Millimeter-Wave and UWB Over a Colorless WDM-PON Based on Polarization Multiplexing Using a Polarization Modulator

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***Abstract*—A broadband millimeter-wave (mmW) at 60-GHz band and an impulse radio ultra-wideband (IR-UWB) over a colorless 100-GHz dense wavelength division multiplexing (DWDM) passive optical network (PON) that supports simultaneous transmission of a broadband mmW signal, a UWB signal and a wireline baseband signal is experimentally demonstrated. At the transmitter, a polarization modulator (PolM) is employed, which operates in conjunction with a polarization controller (PC) and a polarization beam splitter (PBS) as an equivalent Mach-Zehnder modulator (MZM). For 60-GHz and IR-UWB signal transmission, the equivalent MZM is biased at the minimum transmission point to generate two sidebands that are separated at a frequency in the 60-GHz band, and the wireless signals (60 GHz and IR-UWB) are carried by the two sidebands. For the wireline baseband transmission, the equivalent MZM is biased at the maximum transmission point to generate only the optical carrier, and the wireline signal is carried by the optical carrier. The wireline signal and the wireless signals are orthogonally polarized and sent over a single-mode fiber (SMF) to a base station (BS). For each WDM channel in the central station (CS) and the BS, since no optical filters are employed, colorless operation is supported. Point-to-point error-free transmission of a 1.25-Gbps mmW signal, a 1.25-Gbps IR-UWB signal and a 10-Gbps wireline signal over a 25-km SMF is experimentally demonstrated. The number of users that can be supported by the proposed colorless WDM-PON is estimated based on the measured receiver sensitivities.**

***Index Terms*—Colorless, passive optical networks (PON), radio over fiber (RoF), UWB over fiber (UWBoF), wavelength division multiplexing (WDM).**

I. Introduction

THE demand for high data rate wireline and wireless connectivity is rapidly growing. For wireline access, wavelength division multiplexing (WDM) passive optical networks (PONs) have been widely researched thanks to the advantages such as large bandwidth, long reach, high power budget, excellent security, and easy upgradeability [1]. For broadband wireless access, two key techniques, ultra-wideband (UWB) and 60 GHz, have been extensively investigated which can find applications in high speed wireless local area networks (WLAN) and wireless personal area networks (WPAN). UWB, which shares the spectrum resources with existing radio communications systems, is recognized as a promising solution for broadband wireless access [2]. The unlicensed use of a spectral band from 3.1 to 10.6 GHz with a power spectral density (PSD) of less than $-41.3\ \mathrm{dBm/MHz}$ has been approved by the U.S. Federal Communications Commission (FCC) [3]. In particular, impulse-radio UWB (IR-UWB) that is carrier free has attracted much attention thanks to the advantageous features, including low complexity, low cost, and low power consumption [4]. Wireless communications based on 60 GHz is considered as another solution for broadband wireless access. An unlicensed spectral band of 7 GHz from 57 to 64 GHz is available in most of the countries [5].

Due to the constrained PSD of an IR-UWB signal regulated by the FCC and the enormous propagation loss at 60 GHz, the typical transmission distance for both IR-UWB and 60 GHz are a few meters to tens of meters. To extend the area of coverage, a technique, called radio over fiber (RoF), is thus proposed to distribute IR-UWB or/and mmW signals over fiber [6]–[8]. One key advantage of the RoF technology is that the broadband optical/electrical signal processing functions can be performed at the central station (CS), such as optical mmW generation, modulation, wavelength/frequency up or down conversion, with the objective of limiting the use of expensive optical and electronic components in the base stations (BSs), to reduce the overall cost.

Future access networks should provide broadband connectivity to end users, both in wireless and wired form [9]. Hybrid wireline and wireless signal transmission over a WDM-PON that supports multi-gigabit per second baseband transmission and over 1-Gbps wireless transmission has attracted great interest in the past few years. Two main solutions have been proposed: 60 GHz over WDM-PON [10]–[14] and UWB over WDM-PON [15]–[18].

