Ultra-Wideband and 60-GHz Generation and Transmission Over a Wavelength Division Multiplexing-Passive Optical Network

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***Abstract*—A novel scheme to simultaneously generate an on–off keying (OOK) impulse radio ultra-wideband (IR-UWB) signal, a 60-GHz millimeter-wave (mmW) signal, and a baseband signal in the optical domain using a Sagnac loop is proposed and demonstrated. In the proposed system, a polarization beam splitter (PBS), a fiber Bragg grating (FBG), and two back-to-back connected polarization modulators (PolMs) are incorporated in the Sagnac loop. An OOK Gaussian pulse signal is modulated on a clockwise transmitted optical carrier by the first PolM and then converted to an OOK UWB impulse signal at the FBG serving as an edge filter, and the counterclockwise transmitted optical carrier is simultaneously modulated by a baseband signal and a 30-GHz mmW signal at the second PolM. By introducing a π phase shift between the clockwise and counterclockwise optical carriers, the optical carrier of the 30-GHz signal is suppressed when applied to a polarizer. As a result, a frequency-doubled mmW signal at 60 GHz is generated by beating the two first order sidebands at a photodetector. Due to the velocity mismatch between the counterclockwise light wave and the clockwise microwave carrier, the OOK signal and the baseband signal can travel through the other PolM with negligible modulation; thus no interference from another signal would be introduced. Error-free transmission of a UWB signal at 2.5 Gbps and a wired baseband signal at 2.5 and 5 Gbps over a 25-km single-mode fiber is achieved. A frequency-doubled mmW signal at 60 GHz is also obtained.**

***Index Terms*—Frequency multiplication; Passive optical networks (PON); Polarization modulation; UWB over fiber (UWBoF); Wavelength division multiplexing.**

I. INTRODUCTION

The distribution of radio signals over fiber or radio over fiber (RoF) has been a topic of interest in the last few years. The key motivation of distributing radio signals over optical fibers is the large bandwidth and low loss offered by the state-of-the-art optical fibers. To support multigigabit wireless access, impulse radio ultra-wideband (IR-UWB) [1] with a license-free spectral band from 3.1 to 10.6 GHz has been considered a solution for broadband wireless access. Due to the low power spectral density (PSD) of less than −41.3 dBm/MHz, UWB signals can share the spectrum resources with existing radio communications systems with negligible interference. On the other hand, multigigabit wireless access at a millimeter-wave (mmW) frequency in the 60-GHz band has also been proposed [2]. The increased interest in the 60-GHz wireless technologies can be seen from the standardization activities, such as IEEE 802.15.3c [3], European Computer Manufactures Association 387 (ECMA 387) [4], and Wireless-HD [5]. Due to the low PSD of UWB signals and the strong air-link attenuation at 60 GHz, the typical communication distance of a UWB and 60-GHz system is only a few meters to tens of meters. Such short-range networks can operate mainly in a standalone mode, with nearly nonexistent integration into the fixed wired and wireless wide-area infrastructures. To increase the area of coverage and to offer undisrupted services across different networks, a technique is to distribute UWB [6,7] and 60-GHz signals over an optical fiber [8–11]. The distribution of UWB and 60-GHz signals over an existing optical network would be an effective solution to reduce the system cost, such as a wavelength division multiplexing passive optical network (WDM-PON) [12,13].

A few techniques to distribute a UWB [14,15] or a 60-GHz [16–18] signal over a WDM-PON have been proposed recently. As reported in [14], a UWB signal and a wired signal were multiplexed and modulated on a single wavelength for wireless and wired downstream or upstream services. However, the system needs an electrical UWB signal generator. Pan and Yao proposed a simple scheme to generate and transmit a 1.25-Gbps UWB impulse signal and a 1.25-Gbps baseband wired signal over a WDM-PON [15]. Since there was no spectral overlap between the UWB signal and the baseband signal, no interference between the two signals would be generated and an error-free transmission over a 36-km single-mode fiber (SMF) link was demonstrated. In the proposed system, the baseband spectrum is limited to 3.1 GHz to avoid any spectral overlap with the UWB signal. Thus, the data rate is limited. For the next generation WDM-PON, the data rate could be as high as 10 Gbps.

