Frequency Quadrupling and Upconversion in a Radio Over Fiber Link

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***Abstract*—In this paper, a novel technique to realize frequency quadrupling and upconversion in a radio over fiber (RoF) link is proposed and experimentally demonstrated. The frequency quadrupling is achieved by using two cascaded Mach–Zehnder modulators (MZMs) that are biased at the minimum transmission point, with a tunable optical delay line placed between the MZMs. By properly adjusting the time delay between the two MZMs, a pair of optical wavelengths with a wavelength spacing corresponding to four times the frequency of the microwave drive signal is generated. The two wavelengths are then sent to a third MZM to which an intermediate-frequency (IF) signal is applied. At the output of the third MZM, a frequency-upconverted signal at the millimeter-wave (mm-wave) band is obtained. The advantages of the technique are that a relatively low-frequency local oscillator (LO) signal is used to generate a high-frequency LO signal and the upconverted signal is more tolerant to the dispersion-induced power fading compared with a conventional RoF link based on double-sideband (DSB) modulation. Experiments are performed to verify the technique.**

***Index Terms*—Frequency upconversion, Mach–Zehnder modulator (MZM), millimeter-wave signal generation, radio over fiber (RoF).**

I. INTRODUCTION

THE distribution of radio signals over optical fiber, to take advantage of the low loss and broad bandwidth offered by the state-of-the-art optical fibers, has been a topic of research interest for over a decade. Radio over fiber (RoF) technologies can find many important applications such as in broadband wireless access networks, sensor networks, radar and other defense systems [1]. In a RoF system, to simplify the implementation and to reduce the cost it is desirable that a high-frequency microwave or millimeter-wave (mm-wave) can be generated directly in the optical domain [2]–[4] and a low-frequency RF signal can be upconverted to a high-frequency signal in the mm-wave band by mixing it with an optically generated mm-wave.

Several techniques have been proposed to implement mm-wave generation and frequency upconversion in the optical domain. In [5], a technique to realize mm-wave signal generation based on frequency quadrupling using a Mach–Zehnder modulator (MZM) that is biased at the minimum transmission point to suppress the odd-order sidebands is demonstrated. In the system, an ultranarrowband optical filter was employed to remove the optical carrier. By beating the second-order sidebands at a high-speed photodetector (PD), a frequency-quadrupled mm-wave with a high signal integrity was generated. A similar technique that was based on an optical phase modulator for mm-wave generation was also recently proposed [6], [7]. The major advantage of using a phase modulator is that the phase modulator is not biased which eliminates the bias drifting problem [6], [7]. Other techniques to generate mm-wave signals in the optical domain include the use of stimulated Brillouin scattering (SBS) in an optical fiber for frequency tripling [8], cross-gain modulation in a semiconductor optical amplifier (SOA) for frequency doubling [9], and four-wave mixing in an SOA for frequency tripling [10]. The key limitation of the techniques in [5]–[10] is that an ultranarrowband optical filter is required, which makes the system to have poor stability and high cost. To avoid using an ultranarrowband optical filter, a technique based on two cascaded MZMs and a tunable electrical phase shifter for frequency quadrupling was proposed recently [11]. The major difficulty associated with the technique in [11] is that a high-frequency electrical phase shifter is required, which makes the system not all optical but hybrid, with an increased system cost.

On the other hand, in a RoF system the radio signal is usually modulated on an optical carrier based on double-side band (DSB) modulation using a MZM. However, a RoF system that employs DSB modulation suffers from the well-known chromatic-dispersion-induced power fading [12], which would significantly limit the transmission distance. A solution to the problem is to use single-sideband (SSB) modulation. In [13]–[15], optical upconversion schemes with an improved dispersion performance based SSB modulation were proposed, in which the SSB modulation was realized using a dual-port external modulator or an ultranarrowband optical filter to remove one sideband.

