WDM up-conversion employing frequency quadrupling in optical modulator

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Abstract: This work presents an optical up-conversion system with frequency quadrupling for wavelength-division-multiplexing (WDM) communication systems using a dual-parallel Mach-Zehnder modulator without optical filtering. Four-channel 1.25-Gb/s wired fiber-to-the-x (FTTx) and wireless radio-over-fiber (RoF) signals are generated and transmitted simultaneously. Moreover, the decline in receiver sensitivities due to Mach-Zehnder modulator bias drifts is also investigated. Receiver power penalties of the 20-GHz up-converted WDM signals and baseband (BB) FTTx signals are less than 1 dB when bias deviation voltage is less the 20% of the half-wave voltage. After transmission over a 50-km SSMF, the receiver power penalties of both the BB and 20-GHz RF OOK signals are less than 1 dB. Notably, 60-GHz optical up-conversion can be achieved using 15-GHz radio frequency (RF) components and equipment.

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1. Introduction

Optical millimeter-wave generation and up-conversion are essential to Radio-over-Fiber (RoF) communication systems [1-7]. With the rapidly increasing bandwidth requirements for next generation multimedia services, including wireless high definition television (WirelessHD®) and video on demand, the frequencies of the generated millimeter-wave signal and up-conversion system are increasing. Nevertheless, optical millimeter-wave generation and up-conversion with a frequency beyond 40-GHz remain significant challenges. Many studies are proposed in recent years [1-14]. Among these works, using external modulators, such as $LiNbO_3$ Mach-Zehnder modulator (MZM) or phase modulator (PM), are the most reliable and simplest choice for optical millimeter-wave generation. [1-13]. However, frequencies of millimeter-wave generation and up-conversion systems are still restricted by the frequency response of $LiNbO_3$ modulators, which is typically less than 40 GHz. Additionally, the radio frequency (RF) electrical components and equipment with frequency higher the 26 GHz are extremely expensive than those with frequency response below 26 GHz. Therefore, a simple and cost-effective approach for optical millimeter-wave generation and up-conversion beyond 40 GHz is of great interest. Many schemes have recently been developed for optical millimeter wave generation with frequencies exceeding two times that of the RF driving signals [3, 6, 9, 10, 11, 13]. Via these frequency tripling and quadrupling techniques, optical millimeter-wave signals can be generated using low-frequency RF components and equipment which markedly reduces the entire system costs. However, some of these proposed systems require two cased external modulators, which increase system complexity and cost. Furthermore, narrowband optical filters, which are required in some of these systems, hinder the implementation of optical up-conversion in wavelength-division-multiplexing (WDM) RoF systems [7, 11].

In addition to RoF techniques, simultaneous transmission of wired baseband (BB) and wireless RF signals for low-cost quad-play services (wireless, telephone, television and internet) over the constructed passive optical networks (PON) also attract much attention. This work experimentally demonstrates an optical up-conversion system using a frequency quadrupling approach. Four-channel BB 1.25-Gbits/s WDM millimeter-wave signals are simultaneously up-converted with optical carrier suppression using only one external modulator without narrowband optical filtering. Since no narrowband optical filter is needed, the proposed system can be implemented in WDM up-conversion systems. The harmonic distortion suppression ratio (HDSR) of the generated millimeter-wave signals in each channel exceeds 35 dB. Based on the modified double sideband with carrier suppression (DS-CS) modulation scheme, the proposed architecture supports both wireless and wired services [13, 14]. After transmission over 50-km standard single mode fiber (SSMF), the power penalties of 20-GHz wireless and wired signals are less than 1 dB, respectively. 40- and 60-GHz WDM up-conversion are also demonstrated experimentally in this work. The HDSR of the generated 40- and 60-GHz millimeter-wave signals in each channel are also higher than 30 dB.
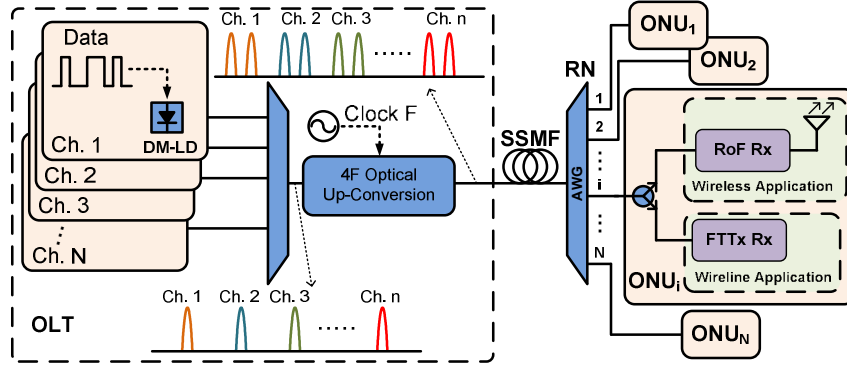
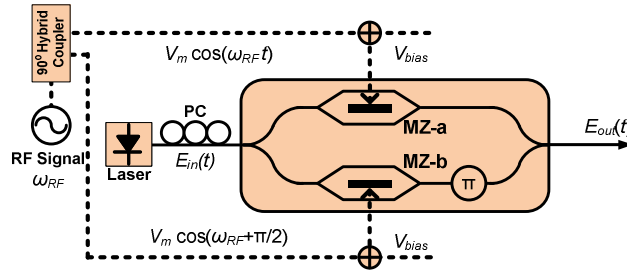Fig. 1. Conceptual diagram of a WDM up-conversion system.