As reported in [10], to decrease the overall system cost, a unique reflective semiconductor optical amplifier (RSOA) is used for wireless and wireline data modulation to the end user. Wireline and wireless signals with the same data stream are generated simultaneously by this configuration. WDM-RoF-PON can also support wireline and wireless transmission with different data modulation. In [11], a wireline signal and an mmW signal are modulated on an optical carrier and two optical sidebands, respectively, at two different optical modulators and transmitted over different WDM channels. To lower the overall cost of the system, in [12] the wireless data

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and wireline data are modulated on a single optical sideband at a single optical modulator and transmitted over a WDM channel. Another un-modulated optical sideband is transmitted over another WDM channel to the BS to beat with the data modulated sideband for mmW generation. In [13], a simultaneous transmission of 60 GHz signal and a wireline signal over one fiber link is experimentally investigated. The wireless on-off keying (OOK) data is intensity modulated to one optical sideband, and wireline signal is phase modulated to both the two optical sidebands with a 60-GHz frequency interval. At the BS, an OOK 60-GHz signal is generated by beating the two optical sidebands. For wireline transmission, an optical filter is employed to select one optical sideband that is phase modulated by the wireline signal. The phase information is recovered by using a Mach-Zehnder delay interferometer (MZDI) followed by a photodetector (PD). In this scheme, since the two optical sidebands are both phase modulated by the DPSK data, chromatic dispersion may induce cross talk from the wireline signal to the wireless signal. Moreover, all of the three architectures in [11]–[13] require two WDM channels or optical filters are needed for simultaneous wireline and wireless signal transmission. Since a 60-GHz signal has a bandwidth less than 5 GHz over a WDM channel, when using a typical WDM channel with a wavelength spacing of 100 GHz, there is a considerable amount of wasted spectrum. In [14], a WDM-based 60 GHz fiber wireless link is studied. A 60-GHz signal is transmitted over a 100-GHz spaced WDM channel. However, only 60 GHz over fiber transmission is investigated in this scheme.

Concerning UWB over WDM-PON, as reported by us recently in [15], a 1.25-Gbps baseband wireline signal and a 1.25-Gbps UWB signal are simultaneously transmitted over a 36-km single-mode fiber (SMF). Since a UWB signal occupies a spectrum from 3.1 to 10.6 GHz, to avoid spectrum overlapping, the data rate of the baseband signal is limited within 3 Gbps. However, for the next generation WDM-PON, it is supposed to support transmission of a baseband signal with a data rate over 10 Gbps [1].

Very recently, an optical transmission system that supports more than two services was proposed [19]. In the system, an mmW, a microwave (mW) and a baseband signal are simultaneously transmitted over one optical link. In each BS, different services are separated by optical filters. Again, since optical filters are employed, the BS is not colorless.

In this paper, we propose and demonstrate a solution to provide simultaneous broadband mmW at 60-GHz band, impulse-radio UWB (IR-UWB), and wireline transmission over a colorless WDM-PON. No optical filters are employed in either the CS or the BSs. The wireline and wireless signals are simultaneously transmitted over a 100-GHz spaced WDM channel. At the transmitter, a polarization modulator (PolM) is employed, which operates in conjunction with a polarization controller (PC) and a polarization beam splitter (PBS) as an equivalent Mach-Zehnder modulator (MZM) [20]. For the 60-GHz and UWB transmission, the equivalent MZM is biased at the minimum transmission point to generate two sidebands that are separated by 58.32 GHz. The wireless signals (mmW and UWB) are carried by the two sidebands. For the baseband wireline transmission, the equivalent MZM is biased at the maximum transmission point to generate only the optical carrier. The wireline signal is carried by the optical carrier. The wireline signal and the wireless signals are then orthogonally polarized and sent over an SMF to the BS. Since the optical signals carrying the wireline and wireless data (mmW and IR-UWB) are orthogonally polarized, in each WDM channel at both of the CS and the BS, no optical filters are needed, which ensures colorless operation of the entire system. The proposed technique is experimentally evaluated. Point-to-point error-free transmission of a 1.25-Gbps mmW signal, a 1.25-Gbps UWB signal and a 10-Gbps wireline signal over a 25-km SMF is experimentally demonstrated.

