

A Frequency Quadrupling Optical mm-Wave Generation for Hybrid Fiber-Wireless Systems

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Abstract—A frequency quadrupling scheme for optical mm-wave signal generation is proposed and demonstrated based on dual-electrode dual-parallel integrated Mach-Zehnder modulator (MZM) consisting of three dual-electrodes MZMs. The electrical filters or optical filters are not required in this scheme. The theoretical analysis is presented to configurate the phases and DC biases of the integrated MZM. The simulation and experiment verification are both conducted to evaluate the performance of the proposed scheme. With 9GHz RF drive signal, the optical sideband suppression ratio (OSSR) higher than 35dB is demonstrated experimentally. The 36GHz mm-wave is generated with the RF spurious suppression ratio (RFSSR) over 30dB.

Index Terms—Fiber-wireless systems, frequency quadrupling, mm-wave, dual-electrode dual-parallel integrated Mach-Zehnder modulator.

I. INTRODUCTION

AS well known, optical fiber network has extremely low transmission loss (0.2 dB/km) and tremendous bandwidth, but not supports mobility. In contrast, the radio frequency (RF) wireless network, has attractive features like mobility and spatial diversity. But, the available spectrum and interference effects would limit the data rates, compared with optical fiber network [1], [2]. Fiber-Wireless (Fi-Wi) technology is the combination of optical fiber network and RF wireless network, in which the front end is the RF wireless network and the back end is the optical fiber network [3]. Because Fi-Wi system can enjoy the advantages of both optical fiber and wireless technologies, it gives high capacity bandwidth and the best solution to meet the explosive growth of global mobile and wireless access technology in recent years [4]. In addition, it is also transparent against modulation techniques, and are able to support various digital formats and wireless standards in a cost-effective manner [5].

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Millimeter-wave (mm-wave) signals have extensive applications [6], including radars, remote sensing, broadband wireless communication and so on. Especially, the unlicensed 60GHz frequency band (57-64 GHz) is significant for high-speed applications [7]. However, mm-wave distribution via wireless or coaxial methods is usually limited to the short-range applications, due to the inherently high propagation losses. Thus, Fi-Wi system operating in the mm-wave frequency range is being actively pursued to transmit and distribute the mm-wave signals over long distance [8], to support indoor wireless applications that such as real time streaming content download for high-definition TV, wireless gigabit Ethernet, etc.

Fig. 1 is a typical fiber-wireless network where an center office (CO) acts as the gateway to the optical metropolitan backbone while serving a large number of widely distributed antenna Base stations (BSs). Because mm-wave systems require a large number of BSs to cover a service area, the BSs are designed to generate and receive the mm-wave. For mm-wave Fi-Wi system, cost-effective and high quality generation of mm-wave is a key technology. Conventional electrical mm-wave signal generation, especially when the frequency above 60GHz, is very difficult because of electromagnetic interference and the slow frequency responses. Compared with the conventional electrical method, optical method is a preferable choice, thanks to the integration of the advantages of the huge available bandwidth, extremely low propagation loss, and immune to electromagnetic interference [9], [10].

High purity and low phase noise optical mm-wave signals can be generated by beating the high-order optical harmonics or/and by beating the high-order optical harmonics with the optical carrier at a photodetector (PD) [9]–[11]. Usually, the optical harmonics are generated from modulator and selected through optical filtering or by adjusting the configuration of the modulator. The frequency of the generated mm-wave signal is therefore multiplied, with low cost and simple configuration. The requirements on optical and electrical components (such as the bandwidth of optical modulator, the electrical drive signal source, the transmission line, and the drive circuit), are lowered greatly, due to the frequency multiplication technique. Therefore, it is widely used in the generation of the mm-wave signals.