In this paper, we propose a novel and simple technique to realize frequency quadrupling and upconversion in a RoF link. The frequency quadrupling is realized by using two cascaded MZMs that are biased at the minimum transmission point, with a tunable optical delay line being placed between the two MZMs. By properly adjusting the time delay between the two MZMs, two optical wavelengths with a wavelength spacing corresponding to four times the frequency of the microwave drive signal are generated. The frequency upconversion is then realized by sending the two optical wavelengths to a third MZM

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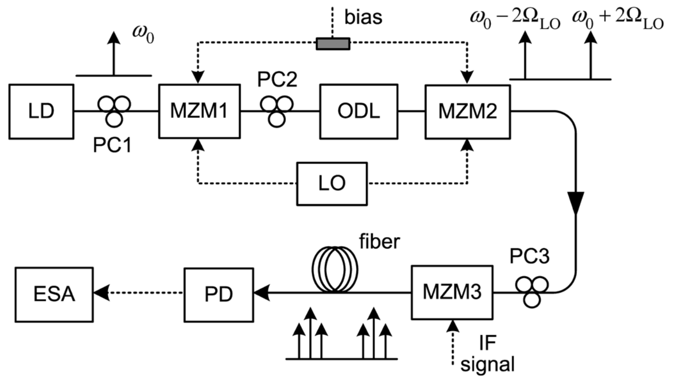


Fig. 1. Schematic diagram of the proposed scheme for frequency quadrupling and upconversion (LD: laser diode; MZM: Mach–Zehnder modulator; ODL: optical delay line; PD: photodetector; PC: polarization controller; ESA: electrical spectral analyzer).

(MZM3), to which an intermediate-frequency (IF) signal is applied. At the output of the third MZM, a frequency-upconverted signal with a frequency at the mm-wave band is obtained. There are two distinct advantages of the proposed technique. First, the frequency quadrupling is realized using two cascaded MZMs connected with a tunable optical delay line. Compared with the system using a tunable electrical phase shifter [11], the use of an optical delay line would make the system all-optical with a reduced cost. Second, the upconverted mm-wave signal would experience much less dispersion-induced power penalty compared to an mm-wave system based on conventional DSB modulation. The proposed technique is experimentally demonstrated. A 33.125-GHz electrical signal is generated when a microwave drive signal at 8.28125 is applied to the two cascaded MZMs. Frequency upconversion using the generated frequency-quadrupled mm-wave signal to mix with an IF signal at 1 GHz is also experimentally demonstrated.

II. OPERATION PRINCIPLE

The schematic diagram of the proposed scheme is illustrated in Fig. 1. Two MZMs (MZM1 and MZM2) that are biased at the minimum transmission point are connected by a tunable optical delay line. A microwave drive signal is applied to the two MZMs via their RF ports. Two polarization controllers (PC1 and PC2) are used to adjust the polarization states of the lightwaves entering the MZMs to minimize the polarization-dependence loss. By carefully adjusting the tunable optical delay line, two second-order sidebands with suppressed optical carrier and first-order sidebands are obtained. A third MZM (MZM3) is connected after MZM2 to perform frequency upconversion, to which an IF signal is applied. The frequency upconverted signal is then distributed to a remote site over an optical fiber which is then recovered at a high-speed PD.

Mathematically, the input lightwave to MZM1 from the laser diode (LD) can be expressed as $E_{\text{in}}(t) = E_0 \times \exp(j\omega_0 t)$, where E_0 is the intensity of the electrical field and ω_0 is the optical angular frequency of the incident lightwave. The optical signal at the output of MZM1 can be expressed as

$$E_{\text{out1}}(t) = \frac{1}{2}\left\{E_{\text{in}}(t) + E_{\text{in}}(t) \times \exp\left[j\varphi(t) + j\varphi_b\right]\right\} \quad (1)$$

where V_π is the half-wave voltage of MZM1, V_b is the bias voltage applied to MZM1, $\varphi_b = \pi V_b / V_\pi$ is the bias phase shift, $\varphi(t) = m\cos(2\pi f_{LO} t)$ is the phase shift introduced by the modulation signal, f_{LO} is the frequency of the modulation signal, $m = \pi V_s / V_\pi$ is the modulation index, and V_s is the signal voltage. Since the modulator is biased at the minimum transmission point, that is, $V_b = V_\pi$, or $\varphi_b = \pi$, we have

$$E_{\text{out1}}(t) = E_0 \times \left\{\sin\left[\frac{1}{2}\varphi(t)\right] \times \exp[j\omega_0 t + j\varphi_c]\right\} \quad (2)$$

where $\varphi_c = \pi/2 + \varphi(t)/2$ is the residual phase of the optical carrier.