II. Hybrid Broadband Wireless and Wireline Over WDM-PON Architecture

Fig. 1 shows the proposed hybrid broadband wireless and wireline signal over WDM-PON architecture. In the optical line terminal (OLT), the light waves from an array of distributed feedback laser diodes (DFB-LDs) are coupled into a PolM, which is driven by a microwave signal from a local oscillator (LO). A 100-GHz WDM Demultiplexer (DEXUM) is employed to select each optical carrier and the two sidebands into a WDM channel. Fig. 2 shows the characterization of a 100-GHz spaced DWDM DEMUX and the spectral allocation for each WDM channel. It can be seen that the insertion loss for a 0.5-nm (or 62.5-GHz) bandwidth around the central wavelength is about -1.5 dB. Thus the optical carrier and two sidebands can be covered by the WDM channel, as shown in Fig. 2. Since the optical sidebands are operating at 0.25 nm offset from the central wavelength of each WDM channel, the cross-talk from the closest neighboring WDM channel would be an issue. As shown in Fig. 2, the rejection for the optical sideband to the closest WDM channel is 22 dB, which is high enough to avoid cross talk induced by the optical sidebands to the neighboring channels.

In each WDM channel, the optical signal is sent to a PBS via a PC. The PolM is a special phase modulator that supports both the TE and TM modes with complementary phase modulation indices. Thus, two phase-modulated signals that are orthogonally polarized are generated which are sent to the PBS via the PC. For the upper path at point B (Fig. 1), the joint operation of the PolM, the PC and the PBS is equivalent to an MZM that is biased at the minimum transmission point (MITP). Thus, the optical carrier is suppressed and only the two sidebands are generated. The two optical sidebands are modulated by the data for 60 GHz and UWB transmission at an MZM. Note that the spectra of the data for the 60 GHz and the UWB are physically located at different spectral bands, thus no spectral overlap will be induced. For the lower path at point C, the joint operation of the PolM, the PC and the PBS is also equivalent to an MZM, but it is biased at the maximum transmission point (MATP). Thus, the two sidebands are suppressed and only the optical carrier is generated. The optical carrier is modulated by a wireline baseband signal at a second MZM. The optical signals in the two paths are adjusted to be orthogonally polarized by two PCs and recombined by a polarization beam coupler (PBC). The optical signals in different WDM channels are combined by a WDM