The frequency doubling can be easily implemented by double harmonics carrier suppression modulation with a single Mach-Zehnder modulator (MZM) [12]–[15]. But, the frequency doubling schemes are not sufficient to reduce requirements on the optical and electrical components. Frequency

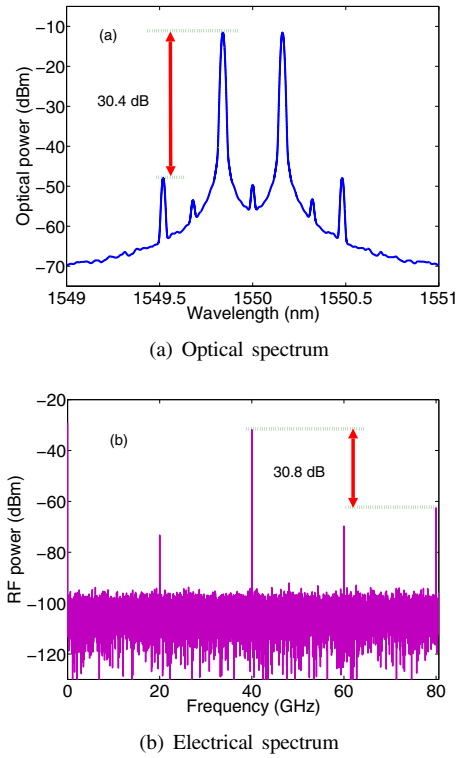


Fig. 3. The simulation results for modulation depth of 0.875 and sub-MZM with extinction ratio of 30dB.

the two sub-MZM. Because the four electrodes were driven by the same RF LO, the initial phase is not considered in the Eq. (2).

If the insertion loss is ignored and the extinction ratio of each sub-MZM is assumed to be infinite, the output optical field of the integrated MZM can be written as

$$E(t) = \frac{1}{4}E_0e^{j\omega_0 t} \left[e^{j\frac{\pi}{2V_\pi}V_{a1}(t)} + e^{j\frac{\pi}{2V_\pi}V_{a2}(t)} \right] + \frac{1}{4}E_0e^{j\omega_0 t} \left[e^{j\frac{\pi}{2V_\pi}V_{b1}(t)} + e^{j\frac{\pi}{2V_\pi}V_{b2}(t)} \right]. \quad (3)$$

Physically, only the second-order harmonics are desired to realize the frequency quadrupling. The optical carrier and the other harmonics should be deleted during the modulation. In our scheme, the phase difference of $\pi/2$ is introduced between the two electrodes for each sub-MZM and the phase difference of π is introduced between the two sub-MZM. i.e., we have

$$\Delta\phi_1 = \pi/2, \Delta\phi_2 = \pi. \quad (4)$$

By employing the Bessel expansion [24], and considering the Eq. (3), Eq. (2) can be expanded and simplified as

$$E(t) = \frac{1}{2}E_0e^{j\omega_0 t} \sum_{n=-\infty}^{+\infty} J_{4n+2}(m)e^{j(4n+2)\omega_{RF}t}, \quad (5)$$

where $n = 0, 1, 2, \dots$, is integer and J_k is the first-kind Bessel function of k order. m is modulation index defined as

$$m = \frac{\pi V_{RF}}{2V_\pi} = \pi M_d, \quad (6)$$

where M_d is the modulation depth.

Judging from Eq. (5), the $4n$ order harmonics, and the odd order harmonic (including the $(4n + 1)$, and $(4n + 3)$ order optical harmonics) are completely suppressed, provided that the MZM-a and MZM-b are designated according to Eqs. (1) and (4). Only the $(4n + 2)$ order optical harmonics are retained and its power is therefore maximized.