Fig. 2. Optical millimeter-wave generation with frequency quadrupling.

Furthermore, the impact of the MZM bias drift on the performance of BB and RF signals is also investigated.

2. Concepts and experimental setup

Figure 1 shows a conceptual diagram of the WDM up-conversion system. In the optical line terminal (OLT), direct modulation laser diodes are employed as optical sources of WDM channels. After combining the channels, the BB WDM signals are sent into the optical up-conversion system and all WDM channels are up-converted simultaneously. After transmission over SSMF, WDM channels are separated using an array wave guide (AWG) and sent to the optical network units (ONU). At the ONU, optical signals are separated by an optical coupler for wireless and wired applications.

Optical millimeter-wave signal generation, using a frequency quadrupling technique and no filtering, is the key to the optical up-conversion system [13]. Figure 2 shows a conceptual diagram of the proposed frequency quadrupling with filtering technique. The key component of the optical up-conversion system is a commercially available dual-parallel MZM which is composed of three sub-MZM: MZ-a, MZ-b and MZ-c. Both MZ-a and MZ-b are biased at the maximum transmission point and MZ-c is biased at the minimum transmission point. Assume that the field of optical source is defined as

$$E_{in}(t) = E_o \cos(\omega_o t)$$

where E_o denotes the amplitude of the optical field, and ω_o is the angular frequency of the optical carrier. Electrical RF driving signals sent into MZ-a and MZ-b are $V_a(t) = V_m \cos(\omega_{RF} t)$ and $V_b(t) = V_m \cos(\omega_{RF} t + \pi/2)$, respectively, where ω_{RF} is the angular frequency of the electrical driving signal. The optical field at the output of the dual-parallel MZM can be expressed as
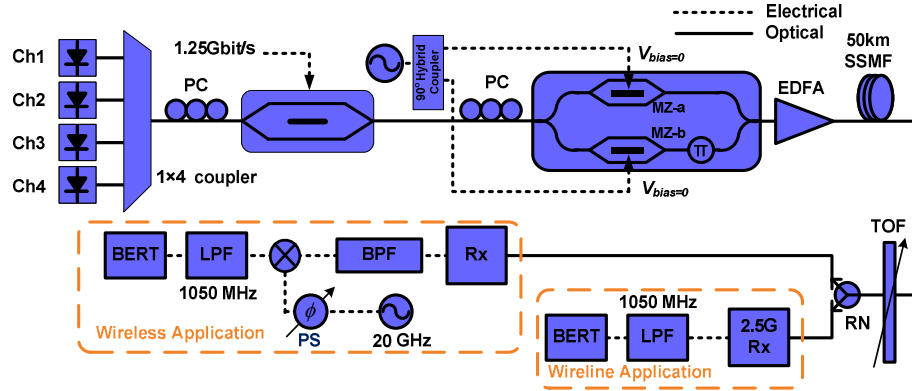
Fig. 3. Experimental setup of the WDM up-conversion system. (PC: polarization controller; TOF: tunable optical filter; RN: remote node; BPF: band pass filter; LPF: low pass filter; BERT: bit error rate tester.)
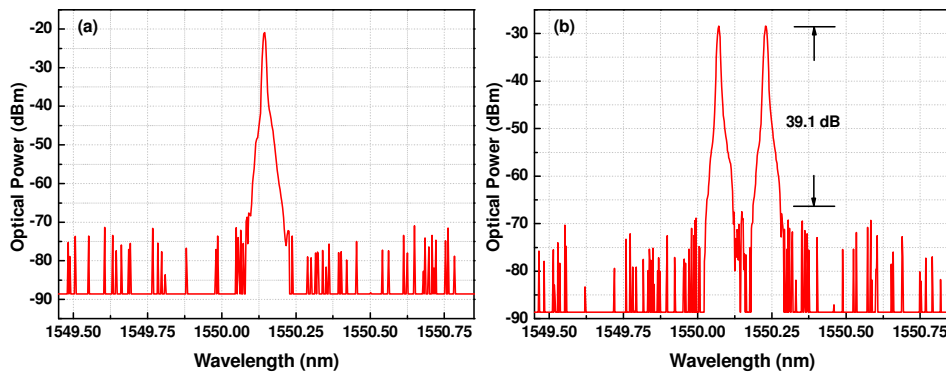