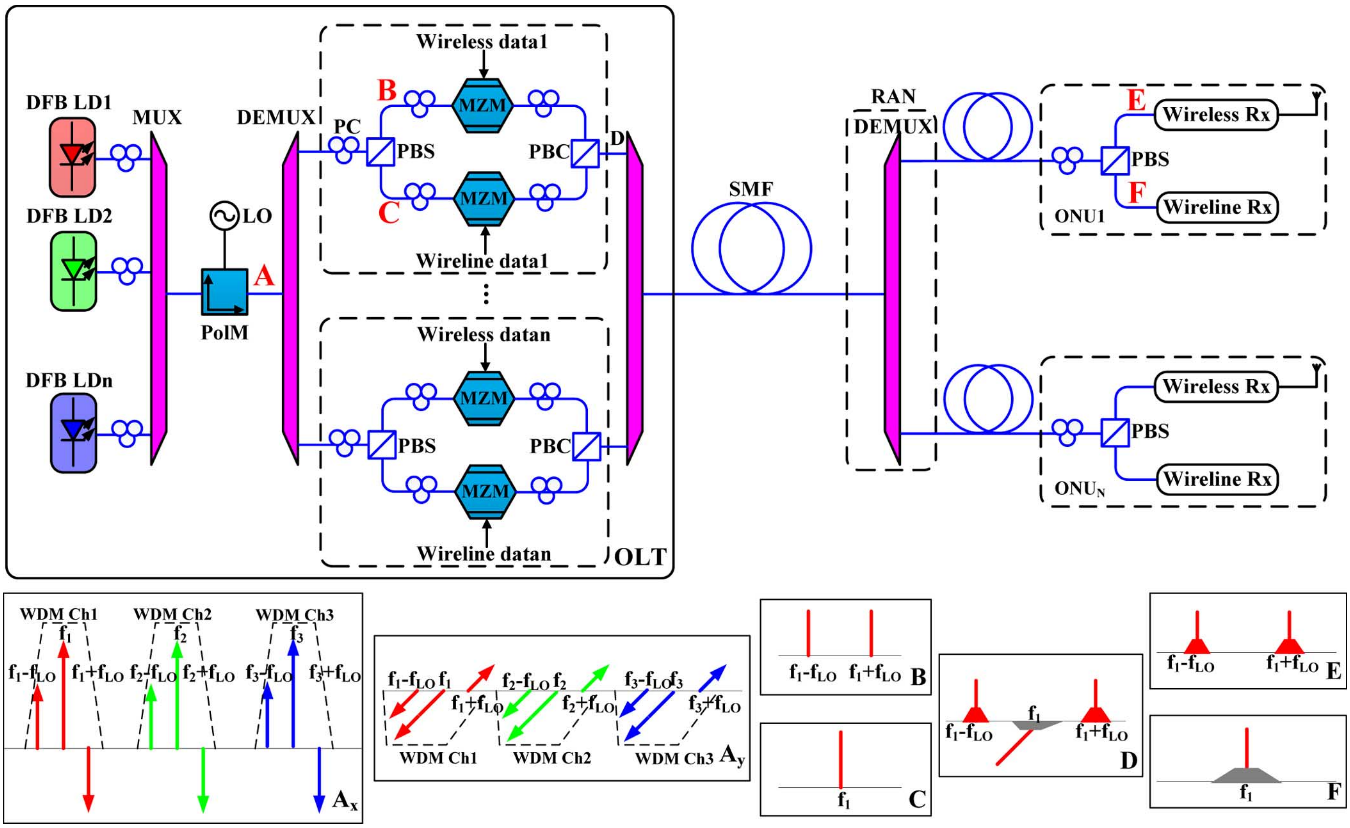

Fig. 1. Principle of the proposed hybrid broadband wireless and wireline signal over WDM-PON. OLT: optical line terminal, DFB LD: distributed feedback laser diode, MZM: Mach-Zehnder modulator, PBS: polarization beam splitter, PBC: polarization beam coupler, PC: polarization controller, MUX: WDM multiplexer, DEMUX: WDM de-multiplexer, RAN: remote access node, PBS: polarization beam splitter, Rx: receiver.

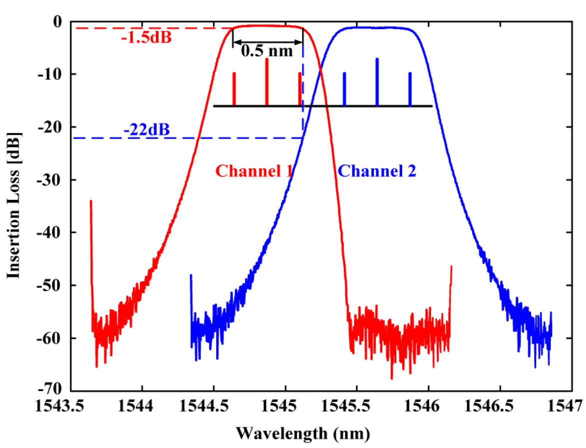

Fig. 2. Characterization of a 100-GHz spaced DWDM DEMUX and the spectral allocation for a WDM channel.

multiplexer (MUX) and transmitted over a 25-km SMF to a remote access node (RAN), where a DEMUX is employed to deliver different optical wavelength to different optical network unit (ONU). In each ONU, a PC and a PBS are employed to separate the wireline signal carried by the optical carrier and the two wireless signals carried by the two sidebands. The wireline signal is recovered at a PD. The 60-GHz electrical signal is generated by beating the two sidebands at a high-frequency PD, and the UWB signal is generated at a relative low-frequency PD.

III. Simultaneous Transmission of a Broadband MMW and Wireline Signal

We first investigate the simultaneous transmission of only a broadband mmW signal and a wireline signal over a colorless WDM-PON.