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Techniques to provide 60-GHz wireless services over a WDM-PON have also been proposed [16–18]. In [16], a single electroabsorption modulator (EAM) was employed to realize a multiband RoF system transmitting 60-GHz and baseband signals simultaneously. However, the system requires a 60-GHz generator and a 60-GHz electro-optical modulator, making the system very costly. To generate a 60-GHz signal from a low frequency source, Shao *et al.* proposed a technique to generate a 60-GHz signal based on frequency multiplication, and a 60-GHz RoF over WDM-PON was demonstrated, which provided simultaneous baseband transmission and 60-GHz band signal generation compliant with the ECMA 387 standard by using a new multiband modulation technique with a single dual-electrode Mach–Zehnder modulator (MZM) [17]. To further maximize the use of the spectral resource for wired and wireless services, Li *et al.* proposed and experimentally demonstrated a baseband (1.25 Gbps)/microwave (mW) (1.25 Gbps/20 GHz)/mmW (1.25 Gbps/40 GHz) transport system by cascading a phase modulator (PM) and an MZM [18].

The frequency multiplication technique can also be used to generate a centralized 60-GHz local oscillator (LO) signal at the central office (CO) [19] and deliver the LO signal to base stations (BSs) for frequency up- or downconversion. This technique would reduce the overall system cost and enhance the system performance.

To support UWB and 60-GHz services in a WDM-PON, a simple solution is to modulate the UWB and 60-GHz signals over different wavelengths and then transmit them in the same fiber with the baseband signal. The system is costly and the spectral efficiency is poor. It is expected that the UWB and 60-GHz services can be added to the existing baseband wired services without using additional wavelength.

In this paper, we propose and experimentally demonstrate a technique to provide simultaneous UWB, mmW LO at 60-GHz, and baseband wireline services over a WDM-PON based on bidirectional asymmetric polarization modulation and frequency multiplication in a Sagnac loop in which two back-to-back connected polarization modulators (PolM1 and PolM2) and a uniform fiber Bragg grating (FBG) are incorporated. Error-free transmission of a UWB signal at 2.5 Gbps and a wired baseband signal at 2.5 and 5 Gbps over a 25-km SMF is achieved. A frequency-doubled mmW LO signal at 60 GHz is also obtained at the BS.

II. UWB AND 60 GHZ OVER WDM-PON ARCHITECTURE

Figure 1 shows the schematic of the proposed UWB and 60 GHz over WDM-PON architecture based on bidirectional asymmetric polarization modulation and frequency multiplication. At the optical line terminal (OLT), the wavelengths from the transmitters are multiplexed at a wavelength multiplexer and sent to a remote access node (RAN). At the RAN, a WDM demultiplexer (DEMUX) is employed to demultiplex the WDM channels and send one wavelength to one optical network unit (ONU).

At the transmitter, two back-to-back connected polarization modulators (PolM1 and PolM2) and a uniform FBG are incorporated in a Sagnac loop. A light wave from a laser diode (LD) is sent to the Sagnac loop via a polarization controller (PC1) and an optical circulator (OC). The light wave is split into two orthogonally polarized light waves by a polarization beam splitter (PBS), with one light wave sent to PolM1 along the clockwise direction and the other sent to PolM2 along the counterclockwise direction. A PolM is a special PM that supports phase modulation along the two principal axes with opposite modulation indices. It was shown that the joint operation of a PolM, a PC, and a polarizer corresponds to an MZM with the bias point determined by the static phase introduced by the PC [20]. Each of the two PolMs in the loop is operating in conjunction with PC3 and the PBS as an MZM. At PolM1, an OOK Gaussian pulse signal is modulated on the clockwise optical carrier. At PolM2, a baseband signal and a 30-GHz mmW signal are modulated on the counterclockwise optical carrier. Note that a PolM is a traveling wave device that is designed to match the velocities of the light wave and the microwave along one direction. For a light wave from the opposite direction, due to the velocity mismatch, the modulation is very weak and can be ignored. Thus, the modulated signal from one PolM can travel through the other PolM with negligible modulation at the other