If the group delay introduced by the optical delay line between the two MZMs is τ, the optical signal at the input of MZM2 is

$$\begin{aligned} E_{\text{out1}}(t-\tau) = E_0 \times \Bigg\{ & \sin\left[\frac{1}{2}\varphi(t-\tau)\right] \\ & \times \exp\left[j\omega_0(t-\tau) + j\varphi_c(t-\tau)\right]\Bigg\}. \quad (3) \end{aligned}$$

At the output of MZM2, we have

$$\begin{aligned} E_{\text{out2}}(t) &= \frac{1}{2}\left\{E_{\text{out1}}(t-\tau) + E_{\text{out1}}(t-\tau) \right. \\ &\qquad \left. \cdot \exp\left[j\varphi(t) + j\varphi_b\right]\right\} \\ &= E_0 \times \left\{\sin\left[\frac{1}{2}\varphi(t)\right] \times \sin\left[\frac{1}{2}\varphi(t-\tau)\right] \right. \\ &\qquad \left. \times \exp\left[j\omega_0(t-\tau) + \varphi_{cc}\right]\right\} \quad (4) \end{aligned}$$

where $\varphi_{cc} = \pi + [\varphi(t-\tau) + \varphi(t)]/2$ is the residual phase of the optical carrier. Under small signal approximation $(m \ll 1)$, we have

$$\begin{aligned} E_{\text{out2}}(t) \approx \frac{1}{4}m^2 \times E_0 \times \cos(2\pi f_{LO} t) \times \cos(2\pi f_{LO} t - \varphi_{RF}) \\ \times \exp\left[j\omega_0(t-\tau) + \varphi_{cc}\right] \quad (5) \end{aligned}$$

where $\varphi_{RF} = 2\pi f_{LO}\tau$ is the phase shift introduced by the group delay of the tunable optical delay line. If $\varphi_{RF} = 2\pi f_{LO}\tau = 2k\pi + \pi/2$ is satisfied, which can be realized by adjusting the tunable optical delay line, we have

$$\begin{aligned} E_{\text{out2}}(t) = \frac{1}{8j}m^2 \times E_0 \times \{&\exp\left[j(\omega_0 + 4\pi f_{LO})(t-\tau) + \varphi_{cc}\right] \\ &- \exp\left[j(\omega_0 - 4\pi f_{LO})(t-\tau) + \varphi_{cc}\right]\}. \quad (6) \end{aligned}$$

It is clearly seen from (6) that only the second-order sidebands with two angular frequencies at $\omega_0 \pm 4\pi f_{LO}$ are present at the output of MZM2; the optical carrier and the first-order sidebands are all suppressed. Note that this conclusion is valid

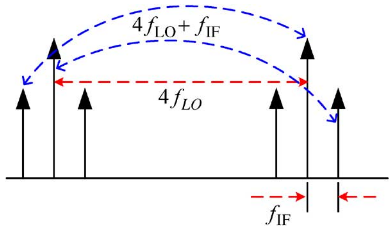


Fig. 2. Illustration of the optical spectrum at the output of MZM3.

if the frequency chirping induced by the residual phase term is neglected. The beating between the two second-order sidebands at a PD would generate an electrical signal with a frequency that is four times the frequency of the microwave drive signal.