Fig. 4. Single Channel Up-conversion (a) Baseband signal; (b) Up-converted 20-GHz signal.

$$E_{out}(t) = -E_o \sum_{n=1}^{\infty} J_{4n-2}(m) \times \left\{ \begin{array}{l} \cos\left[(\omega_o + (4n-2)\omega_{RF})t\right] \\ + \cos\left[(\omega_o - (4n-2)\omega_{RF})t\right] \end{array} \right\}$$

where the phase modulation index m is $\pi V_m / 2V_\pi$ and J_{4n-2} denotes the Bessel function of the first kind of order $4n-2$. Due to the properties of Bessel function, the optical sidebands with the orders exceeding J_2 can be ignored without generating considerable error. Therefore, the output optical field can be simplified as

$$E_{out}(t) = -E_o \{ J_2(m)\cos[(\omega_o + 2\omega_{RF})t] + J_2(m)\cos[(\omega_o - 2\omega_{RF})t] \}$$

After square-law detection using a photo diode, only the electrical signal with a frequency four times that of the electrical driving signal, ω_{RF}, will be detected [13].

Figure 3 shows the experimental setup of the WDM optical up-conversion system with frequency quadrupling. Four distributed feedback (DFB) lasers are utilized as the four-channel WDM signals with optical wavelengths from 1544.53 to 1546.92 nm with 100-GHz channel spacing. A 1.25-Gb/s on-off-keying (OOK) pseudo random bit sequences (PRBS) signal with a word length of 2^{31}-1 are simultaneously modulated on all of the WDM channels using a single electrode MZM. The WDM BB channels are then sent into the optical up-conversion system with frequency quadrupling, and all WDM channels are up-converted simultaneously. The up-converted millimeter-wave signals are then amplified by an erbium-doped fiber amplifier (EDFA) before being transmitted over 50-km SSMF. After the transmission, a tunable optical filter (TOF) is employed to select the desired channel. At the
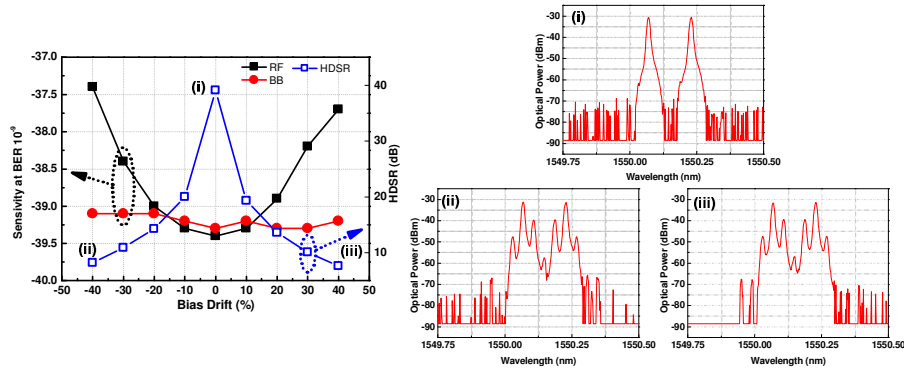
Fig. 5. Sensitivities and HDSR versus MZ-a bias drifts, and optical spectrum with different bias drifts.
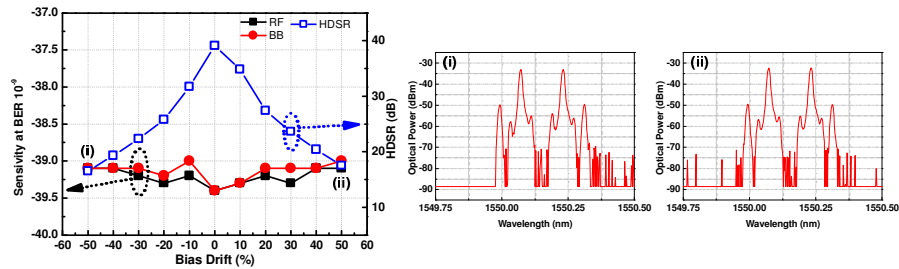