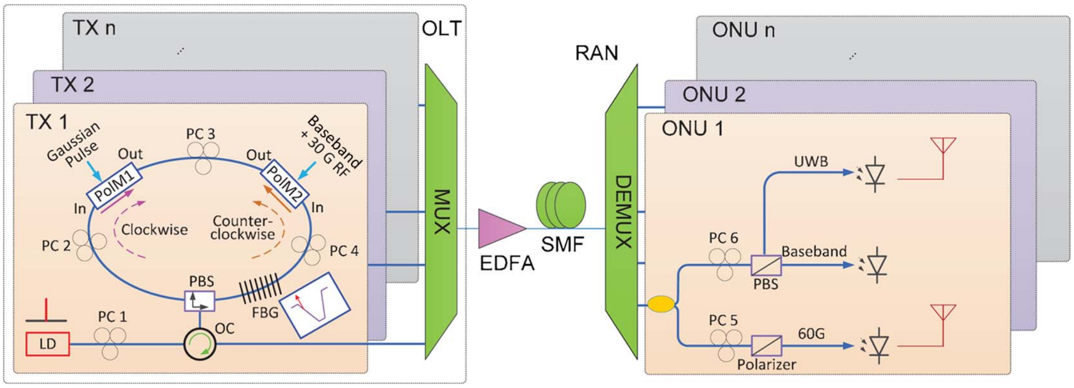

Fig. 1. UWB and 60 GHz over WDM-PON architecture. LD, laser diode; OLT, optical line terminal; MUX, WDM multiplexer; RAN, remote access node; DEMUX, WDM demultiplexer.

PolM; thus the interference from the other signal would be small and negligible. By locating the optical carrier at the edge of the FBG, which serves as an edge filter (or a frequency discriminator), the Gaussian pulse signal is converted to a UWB impulse signal [21]. In addition, the clockwise and counterclockwise optical carriers have a π phase difference; thus the optical carrier of the 30-GHz signal can be suppressed when applied to a polarizer. As a result, a frequency-doubled mmW signal at 60 GHz is generated by beating the two first order sidebands at a photodetector (PD). The 60-GHz signal can be used as an LO signal for frequency up- or downconversion. If information is modulated on the 60-GHz signal, it can be radiated to free space via an mmW antenna for mmW communications.

III. EXPERIMENTAL SETUP

The proposed scheme is experimentally evaluated. Figure 2 shows the experimental setup for the generation and simultaneous transmission of a baseband, a UWB, and a 60-GHz signal over a length of SMF based on bidirectional asymmetric polarization modulation and frequency multiplication. In the central station (CS), a linearly polarized optical light wave emitted from an LD is split into two orthogonally polarized light waves with opposite propagation directions by a PBS. In the clockwise direction, a Gaussian pulse signal with a data rate of 2.5 Gbps, generated by an arbitrary waveform generator (AWG, Tektronix AWG7102), is applied to the first PolM (PolM1), which is converted to a UWB monocycle impulse signal after passing through an FBG. In the counterclockwise direction, the baseband signal with a data rate of 2.5 Gbps or 5 Gbps, generated by a bit error rate tester (BERT, Agilent N4901B), and a 30-GHz mmW signal generated by a signal generator (Agilent, E8254A) are modulated on the optical carrier at the second PolM (PolM2) for baseband and 60-GHz generation and transmission. After traveling through the Sagnac loop, the modulated clockwise UWB signal and the counterclockwise baseband and 30-GHz signal are combined at the PBS. At the output of the PBS, three signals carried by a single optical wavelength are obtained. Note that the polarization directions of the UWB signal and the baseband signal are orthogonal, which can be separated at a BS using a PBS. The optical signals are amplified by an erbium-doped fiber amplifier (EDFA) and transmitted over a 25-km SMF before sending to a WDM DEMUX. The optical signals carried by an optical carrier at a specific wavelength are sent to a specific BS. In the experiment, only a single channel is demonstrated. Thus, no WDM DEMUX is employed.