To perform frequency upconversion, the two second-order sidebands from MZM2 are sent to MZM3. An IF signal with an electrical carrier frequency f_{IF} is applied to MZM3 via its RF port. As can be seen from Fig. 2, a frequency upconverted signal with a frequency $f_{RF} = 4f_{LO} + f_{If}$ is obtained at the output of MZM3.

The upconverted signal is then distributed to a remote site over an optical fiber. Due to the chromatic dispersion of the fiber, power fading would be resulted. Mathematically, the dispersion-induced power fading can be expressed as [16]

$$P_{\text{upcon}} \propto \cos^2(\beta f_{RF} f_{IF}) \tag{7}$$

where $\beta = \pi D L \lambda^2 / c$, L and D are the length and the dispersion parameter of the optical fiber, respectively, λ is the optical wavelength, and c is the speed of light in vacuum. As a comparison, in a conventional RoF link employing DSB modulation, the power fading due to the chromatic dispersion is given by

$$P_{\text{conv}} \propto \cos^2\left(\beta f_{RF}^2\right). \tag{8}$$

By comparing (7) with (8), we can see that the signal transmission based on the proposed frequency upconversion scheme is more tolerant to the fiber dispersion than the conventional scheme without frequency upconversion, since the IF frequency is much lower than the RF frequency.

III. RESULTS

The setup shown in Fig. 1 is experimentally implemented. An optical carrier with a wavelength at 1550.02 nm generated by a tunable laser source (TLS) is sent to MZM1 through PC1. The first two MZMs are biased at the minimum transmission point by carefully tuning the bias voltages. A microwave drive signal with a frequency $f_{LO} = 8.28125$ GHz from a signal generator (Agilent E8254A) is applied to MZM1 and MZM2. An IF signal with a frequency $f_{IF} = 1$ GHz is fed to MZM3. MZM3 is biased at the quadrature point. The frequency-upconverted signal is sent to a remote site over standard single mode fiber. A PD with 45-GHz bandwidth is used to detect the upconverted electrical signal at the remote site. The recovered electrical signal is monitored by an electrical spectral analyzer (Agilent E4448A). In the experiment, PC1, PC2, and PC3 are carefully adjusted to minimize the polarization-dependent loss.

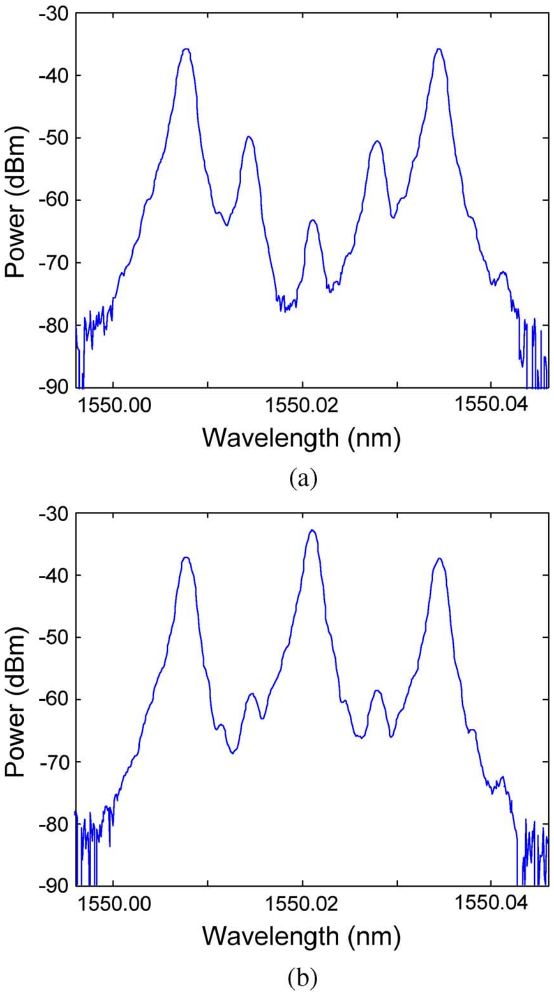
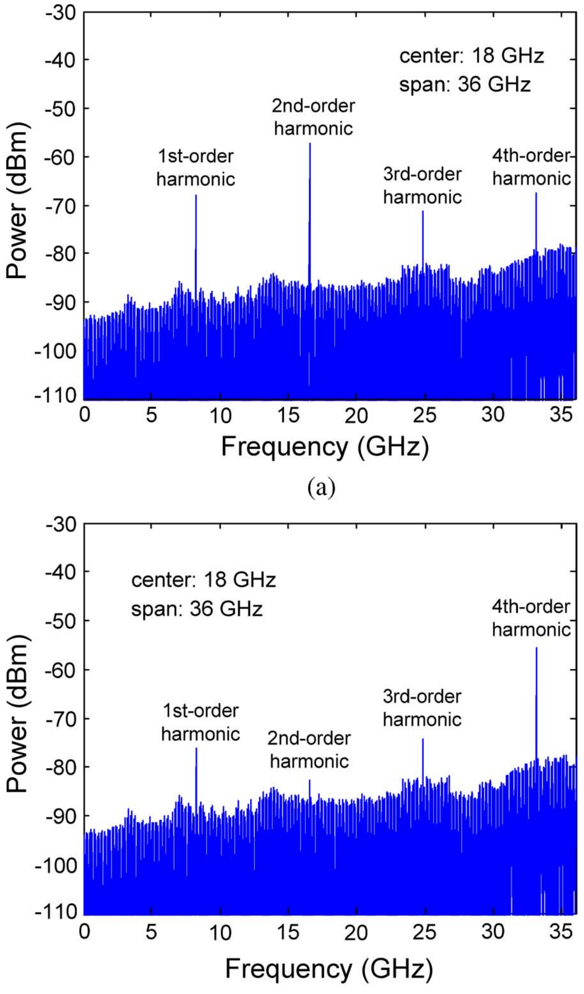