Fig. 6. Sensitivities and HDSR versus MZ-c bias drifts, and optical spectrum with different bias drift.
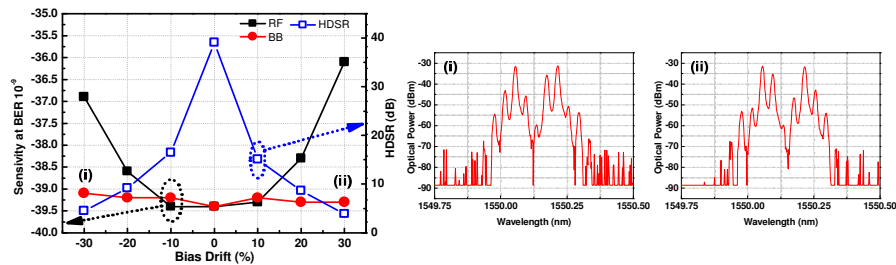

Fig. 7. Sensitivities and HDSR versus all sub-MZ bias drifts, and optical spectrum with different bias drift.

remote node (RN), an optical coupler is utilized to separate the optical power for wireless and wired applications. For wireless application, RF OOK signals are detected using a high-frequency photo receiver along with an electrical band pass filter to select the desired RF signal. The electrical RF OOK signals are then down-converted to BB and sent into a bit error rate tester (BERT). On the other hand, the BB OOK signals are received directly using a 1.25-GHz photo receiver, which is compatible with existing PON, and analyzed using the BERT.

3. Results and discussion

Figure 4(a) presents the optical spectrum of a single channel 1.25-Gb/s BB OOK signal. Figure 4(b) shows the optical spectrum of the up-converted millimeter-wave signal using the proposed system with a 5-GHz RF driving signal. Following the optical up-conversion, the HDSR of the generated 20-GHz millimeter-wave signal exceeds 39 dB.

Although the MZM has been used for several decades, bias drift, which affects MZM performance, remains an important issue when the MZM is biased at the maximum or minimum transmission point. In the proposed optical up-conversion system, both MZ-a and MZ-b are biased at the maximum transmission point, and MZ-c is biased at the minimum
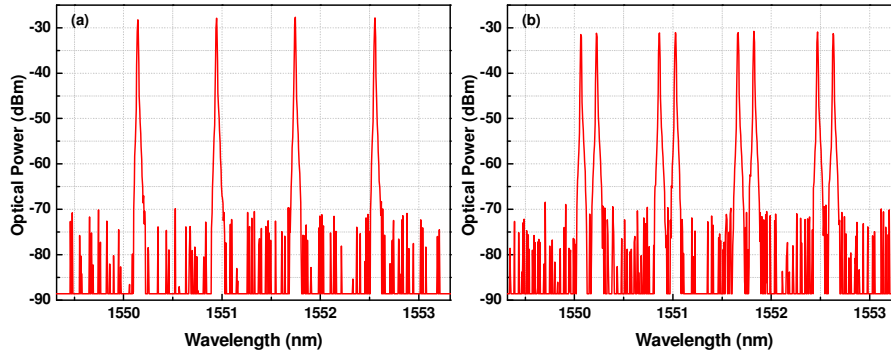
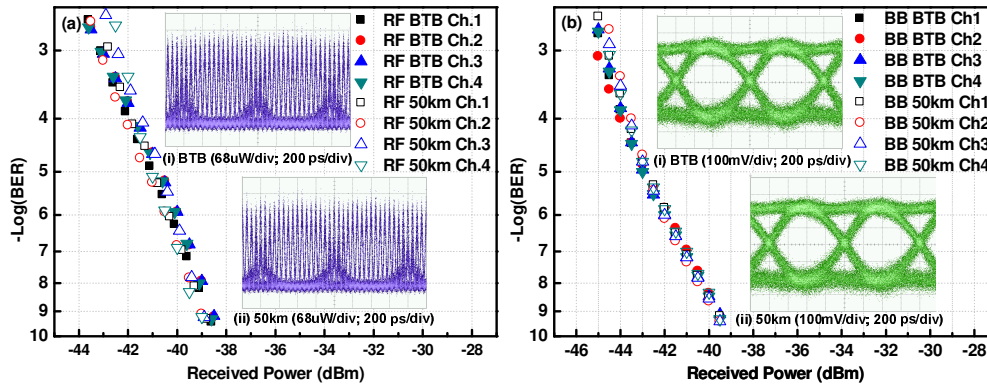Fig. 8. Optical spectrum of the (a) BB WDM signals; (b) 20-GHz WDM signals.