For the commercial available MZM, the maximal modulation index is about π , or the maximal modulation depth is 1. In this case, the power of second-order harmonics is much higher than that of other harmonics. Therefore, the second-order harmonics are the biggest among the the $(4n + 2)$ order ones. The output field of the integrated MZM can be regarded as the second-order harmonics and can be written as

$$E_{2m}(t) \simeq \frac{1}{2}E_0e^{j\omega_0 t} J_2(m)[e^{j2\omega_{RF}t} + e^{-j2\omega_{RF}t}]. \quad (7)$$

When the generated optical mm-wave signal is injected into PD, frequency quadrupling mm-wave signal is generated by beating of the upper and lower sideband of the second-order harmonics.

The photocurrent of PD is given by

$$I_{PD} = R \cdot |E_{2m}(t)|^2 = R \cdot P_{2m}, \quad (8)$$

where R is the responsivity of photodetector, P_{2m} is the maximum power of the second-order harmonics.

III. SIMULATION RESULTS

To verify the validity of the proposed scheme, the system shown in Fig. 2 is simulated with the VPI Transmission Maker tool. It is assumed that the continuous wave (CW) laser emits the lightwave with the central wavelength of 1550nm, the linewidth of 20MHz and the power of 0dBm. MZM-a and MZM-b are driven by the same RF local oscillator of 10GHz. According to Eq. (4), the phase difference of $\pi/2$ and π is introduced by phase shifters between RF drive signal of MZM-a and MZM-b, and two electrodes of MZM-a and MZM-b. The insertion loss of the integrated MZM is 5dB. The three sub-MZMs of the integrated MZM are assumed to have identical parameters. Following the integrated MZM, an EDFA with gain of 12dB and noise figure of 4dB is utilized to compensate the insert loss of the integrated MZM. For the square-law PD, the responsivity is $R = 0.5A/W$, dark current is $2nA$ and thermal noise is $1 \times 10^{-11}A/\sqrt{Hz}$.

A. Optical Spectrum and Electrical Spectrum

Fig. 3 shows the simulated optical spectrum and RF spectrum for modulation depth of 0.875 and sub-MZM with extinction ratio of 30dB. As shown in Fig. 3(a), the power of the second-order harmonics are maximized and the other harmonics are well suppressed, by setting the DC bias and the phase according to Eq. (1) and (4). The OSSR exceeds 30dB. As shown in Fig. 3(b), the power of the desired frequency quadrupling 40GHz mm-wave signal is higher than other spurious RF components, with RF spurious suppression ratio (RFSSR) 30.8dB.

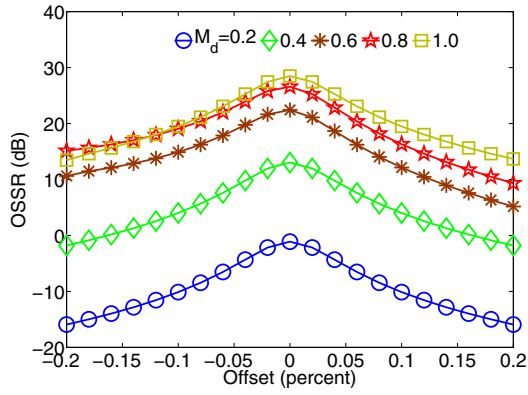


Fig. 4. The influence of bias offset on OSSR for sub-MZM with extinction of 25dB at different modulation depth.

B. The influence of bias offset, modulation depth, non-ideal phase difference on OSSR

In the above simulation, the proposed scheme is implemented by employing the ideal power splitter ratio, DC bias and phase difference of RF drive signal of MZMs. When those parameters deviate from the ideal value, the OSSR and the RFSSR of the generated optical mm-wave signal are bound to be affected. Therefore, it is necessary to investigate the influence of those non-ideal factors, to generate high quality optical mm-wave signal.

For simplicity, the power splitter ratio of the upper Y branch of each sub-MZM is assumed to be γ , given by

$$\gamma = \frac{1}{2}(1 - E_r^{-1/2}), \quad (7)$$

where E_r is extinction ratio of sub-MZM.