At the BS, the received signal is split into two paths by an optical coupler. In the lower path, the optical signal is applied to a polarizer through a PC (PC5). By tuning PC5 to make the polarization directions of the two optical carriers have an angle of 45° and 135° relative to the principal axis of the polarizer, the two optical carriers are out of phase and are suppressed at the output of the polarizer; thus an optical signal with two first order sidebands is obtained. The beating of the two sidebands at a high speed PD (PD3) would generate a 60-GHz signal. In the upper path, the baseband and UWB signals that are orthogonally polarized are demultiplexed at the PBS. A PC (PC6) connected before the PBS is employed to adjust the polarization directions of the two optical signals to make them aligned with the two axes of the PBS. The optical UWB and baseband signals are converted to electrical signals at two PDs (PD1 and PD2), respectively. The UWB signal at the output of PD1 is amplified by a 23-dB electrical amplifier (AMP1), sent to a UWB transmitting antenna (SkyCross, SMT-3TO10M), and radiated to free space. The radiated UWB signal is received by a UWB receiving antenna and amplified by an electrical amplifier (AMP2) before being sent to a BERT (Agilent N4901B) for BER performance measurement. The electrical baseband signal from PD2 is also amplified by a 23-dB electrical amplifier (AMP3) and sent to a BERT to evaluate the BER performance.

IV. EXPERIMENTAL RESULTS

A. 60-GHz and UWB Generation and Transmission

The performance of the system for UWB and 60-GHz services with and without a baseband signal is first evaluated. Figure 3(a) shows the optical spectrum of the 30-GHz signal with carrier suppression at the output of the polarizer. It can be seen that the optical carrier is highly suppressed. The power of the carrier is 33.01 dB less than that of the first order sidebands. By beating the two first order sidebands at PD3, a 60-GHz signal is obtained. The electrical

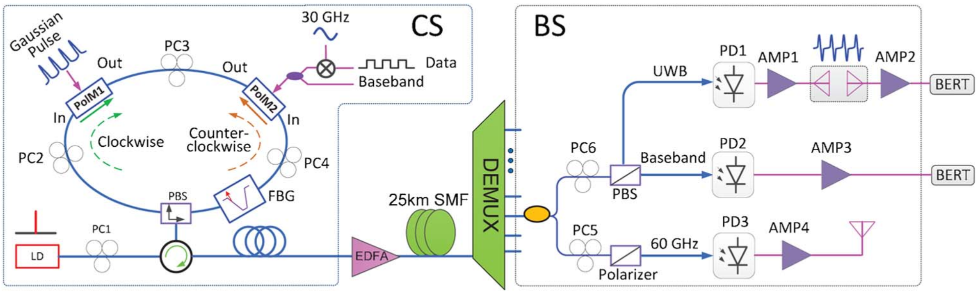

Fig. 2. Experimental setup for the simultaneous generation and transmission of a UWB, mmW, and baseband signal over a SMF. CS, central office; EDFA, erbium-doped fiber amplifier; BS, base station; BERT, bit error rate tester; AMP, amplifier.

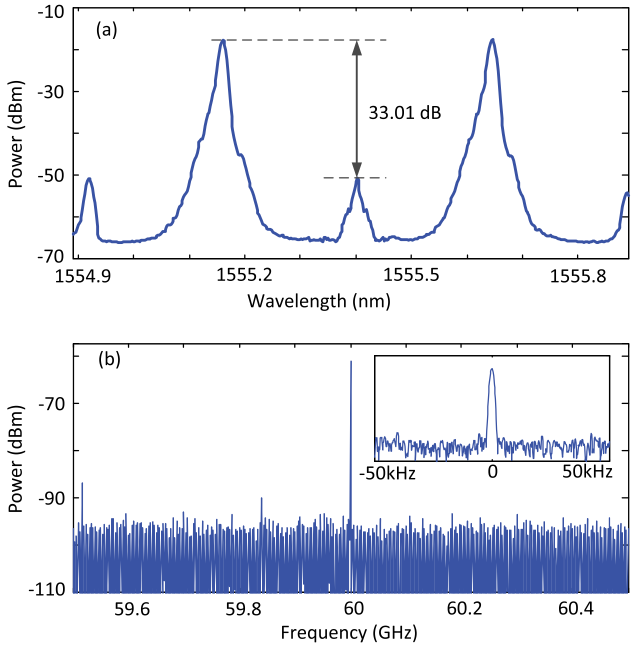

Fig. 3. Experiment results. (a) The optical spectrum of the carrier suppressed 30-GHz signal measured at the output of the polarizer. (b) Electrical spectrum of the generated 60-GHz signal at the output of AMP3. The inset shows a zoom-in view of the spectrum of the 60-GHz signal.