A. Experimental Setup

Fig. 3 shows the experimental setup. In the CS, a light wave emitted from a DFB-LD at 1545.62 nm corresponding to the central wavelength of channel 2 of the DWDM DEMUX, as shown in Fig. 2, is sent to a PolM (Versawave Technologies) via a PC (PC1). The PolM is driven by an LO signal at 29.16 GHz in order to generate an mmW signal at $2f_{\rm LO} = 58.32$ GHz, which falls in the spectral range defined by IEEE 802.15.3C [21]. The polarization direction of the CW light wave from the DFB-LD is oriented at an angle of 45° to one principle axis of the PolM by adjusting PC1. Thus, the light wave is equally projected to the two orthogonal principal axes. The PolM is a special phase modulator that supports TE and TM modes with opposite modulation indices. Thus, two phase modulated signals that are orthogonally polarized are generated which are sent to a PBS via a PC (PC2). The electrical fields of the output optical signal from the PolM along the two orthogonal directions are given by

$$\begin{bmatrix} E_{xPolM} \\ E_{yPolM} \end{bmatrix} = \frac{\sqrt{2}}{2} E_0 \exp\left(j2\pi f_0 t\right) \times \begin{bmatrix} \exp\left[j\beta A_{LO}\cos\left(2\pi f_{LO} t\right)\right] \\ \exp\left[-j\beta A_{LO}\cos\left(2\pi f_{LO} t\right)\right] \end{bmatrix} \quad (1)$$

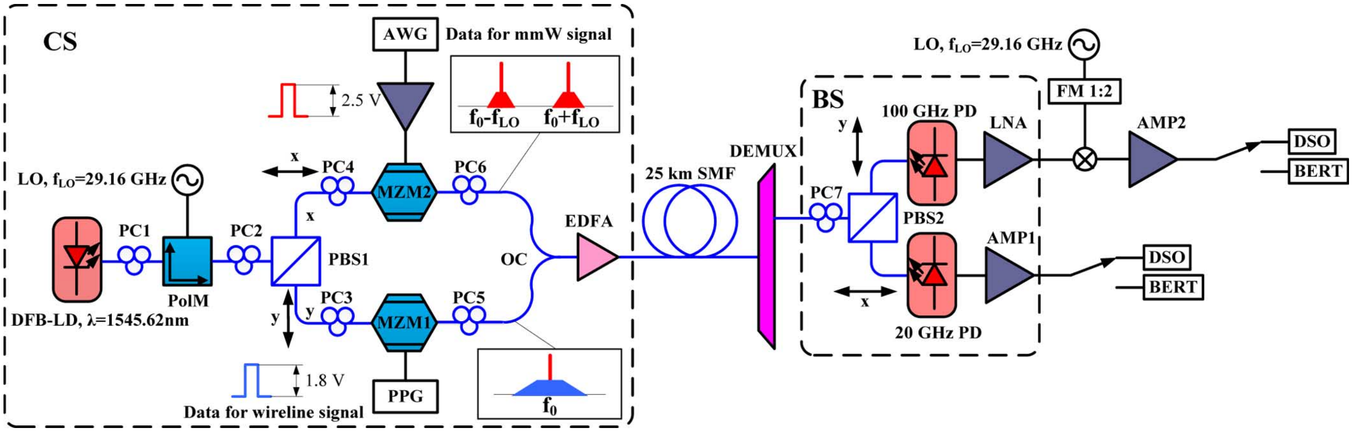

Fig. 3. Experimental setup. PPG: pulse pattern generator, AWG: arbitrary waveform generator, EDFA: erbium-doped fiber amplifier, PD: photodetector, AMP: electrical amplifier, LNA: low noise amplifier, FM: frequency multiplier, DSO: digital storage oscilloscope, BERT: bit error tester.

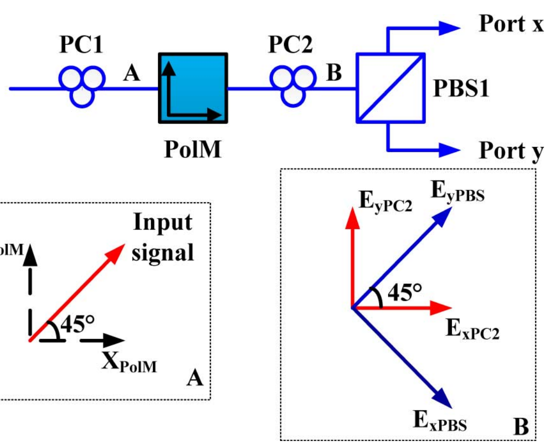

Fig. 4. Equivalent MZM using a PolM, a PC (PC1) and a PBS (PBS1).