To consider the non-ideal factors, Eqs. (1), and (4) are rewritten as

$$\begin{aligned} V_{DCa1} &= V_{DCb1} = V_{DCc1} = 0, \\ V_{DCa2} &= V_{DCb2} = V_\pi(1 + \delta), \\ V_{DCc1} &= V_\pi \\ V_{DCc2} &= \delta V_\pi, \\ \Delta\phi_1 &= (1 + \delta_1)\frac{\pi}{2}, \end{aligned} \quad (8)$$

where δ represents the bias offset. δ_1 represent the phase offset deviated from the desired phase difference between the two electrodes of sub-MZM. Thus, the optical field of the integrated MZM can be expressed as

$$\begin{aligned} E(t) &= E_0\gamma e^{j\omega_0 t} \sum_{n=-\infty}^{+\infty} J_n(m) e^{jn\omega_{RF} t} \\ &\quad \times \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{jn(1+\delta_1)\pi/2} \right] \\ &+ E_0(1 - \gamma) e^{j\omega_0 t} \sum_{n=-\infty}^{+\infty} J_n(-m) e^{jn\omega_{RF} t} \\ &\quad \times \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{jn(1+\delta_1)\pi/2} \right] e^{j\pi\delta} \\ &= E_0 e^{j\omega_0 t} \sum_{n=-\infty}^{+\infty} \left\{ \left[\gamma + (1 - \gamma) e^{j\pi\delta} \right] \right. \end{aligned} \quad (9)$$

$$\begin{aligned} &\quad \times \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{2jn\pi\delta_1} \right] J_{4n}(m) e^{j4n\omega_{RF} t} \left. \right\} \\ &+ \left\{ \left[\gamma - (1 - \gamma) e^{j\pi\delta} \right] \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{j(4n+1)\pi\delta_1/2} \right] \right. \\ &\quad \times J_{(4n+1)}(m) e^{j(4n+1)\omega_{RF} t} \left. \right\} \\ &- \left\{ \left[\gamma + (1 - \gamma) e^{j\pi\delta} \right] \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{j(4n+2)\pi\delta_1/2} \right] \right. \\ &\quad \times J_{4n+2}(m) e^{j(4n+2)\omega_{RF} t} \left. \right\} \\ &- \left\{ \left[\gamma - (1 - \gamma) e^{j\pi\delta} \right] \left[\gamma - (1 - \gamma) e^{j\pi\delta} e^{j(4n+3)\pi\delta_1/2} \right] \right. \\ &\quad \times J_{4n+3}(m) e^{j(4n+3)\omega_{RF} t} \left. \right\}. \end{aligned}$$

The OSSR, defined as the ration between the desired second-order harmonics and other undesired harmonics (including the optical carrier), is of the form

$$OSSR = 10 \log \frac{P_2}{P_i}, \quad (10)$$

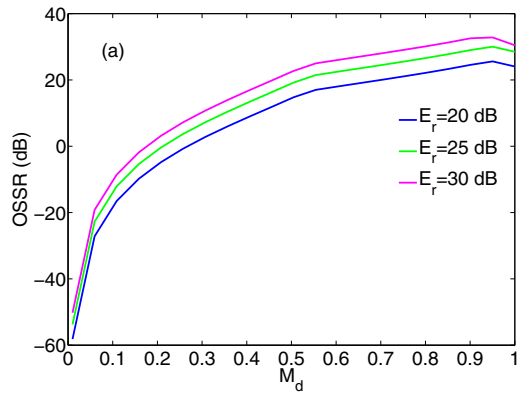
where P_2 is the power of second-order harmonics, P_i ($i = 0, 1, 3, 4, 5, \dots, i \neq 2$) represents the power of optical carrier ($i = 0$) or other undesired harmonics.

Based on Eqs. (9) and (10), the bias offset (δ), the influence of modulation depth (M_d), the extinction ratio of sub-MZM (E_r) and non-ideal phase difference (δ_1) on OSSR is investigated numerically.