spectrum of the generated 60-GHz signal is shown in Fig. 3(b). In the experiment, no data information is modulated on the 60-GHz signal due to the lack of a 60-GHz mixer at the receiver for frequency downconversion. However, one important application of the generated 60-GHz signal is to use it as an LO signal for frequency up- or downconversion in the BS.

To generate a UWB monocycle impulse signal, a Gaussian pulse signal, shown in Fig. 4(a), is modulated on the light wave traveling along the clockwise direction at PolM1 in the Sagnac loop. A PolM is a special PM that supports phase modulation along the two principal axes with opposite modulation indices. By locating the optical carrier of the phase-modulated signal at one linear slope of the FBG transmission spectrum, as shown in Fig. 4(b), the Gaussian pulse signal is differentiated, and a UWB monocycle impulse signal is, thus, generated, as shown in Fig. 4(c). The electrical spectrum of the generated UWB signal before the transmitter antenna is shown in Fig. 4(d). It can be seen that the spectrum of the UWB impulse signal is well compliant with the spectral mask (red solid line) defined by the U.S. Federal Communications Commission (FCC).

The generated UWB signal is polarization multiplexed with a baseband signal at 5 Gbps and sent over a 25-km SMF link to the BS. After demultiplexing at the PBS, the UWB is recovered at PD1. The eye diagram of the UWB signal is shown in Fig. 5(a). It can be seen that the eye diagram is widely open and the interference from the baseband signal to the UWB signal after 25-km transmission is small and no obvious deterioration can be observed. The UWB signal is then amplified by an electrical amplifier before radiating to free space. Figure 5(b) shows the UWB monocycle impulse train at a receiving UWB antenna after amplification. As can be seen, the UWB signal in Fig. 5(b) is well received except for a slight distortion as compared with the eye diagram shown in Fig. 5(a) since the received UWB monocycle impulse is spectrally tailored by the UWB antenna and the multipath effect when transmission is in the wireless channel.

The BER of the 2.5-Gbps UWB signal with a 60-GHz LO and a 5-Gbps baseband signal is also measured, which is shown in Fig. 6. It can be seen that error-free transmission of the 2.5-Gbps UWB signal for a received optical power of -8.5 dBm is achieved. Here error free is defined as the transmission of a signal with a BER of no more than 10^{-9}.

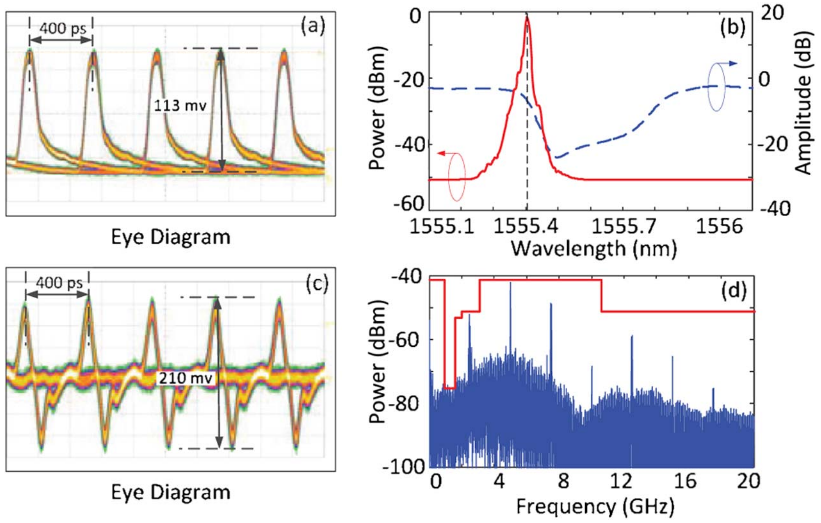

Fig. 4. Experiment results. (a) Eye diagram of the Gaussian pulse signal at 2.5 Gbps. (b) Optical spectrum of the CW carrier and the transmission spectrum of the FBG. (c) Eye diagram of the generated UWB monocycle impulse signal at the transmitter. (d) Electrical spectrum of the generated UWB pulse.