where E_{xPolM} and E_{yPolM} are the electrical fields at the output of the PolM along the two orthogonal polarization directions, E_0 is the amplitude of the electrical field of the light wave from the DFB-LD, f_0 is the frequency of the light wave, β is the phase modulation index, and A_{LO} is the amplitude of the LO signal. By adjusting PC2, the two orthogonally polarized light waves at the output of PC2 are oriented to have an angle of 45° with respect to the two polarization directions of the PBS (PBS1), as shown in Fig. 4. Moreover, PC2 also introduces a phase shift of ϕ between the two orthogonally polarized light waves. Thus, the electrical field of the output optical signal from PC2 along the two orthogonal directions is given by

$$\begin{bmatrix} E_{xPC2} \\ E_{yPC2} \end{bmatrix} = \frac{\sqrt{2}}{2} E_0 \exp\left(j2\pi f_0 t\right) \times \begin{bmatrix} \exp\left[j\beta A_{LO}\cos\left(2\pi f_{LO}t\right) + j\phi\right] \\ \exp\left[-j\beta A_{LO}\cos\left(2\pi f_{LO}t\right)\right] \end{bmatrix}. \quad (2)$$

The electrical fields at the two output ports of PBS1 are

$$\begin{aligned} E_{xPBS} &= \frac{\sqrt{2}}{2}\left(E_{xPC2} - E_{yPC2}\right) \\ &= jE_0 \exp\left(j\left(\omega_0 t + \frac{\phi}{2}\right)\right) \\ &\quad \times \sin\left[\beta A_{LO}\cos\left(2\pi f_{LO}t\right) + \frac{\phi}{2}\right] \end{aligned} \quad (3a)$$

$$\begin{aligned} E_{yPBS} &= \frac{\sqrt{2}}{2}\left(E_{xPolM} + E_{yPolM}\right) \\ &= E_0 \exp\left(j\left(\omega_0 t + \frac{\phi}{2}\right)\right) \\ &\quad \times \cos\left[\beta A_{LO}\cos\left(2\pi f_{LO}t\right) + \frac{\phi}{2}\right]. \end{aligned} \quad (3b)$$

From (3a) and (3b), it can be seen that the joint operation of the PolM, PC2 and PBS1 is equivalent to an MZM, which can be biased at either the MITP or the MATP by adjusting the phase shift of ϕ between the two orthogonally polarized light waves from PC2. Here the phase shift of ϕ is set to be 0 by adjusting PC2 to suppress either the optical carrier or the sidebands at the two ports of PBS1. In this case, by using Jacobi Anger expansion, (3a) and (3b) can be further written as See equation (4a) and (4b) at the bottom of the following page. where $J_{\mathrm{n}}(\cdot)$ is the n^{th}-order Bessel function of the first-kind. From (4a) and (4b), it can be seen that the optical field at the output of the x port (E_{xPBS}) only contains the two optical sidebands with the optical carrier fully suppressed and the optical field at the output of the y port (E_{yPBS}) only contains the optical carrier with the two optical sidebands fully suppressed.

The optical carrier in the lower path is sent to an MZM (MZM1) via PC3. MZM1 is biased at the quadrature point and is driven by a pseudo random binary sequence (PRBS) non-return-to-zero (NRZ) signal with a word length of 2^{14} generated by a pulse pattern generator (PPG). The data rate of the wireline signal is 2.5 Gbps, 5 Gbps or 10 Gbps and the peak-to-peak amplitude of the NRZ signal is set at 1.8 V. The two optical sidebands with a frequency interval of $2f_{\mathrm{LO}} = 58.32$ GHz in the upper path are sent to a second MZM (MZM2) via PC4. The two optical sidebands are modulated by a 1.25-Gbps or 2.5-Gbps PRBS NRZ signal with a word length of 2^{14} generated by an arbitrary waveform generator (AWG) with a sampling rate of 10 GS/s. The NRZ signal is amplified by a 10-dB electrical amplifier (AMP1). Thus, the peak-to-peak amplitude of the NRZ signal is 2.5 V. The optical carrier and two optical sidebands are adjusted to be orthogonally polarized by two PCs (PC5 and PC6) and recombined by an optical coupler (OC). The recombined optical signal including the optical carrier and

