2] Equivalent to the two approaches mentioned above, SSB modulation can also be achieved by greatly amplifying one of the sidebands. In our experiment, the pump light provided by another tunable laser (Agilent 81600B) was injected into the 10-km SMF through a variable optical attenuator (Att.), an optical isolator, and a 3-dB fiber coupler. There was 1% of the pump power extracted from a 20-dB coupler to measure the pump power by an optical powermeter. The pump and DFB output signals counterpropagated in the 10-km SMF and interacted with each other. It is evident that when the −3rd LO-sideband of the DFB output is aligned with the Brillouin scattering peak of the pump light (8.24 dBm), it is amplified with an optical gain of 34.73 dB as shown in Fig. 2(d). The EDFA in Fig. 1(b) was used to increase the power of the −3rd LO-sideband and to compensate for the transmission loss of the fiber. If the seed (the −3rd LO-sideband) power was sufficiently strong, the stimulated emission induced by the seed could dominate and deplete the energy that might otherwise be converted to Brillouin spontaneous noise.[7]

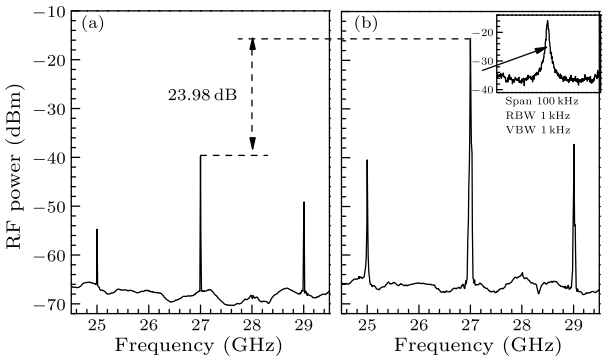


Fig. 3. Measured rf spectra (a) without BSSA and (b) with BSSA by 8.24 dBm optical pumping in a 10-km SMF.

When the DFB laser was directly modulated by a 2-GHz IF signal (0 dBm) from VNA2 (HP 8720D), all modes in the DFB laser were modulated simultaneously as shown in Fig. 2(e). A 5-GHz modulation optical spectrum is added in Fig. 2(f) to clearly illustrate the direct modulation sidebands. The IF modulation sidebands of the -3rd LO-mode were much lower than that of the locked carrier and could not be amplified because the BSSA has a narrow gain bandwidth.[7] Therefore, we could reasonably regard that only the locked carrier mode was effectively modulated by the IF signal. This is exactly the reason why we used injection locking technique. Since the up-converted mm-wave signals involved the beat between the −3rd LO-sideband and the ±1st IF-sidebands of the locked carrier, amplifying the −3rd LO-sideband would simultaneously increase the up-converted IF signals as shown in Fig. 3. Two polarization controllers (PC1,

PC2) were added to adjust the polarizations of the lights. The output from the DFB laser was monitored by an optical spectrum analyzer (OSA, Advantest Q8384) with 0.01 nm resolution. A high-speed photodetector (PD, New Focus) with a bandwidth of 45 GHz and 30-GHz rf spectrum analyzer (SA, R&S FSP30) was used to characterize the rf performance of the system. Figures 3(a) and 3(b) show the measured rf spectra without and with a 10-km SMF for generation of BSSA, respectively. With an 8.24 dBm pump power in a 10-km SMF, a 23.98 dB mm-wave carrier power gain was obtained. Total optical input power at the PD was 2 dBm. The inset shows the extremely narrow signal of the generated 27 GHz harmonic mm-wave due to the phase correlation of the two modes (carrier and the −3rd LO sideband). Figure 4 shows the measured rf power gains of the 27 GHz mm-wave and two up-converted signals (25 and 29 GHz) at different pump powers. Although the rf power gain drastically increased with the pump power, the optical pump power should be lower than the stimulated Brillouin scattering (SBS) threshold ($\sim$ 10 dBm in our experiment)[5,6,9] to avoid producing its own Stokes wave with the same direction as the −3rd LO-sideband. The unnecessary stokes wave would decrease the rf power gain and result in noise. The phase noise characteristic of the generated carrier is shown in Fig. 5, which indicates only 3 dB degradation from the signal source in the low frequency offset region. The phase-noise appears to be large in the high frequency offset region due to the spontaneous emission from the SBS. The insets show the rf signals of the generated carrier and the signal source.