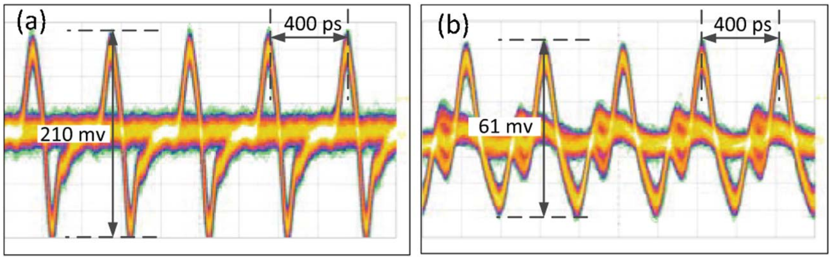

Fig. 5. Eye diagrams of the UWB monocycle impulse signal (a) after transmission over a 25-km SMF link with a baseband signal at 5 Gbps and (b) received at a receiving UWB antenna.

B. Baseband Signal Measurement

The performance of the baseband signal transmission for three situations is evaluated: 1) with and without a 60-GHz signal, 2) with and without a UWB signal, or 3) with and without both a 60-GHz and UWB signal. Figure 7(a) shows BER measurements as a function of the received optical power for a 2.5-Gbps baseband signal with and without a 60-GHz signal, with and without a 2.5-Gbps UWB signal, or with and without both a 60-GHz and UWB signal. Figure 7(b) shows the same measurements for the baseband signal at 5 Gbps. An error-free transmission of the 2.5- and 5-Gbps baseband signals with a 60-GHz signal, a 2.5-Gbps UWB signal, or both the 60-GHz and UWB signals is achieved. The performance of the transmission of the baseband signal for the three situations is summarized in Table I. As can be seen the sensitivity for the 2.5-Gbps baseband signal transmission without UWB or 60-GHz services is −16.41 dBm. With both the 60-GHz and the 2.5-Gbps UWB signals, the sensitivity is −15.61 dBm; thus a power penalty of 0.8 dB results. Here the sensitivity is defined as the optical power required achieving a BER of 10^{-9}. When the data rate of the baseband is 5 Gbps, which means that the orthogonally polarized UWB signal and baseband have spectral overlap, the power penalty is 0.83 dB. The small power penalty is due to the polarization orthogonality of the baseband and the UWB signals. However, due to the nonflat frequency response of the PolMs, the system cannot support error-free transmission of a baseband signal at 10 Gbps. It is expected that a UWB signal and a baseband signal at a data rate greater than 10 Gbps would be supported if the PolMs have better frequency response.

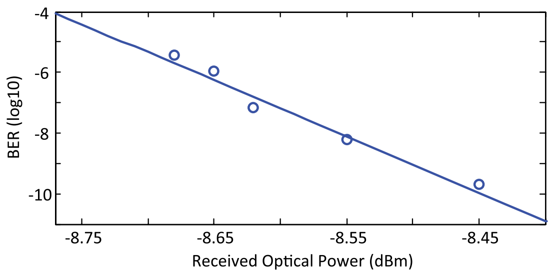

Fig. 6. BER measurements of the 2.5-Gbps UWB signal at the receiving antenna.

V. DISCUSSION

As shown in Fig. 6, the receiver sensitivity for the transmission of a 2.5-Gbps UWB signal with a 60-GHz and a 5-Gbps baseband signal is −8.5 dBm. In the optical link shown in Fig. 1, the insertion loss of a 25-km SMF link and the loss of the optical coupler are 5 dB and 3 dB, respectively. In real applications, the loss of the WDM