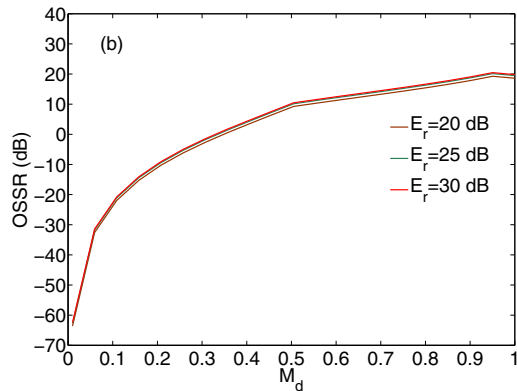
The influence of bias offset (δ) on OSSR for sub-MZM with $E_r = 25dB$ at different modulation depth (M_d) is shown in Fig. 4. It can be seen that bias offset has important influence on OSSR. The maximal OSSR can be obtained for the ideal bias voltage. When the Bias voltage deviates far from the desired value, the OSSR declines obviously. Approximately, the larger modulation depth would result in the higher OSSR, within the range of 0 and 1.

Figs. 5(a) and 5(b) show the influence of modulation depth (M_d) on OSSR at different extinction of sub-MZM (E_r) for $\delta = 0$ and $\delta = 10\%$, respectively. There is an optimal modulation depth that corresponds to the maximal OSSR. For no bias offset and bias offset of 10%, the optimal modulation depth is both about 0.95 for extinction of 20, 25 and 30dB. On the other hand, the difference of the OSSR is reduced in the presence of the bias offset, for different extinction ratio. That is to say, the OSSR is more sensitive to the bias offset, compared with the extinction ratio changing.

The influence of phase offset from the idea $\Delta\phi_1$, which is the phase difference between RF drive signal of two electrodes of sub-MZM, is shown in Fig. 6(a), with extinction of 20, 25, and 30dB, respectively. As shown, the OSSR is susceptible to non-ideal phase offset. As the phase offset increasing, the difference of the OSSR between different extinction of sub-MZM decreases gradually. In Fig. 6(b), the influence of phase offset from the idea $\Delta\phi_2$, which is the phase difference between MZM-a and MZM-b, is presented with extinction of 20, 25, and 30dB, respectively. In comparison, the OSSR is more sensitive to the phase offset from the idea $\Delta\phi_2$. So, it is necessary to control the $\Delta\phi_2 = \pi$.



(a) No bias offset



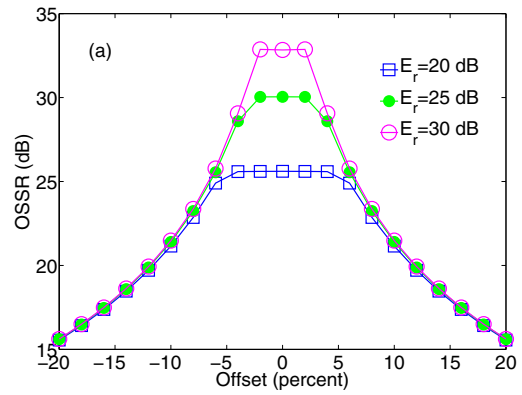
(b) Bias offset of 10%

Fig. 5. The influence of modulation depth on OSSR for different extinction ratio of sub-MZM.