Fig. 9. BER curves of the 20-GHz WDM signals at (a) 20-GHz; (b) Baseband.

transmission point. Therefore, the single channel HDSR and performance degrading due to bias drift are investigated in this work.

Since MZ-a is biased at the maximum transmission point, bias drift of MZ-a decreases the suppression of odd-order optical sidebands. Figure 5 illustrates the 20-GHz optical millimeter-wave signal receiver sensitivities at BER of 10^{-9} and HDSR versus different MZ-a bias voltage deviation ratios. Optical spectrum with optimized, -40 %, and 40 % bias deviation ratios are also shown in Fig. 5. The voltage deviation ratio is defined as $(\Delta V / V_\pi) \times 100\%$, where ΔV is voltage deviation and V_π is the half-wave voltage of the sub-MZ (i.e. 4.2 volts in this case). The HDSR declines from 39 dB to 7.5 dB when bias deviation ratio becomes 40%, and the receiver sensitivity penalty of the 20-GHz RF OOK signal is about 2 dB. However, with detail explanation given in the following section, no significant reductions in receiver sensitivities exist for the 1.25-Gb/s BB OOK signals. The behavior of MZ-b voltage deviation is similar to the results of that in MZ-a. Figure 6 shows the 20-GHz optical millimeter-wave signal receiver sensitivities at BER of 10^{-9} and HDSR versus different MZ-c bias voltage deviation ratios. Optical spectrum with -50 % and 50 % bias deviation ratios are also shown in Fig. 6. Differing from the voltage drift effects of MZ-a and MZ-b, the HDSR decreases form 39 dB to 17 dB when bias drift is almost 50%, which corresponds to a voltage deviation of roughly 2.1 volts and can be considered an extreme case. However, no significant sensitivity penalties of the 20-GHz RF OOK and BB OOK signals are observed. This work also investigates the declines of HDSR and receiver sensitivities when all biases of the dual-parallel MZM drift from the optimal point. Figure 7 shows the 20-GHz optical millimeter-wave signal receiver sensitivities at BER of 10^{-9} and HDSR versus different bias voltage deviation ratios in all sub-MZM. Optical spectrum with -30 % and 30 % bias deviation ratios are also shown in Fig. 7. When the biases of all sub-MZM drift 30% from the optimal point,
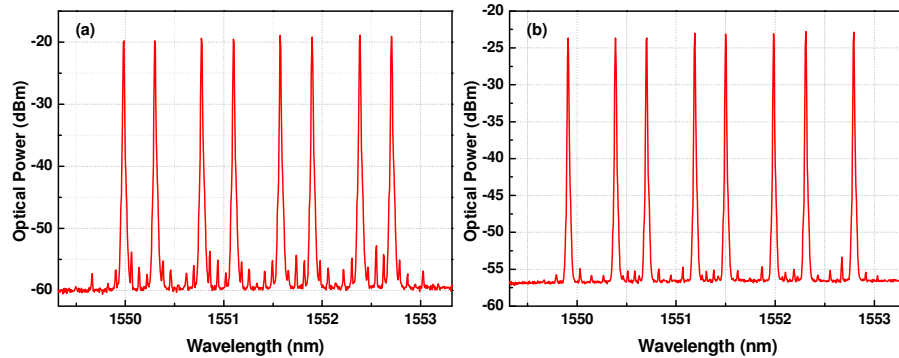
Fig. 10. Spectrum of Up-converted WDM signals at (a) 40-GHz; (b) 60-GHz.

the HDSR degrades from 39 dB to 5 dB, and the 20-GHz RF OOK signal has a penalty of about 3 dB. And there are still no significant power penalties of the BB OOK signal.