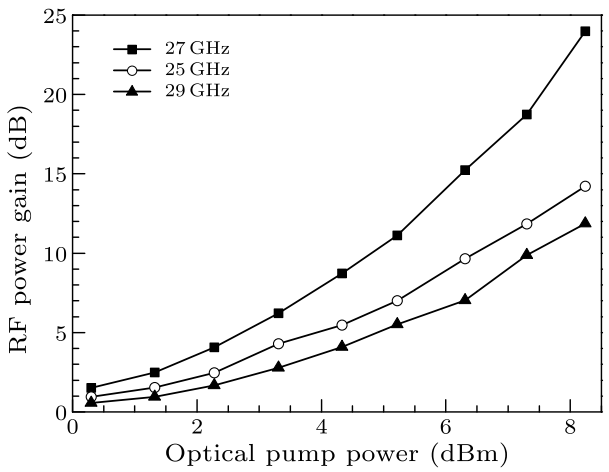


Fig. 4. Measured rf power gain versus optical pump power.

Finally, we examined the fiber transmission (1–25 km) of the generated carrier and the up-converted signals. In this experiment, an optical variable attenuator (Att.) was inserted at the PD to feed a constant optical power of −6 dBm into the PD (Fig. 1(b)). The rf power deviations are within 1.5 dB as shown in Fig. 6. The mm-wave powers were normalized to the carrier (27 GHz) power at 0 km. The carrier and the up-converted signals indicated strong immunity against the chromatic dispersion of the fibers because only the carrier mode was effectively modulated by the IF signal.

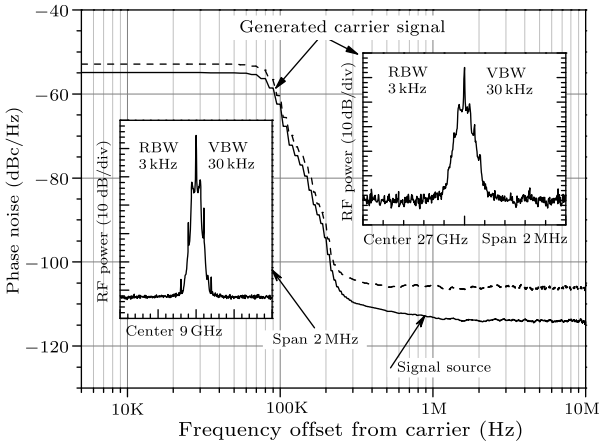


Fig. 5. Phase noise characteristics of generated carrier and local oscillator.

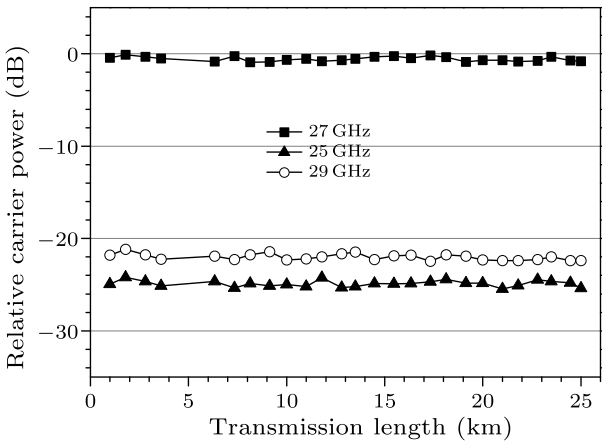


Fig. 6. Relationship between the transmission length and the relative carrier power.

In conclusion, we have demonstrated the third-harmonic mm-wave generation at 27 GHz with $f_{\rm LO}$ of 9 GHz and the up-conversion of IF signal at 2 GHz into the mm-wave band by using optical injection locking and BSSA in a 10-km SMF. The SSB modulation is achieved by the BSSA of another pump light. The injection locking technique is mainly used to realize IF signal single mode modulation of the SSB modes. The generated carrier and the up-converted signals indicate immunity against the chromatic dispersion of the fibers. The generated carrier could be tunable by adjusting the LO frequency and the wavelength of the pump light.

Since we have used two commercial external cavity tunable lasers as the pump and the seed sources, their relative frequency difference is more stable. However, it may cost too much in practical applications. The pump light can also be provided by a fraction of the modulated master light (Fig. 1(b)) after an optical filter. For example, the desired +2nd sideband is left after the filter and is amplified by an EDFA before injected into the 10-km SMF. The modulation frequency is the Brillouin scattering frequency (~ 11 GHz). Therefore, the mm-carrier of ~ 33 GHz can be generated.

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