Fig. 3. Optical spectra measured at the output of MZM2 (resolution: 0.01 nm). (a) With optical carrier suppression. (b) Without optical carrier suppression.

A. *Optical Frequency Quadrupling: Optical Spectra*

The time delay between the two first MZMs is carefully adjusted by tuning the tunable optical delay line (General Photonics VDL001), to achieve a good suppression of the optical carrier. The optical spectrum with suppressed optical carrier and the first-order sidebands is shown in Fig. 3(a). It is seen that the suppression of the first-order sidebands is over 15 dB and the suppression of the optical carrier is as high as 30 dB. For comparison, the optical spectrum without optical carrier suppression is shown in Fig. 3(b), which is measured when the tunable optical delay line is intentionally tuned to maximize the optical carrier. The incomplete suppression of the optical carrier and the first-order sidebands is owing to the frequency chirping due to the residual phase term in the optical carrier as shown in (6) and the higher-order sidebands generated in the modulation process, which are not considered in the theoretical treatment. We believe that the use of a dual-drive MZM would lead to a better suppression of the unwanted optical carrier and high-order sidebands, since there is no frequency chirping in the optical carrier for the case when a dual-drive MZM is employed [17].



(a)

(b)

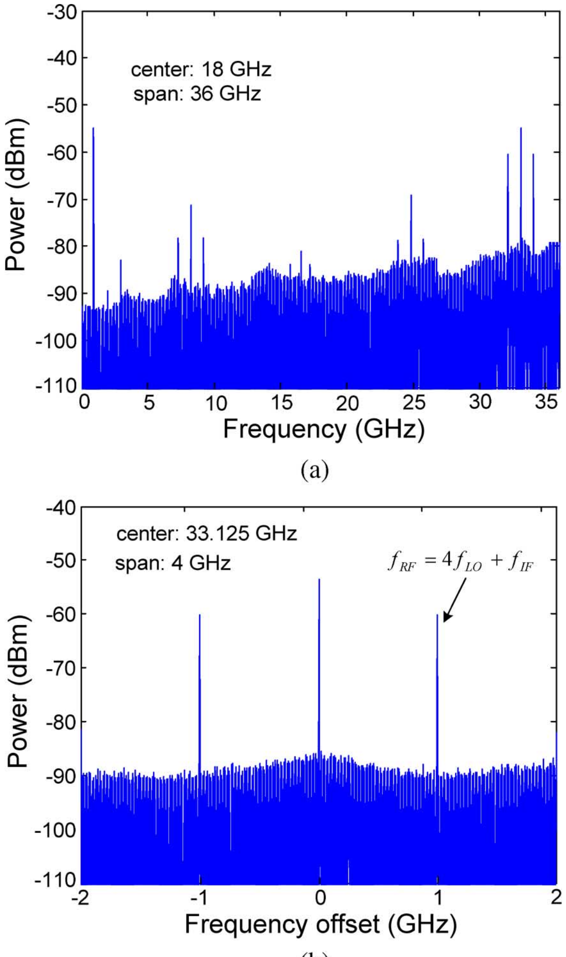
Fig. 4. The electrical spectra without IF modulation. (a) Without optical carrier suppression. (b) With optical carrier suppression.

B. Optical Frequency Quadrupling: Electrical Spectra

We then measure the spectra of the frequency-quadrupled electrical signal. To boost up the signal power, an erbium-doped fiber amplifier (EDFA) is placed before the PD. The electrical spectra with or without carrier suppression are measured when the received optical power is set at 1 dBm realized by controlling the gain of the EDFA. The measured spectra are shown in Fig. 4(a) and (b), with no IF signal being applied to the MZM3. Fig. 4(a) shows the electrical spectrum when the optical delay line is tuned to maximize the optical carrier, which corresponds to the optical spectrum shown in Fig. 3(b). It is seen that the second-order harmonic has the highest power. Then, we tuned the optical delay line to suppress the optical carrier. Fig. 4(b) shows the electrical spectrum with optical carrier suppression, which corresponds to the optical spectrum shown in Fig. 3(a). It is seen that the first-, second-, and third-order harmonics are all well suppressed. Compared with the fourth-order harmonic, over 20 dB suppression of the all the other harmonics is realized.

C. Optical Frequency Upconversion: Electrical Spectra

The two optical wavelengths from MZM2 are then sent to the third MZM (MZM3), to which an IF signal is applied to achieve frequency upconversion. The electrical spectrum of the mixing signal is shown in Fig. 5(a). The frequency of the upconverted signal is $f_{RF} = 4f_{LO} + f_{IF}$, 34.125 GHz in our experiment. The zoom-in display near the quadrupled frequency is shown in Fig. 5(b). The spectrum includes the harmonic components of 0–4 orders. Thanks to the optical carrier suppression, the power of the fourth-order harmonic is higher than those of the first-, second-, and third-order harmonics.



(a)

(b)

Fig. 5. (a) The electrical spectrum after mixing at MZM3. (b) Zoom-in display near the quadrupled frequency.

D. Dispersion-Induced Power Penalty

A study is made to investigate the dispersion-induced power penalty when the upconverted signal is transmitted over an optical fiber. Numerical results illustrating the power penalty of the RF signal along fiber link are shown in Fig. 6. In the simulation, the dispersion parameter of the fiber is set at 17 ps/nm/km. For comparison, the power fading of a conventional RoF link based on DSB modulation is also shown in Fig. 6. It is seen that the RoF link based on the proposed upconversion technique has a much better dispersion tolerance than the conventional RoF link based on the DSB modulation. The first power dip is found at $L = 108\ \mathrm{km}$ in our system; while for the conventional RoF link the first power dip is found at $L = 3.2\ \mathrm{km}$. In the experiment, we also measure the electrical spectra of the upconverted electrical signal before and after optical transmission over transmission distances of 20 and 40 km. Experimental results are shown