After the square-law detection, the RF OOK signal comes from the beating terms of the two second-order optical sidebands. However, the receiver sensitivity is defined as the total received optical power. If the HDSR degrades due to bias drifts of the dual-parallel MZM, a portion of the total optical power is taken by the undesired optical sidebands; thus, the receiver sensitivity of the desired millimeter-wave signal is diminished. In the case of bias drifting in MZ-a and MZ-b, odd order optical sidebands steal a significant portion of the total optical power, resulting in receiver sensitivity penalties. Nevertheless, in the case of bias drifting in MZ-c, only the optical carrier and 4th order optical sidebands emerge with bias drifting. In the proposed system, the original optical carrier can be totally suppressed due to the advantage of the modulation depth trimming of the proposed frequency technique. The modulation depth trimming is done by adjusting the amplitudes of electrical signals for driving MZ-a and MZ-b. Therefore, only the 4th order optical sidebands contribute to the decline of RF receiver sensitivity when MZ-c bias drifts. Base on the properties of Bessel function, the optical power of 4th order optical sidebands are quite small compared with the desired 2nd optical sidebands. The HDSR still exceed 20 dB when the MZ-c bias drifts about 50%. With such high HDSR, no significant power penalty of RF signals exists when the MZ-c bias drifts. Receiver sensitivities of the proposed system can be less than 1 dB when bias drifts are controlled within 20% of the half-wave voltage using a bias feed-back control system. On the other hand, the BB OOK signal is related to the square terms of all optical sidebands; therefore, the BB OOK signal is insensitive to the biased drifts.

Figure 8 shows the optical spectrum of the 4×1.25-Gb/s BB WDM signals and the up-converted 4×1.25-Gb/s 20-GHz WDM signals. All WDM channels are up-converted simultaneously using only one dual-parallel MZM. Figure 9(a) shows the BER curves and eye diagrams of the back-to-back (BTB) and transmitted 20-GHz WDM RF OOK signals. After transmission over 50-km SSMF, the receiver power penalty of each channel is less than 1 dB. Fig. 9(b) shows the BER curves and eye diagrams of the BTB and transmitted WDM BB OOK signals. Receiver power penalties are negligible after transmission over the 50-km SSMF. 40-GHz and 60-GHz WDM optical up-conversion systems are also demonstrated in this work. Nevertheless, the receiver sensitivities and BER analysis are not shown here due to the unavailability of 40- and 60-GHz receiver systems in the laboratory. Figure 10(a) shows the optical spectra of the 40-GHz up-converted WDM signals. The HDSR of the up-converted WDM signals are more than 35 dB. Figure 10(b) shows the spectra of up-converted 60-GHz WDM signals. The HDSR of the WDM channels are also more than 35 dB.

4. Conclusions

WDM up-conversion system using the frequency quadrupling technique is proposed and experimentally demonstrated in this work. An optical millimeter-wave signal generation

without optical filtering is the key to the up-conversion system. The HDSR of the proposed system are more than 39 dB. Both of wired BB and wireless RF signals are transmitted simultaneously. Additionally, receiver sensitivity degraded due to MZM bias drifts is also investigated in this work for 20-GHz WDM signals. The receiver power penalty can be less than 1 dB when bias deviation ratios are less than 20 % of the half-wave voltage, which can be achieved using a bias feedback control system. After transmission over a 50-km SSMF, the receiver power penalties of both the BB and 20-GHz RF OOK signals are less than 1 dB. The 40- and 60-GHz WDM up-conversion using 10- and 15-GHz RF driving signals are also demonstrated. The proposed system is compatible with existing WDM PON system. Since only low-frequency RF components and equipment are required, the proposed system is a potential solution for future WDM up-conversion system.

Acknowledgment