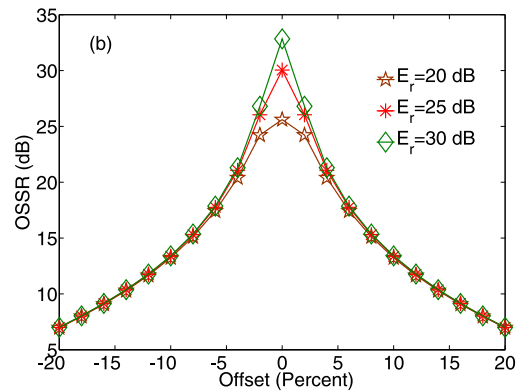
IV. EXPERIMENT RESULTS

Experiment system as shown in Fig. 7 was proposed to evaluate the performance of the proposed scheme. The CW Laser emits the lightwave with central wavelength of $1537.06nm$, with linewidth of $20MHz$. The $9GHz$ RF signal is emitted from RF source (Anritsu 68047C) and amplified by the four RF amplifiers. The phase of the four RF signals are adjusted by the PS (ATM P1408). The integrated integrated dual-parallel dual-electrodes MZM (FUJITSU FTM7960EX) has low half-wave voltage about $2V$. According to the Eqs. (1), (2) and (4), the phase-matched four RF signals are launched into the MZ-a and MZ-b of the integrated MZM, respectively. A PD (U^2t XPDV2150R) with $50GHz$ bandwidth is utilized to detect the generated mm-wave signal. The optical spectrum and electrical spectrum are monitored by an optical spectrum analyzer (Ando AQ 6319) and electrical spectrum analyzer (MS2726C, $9k-40GHz$).

The $36GHz$ mm-wave signal is generated through frequency quadrupling and the Fig. 8 shows the measured optical spectrum and RF spectrum. As shown in Fig. 8(a), the second-order harmonic is much higher than other undesired harmonics, with the OSSR $35.4dB$. As shown in Fig. 8(b), the high purity RF spectrum is obtained for back-to back (BTB) without EDFA. RFSSR of $30dB$ is achieved, due to high OSSR. Fig. 8(c) is presented to show the RFSSR spectrum after transmission



(a) OSSR against phase offset from the idea $\Delta\phi_1$



(b) OSSR against phase offset from the idea $\Delta\phi_2$

Fig. 6. The influence of non-ideal phase difference of RF drive signal on OSSR for sub-MZM with extinction ratio of 20dB, 25dB and 30dB.

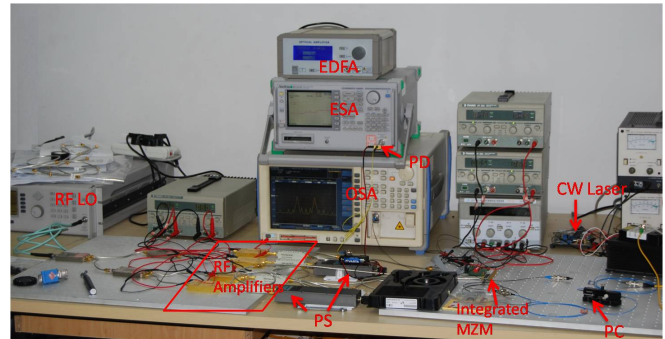


Fig. 7. The experimental setup of back-to-back for frequency quadrupling mm-wave signal generation.

over $40km$ with EDFA. The RFSSR is reduced $5dB$ because of the propagation damages. However, the linewidth of the generated $36GHz$ mm-wave is maintained after transmission over fiber $40km$, which is almost equal to that of BTB, as shown in Fig. 8(d).

V. CONCLUSIONS

A frequency quadrupling scheme is proposed for the high quality optical mm-wave signal generation. The optical filters or electrical filters are not required in this scheme. A high quality $36GHz$ optical mm-wave signal is obtained with a