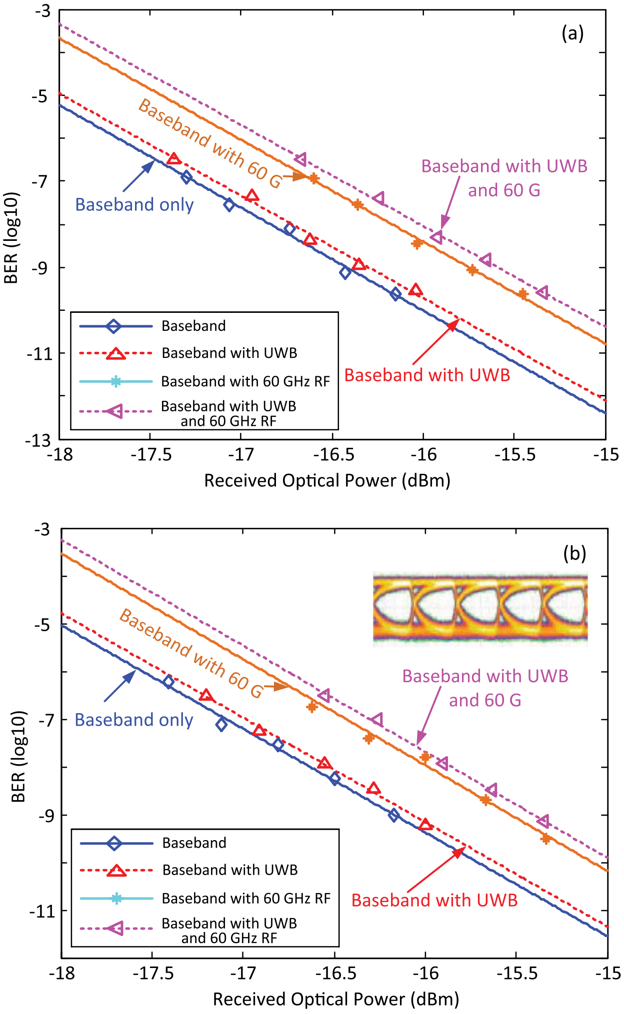

Fig. 7. BER measurements of the baseband signal with or without a UWB or a 60-GHz signal. (a) Baseband data rate is 2.5 Gbps. (b) Baseband data rate is 5 Gbps.

TABLE I
RECEIVER SENSITIVITIES FOR BASEBAND TRANSMISSION[a]

Services	2.5 Gbps BB[b]	5 Gbps BB
BB only	−16.41	−16.22
BB with UWB	−16.30	−16.12
BB with 60 GHz	−15.75	−15.53
BB with UWB and 60 GHz	−15.61	−15.39

[a] Unit, dBm.
[b] BB, baseband.

DEMUX is considered to be 1 dB. As a result, the emission power of each transmitter in an OLT for error-free transmission is 1.3 dBm.

Considering that the output power of an EDFA should be maintained to be within 12 dBm to avoid nonlinear effects of the fiber link [22], the proposed 60-GHz and UWB services over WDM-PON architecture can support 11 users. The typical number of channels for a WDM-PON is 16, 32, or 64, although no standard has been released. Note that the sensitivity of the BERT is 50 mV. It can be expected that the use of additional low noise amplifiers before the BERT can significantly improve the sensitivities of the baseband receiver and the UWB receiver so that the proposed 60-GHz and UWB over WDM-PON architecture can support more users to meet the requirement for fiber to the home applications.

VI. CONCLUSION

A novel WDM-PON architecture that supports simultaneous mmW at 60 GHz, UWB, and baseband signal generation and transmission based on bidirectional asymmetric polarization modulation and frequency multiplication was proposed and experimentally demonstrated. An error-free point-to-point simultaneous transmission of a 2.5-Gbps UWB signal, a 60-GHz signal, and a 2.5 or 5-Gbps baseband signal was achieved. The experimental results showed that the interference between the UWB signal and the baseband signal was small and could be ignored. When providing simultaneously the three services, the receiver sensitivities for the baseband transmission was measured to be −15.39 dBm and for the UWB transmission was measured to be −8.5 dBm. The number of users that could be supported was also evaluated. For the experimental setup, 11 users could be supported if an optical signal with an optical power of 12 dBm was applied to the fiber link. More users could be supported if additional low noise amplifiers are employed in the receivers.

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