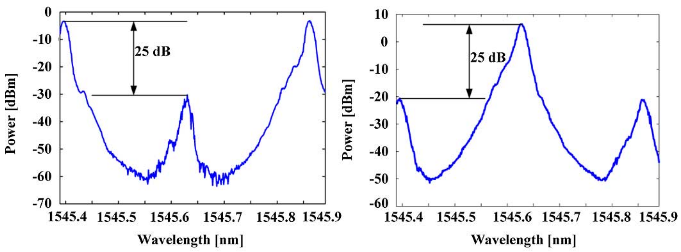

Fig. 5. Spectrums of the optical signals at the outputs of the two ports of PBS1.

two optical sidebands is amplified by an erbium-doped fiber amplifier (EDFA) and then transmitted over a 25-km SMF to a WDM DEMUX. Both the optical carrier and the two sidebands can pass through channel 1 of the DEMUX. Note that the WDM DEMUX also performs as an optical filter which can significantly suppress the optical noise out of the passband, such as the amplified spontaneous emission (ASE) noise from the EDFA. The optical carrier carrying the wireline signal and the two sidebands carrying the wireless signal are separated by a second PBS (PBS2) as they are orthogonally polarized. The wireline signal is recovered by a 20-GHz PD and then amplified by a 23-dB amplifier (AMP1). The wireline signal is either sent to a Digital Storage Oscilloscope (DSO) or a Bit Error Rate Tester (BERT) to evaluate the transmission performance. The OOK modulated mmW signal at $2f_{\rm LO} = 58.32$ GHz is generated by beating the two sidebands at a 100-GHz PD and amplified by a 40-dB low-noise amplifier (LNA). The mmW signal is then down-converted to the baseband by using an external mixer, to which a 58.32-GHz LO signal from a frequency multiplier driven by an mmW signal at 29.16 GHz is applied. Since this LO signal is phase synchronized with the LO signal employed in the CS, the photonic-generated mmW signal can be directly down-converted to the baseband. The down-converted mmW signal is amplified by another 20-dB amplifier (AMP2) and is sent either to the DSO or the BERT for performance analysis.

B. Experimental Results

Fig. 5 shows the optical spectrums of the optical signals at the two output ports of PBS1 (port x and port y in Fig. 4). It can be seen that, for the upper path (the wireless port, port x), the optical carrier is suppressed over 25 dB. For the lower path (the wireline port, port y), the optical sidebands are suppressed over 25 dB. Thus, the optical carrier and the optical sidebands are well separated by PBS1.

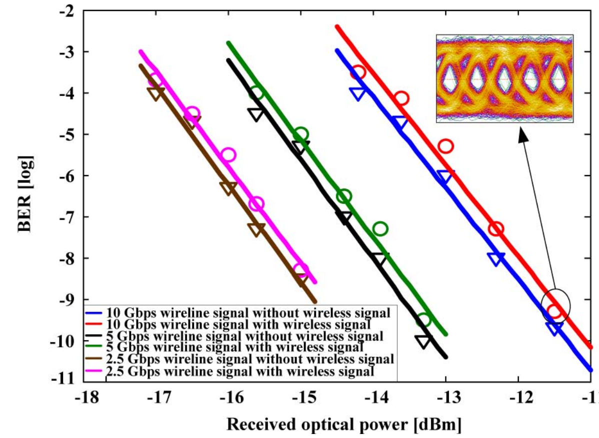

Fig. 6. BER for the transmission of a wireline signal with or without simultaneous transmission of a wireless mmW signal. Inset: eyediagram of the 10-Gbps baseband signal with simultaneous transmission of a 2.5-Gbps wireless mmW signal.

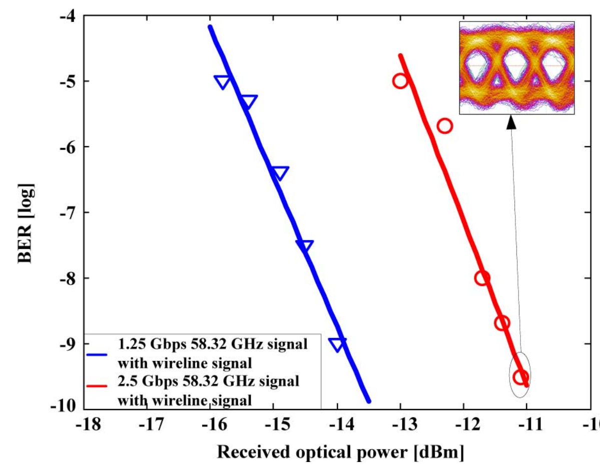

Fig. 7. BER for the transmission of a 58.32-GHz mmW signal with simultaneous transmission of a 10-Gbps wireline signal. Inset: eyediagram of the down-converted 2.5-Gbps OOK-modulated 58.32-GHz mmW signal.