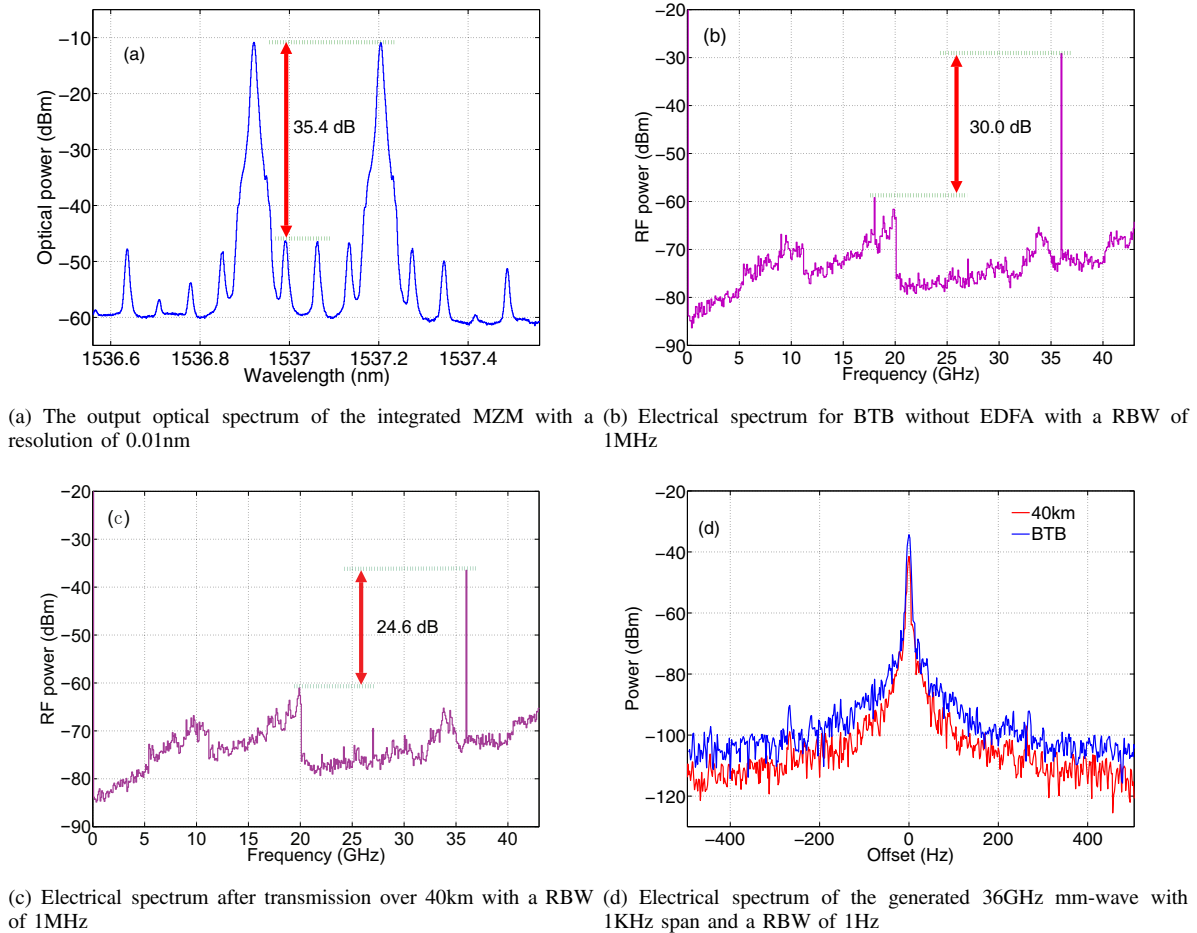


Fig. 8. The experiment results of the optical spectrum and electrical spectrum. (RBW: resolution bandwidth)

9GHz RF drive signal through frequency quadrupling. The OSSR exceeding 35.4dB and the RFSSR exceeding 30dB are demonstrated. After transmission over 40km fiber, the linewidth of the generated 36GHz mm-wave signal is almost equal to that of BTB. Through numerical analysis, an optimal modulation depth, which corresponds to a maximal OSSR, is about 0.95. In addition, numerical simulations are presented to analyse the influence of the non-ideal extinction ratio of sub-MZM, the DC bias offset and the phase offset.

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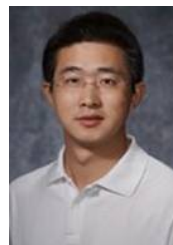
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