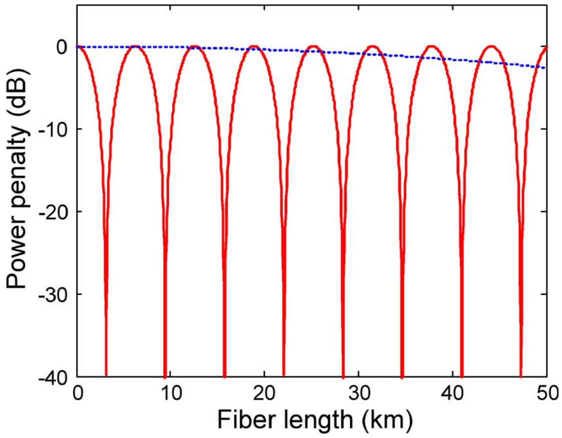
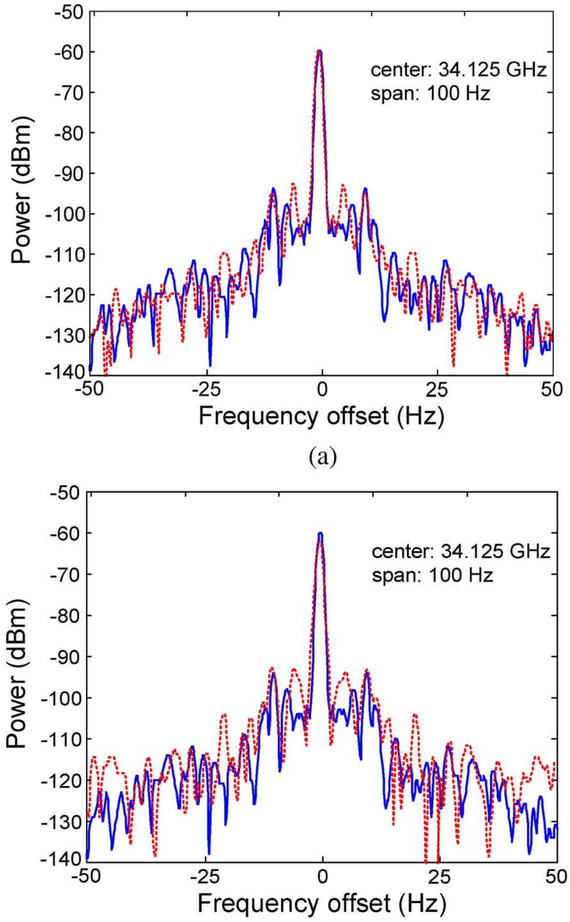


Fig. 6. Simulation results of the chromatic-dispersion-induced power penalty along fiber link (solid: conventional DSB modulation; dotted: RF generated based on the proposed upconversion scheme).



(a)

(b)

Fig. 7. The electrical spectra before and after the fiber transmission (solid: before; dashed: after). (a) 20 km. (b) 40 km.

in Fig. 7(a) and (b). The electrical spectra are measured when the received optical power is set at 1 dBm. As can be seen very small power fading is observed for both transmission distances, which agrees well with the numerical results shown in Fig. 6.

IV. CONCLUSION

A novel technique to realize frequency quadrupling for mm-wave generation and upconversion in a RoF link was proposed and experimentally demonstrated. The frequency quadrupling was realized by using two cascaded MZMs that were biased at the minimum transmission point. By tuning the time delay between the two MZMs using a tunable optical delay line, two second-order optical sidebands with suppressed optical carrier and the first-order sidebands were generated. The effectiveness of the technique was experimentally verified, in which a 33.125-GHz electrical signal was generated when a microwave drive signal at 8.28125 GHz was applied to the two cascaded MZMs. The two second-order sidebands were then sent to a third MZM to implement frequency upconversion. At the output of the third MZM, a frequency-upconverted signal at the mm-wave band was obtained. The key advantages of the technique include: 1) the use of a tunable optical delay line makes the system much simpler than using an electrical phase shifter; and 2) the upconverted signal is more tolerant to the dispersion-induced power fading compared with the conventional RoF link based on DSB modulation. The proposed technique has a high potential for applications in wireless access networks operating at the mm-wave band.

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