Fig. 6 shows the bit error rate (BER) for the transmission of a wireline signal at 2.5 Gbps, 5 Gbps and 10 Gbps as a function of the received optical power with or without simultaneous transmission of a wireless mmW signal. It can be seen that the

$$E_{xPBS} = -2E_0 \exp j\left(\omega_0 t + \frac{\pi}{2}\right)\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta A_{LO})\cos(2\pi(2n-1)f_{LO}t) \approx 2J_1(\beta A_{LO})E_0\exp\left(j\left(\omega_0 t + \frac{\pi}{2}\right)\right)\cos(2\pi f_{LO}t) \quad (4a)$$

$$E_{yPBS} = E_0\exp(j\omega_0 t)\left[J_0(\beta A_{LO}) + 2\sum_{n=1}^{\infty} j^n J_{2n}(\beta A_{LO})\cos(4\pi n f_{LO}t)\right] \approx J_0(\beta A_{LO})E_0\exp(j\omega_0 t) \quad (4b)$$

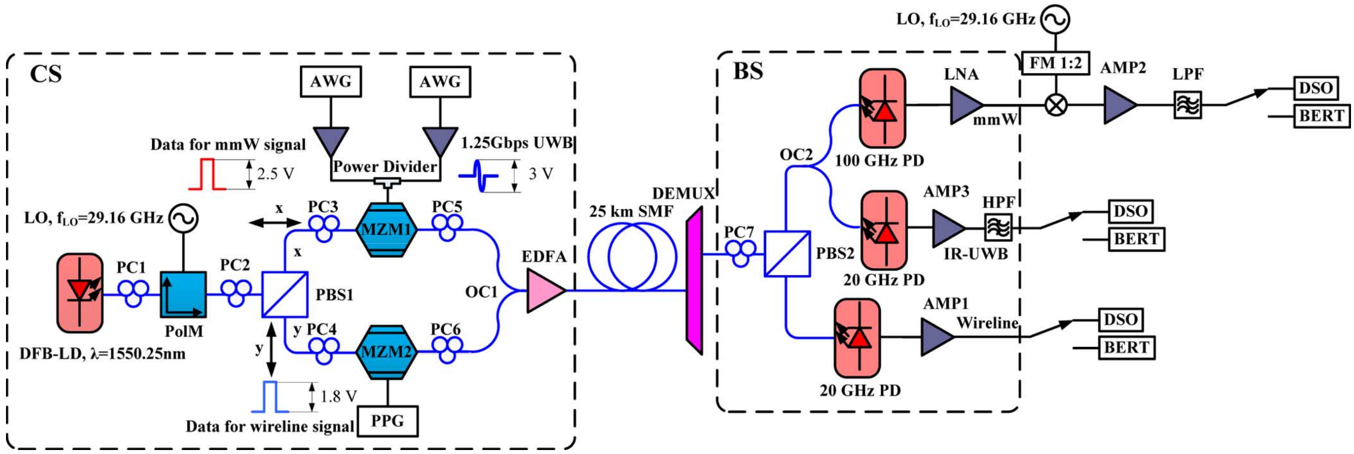

Fig. 8. Experimental setup for the simultaneous transmission of a broadband mmW, an IR-UWB and a wireline signal.

receiver sensitivity for the 10-Gbps wireline signal with simultaneous transmission of a 2.5-Gbps 58.32-GHz mmW signal is -11.5 dBm. Comparing the BER measurements with or without the wireless mmW transmission, it can be seen that a power penalty induced by the simultaneous transmission of an mmW signal as low as 0.3 dB is resulted thanks to the orthogonal polarization of the two signals. From the eyediagram of the 10-Gbps wireline signal shown in Fig. 6 it can be seen that the eyediagram is still widely open. It can prove that the chromatic dispersion of the 25-km SMF link does not bring significant impact on the 10-Gbps wireline signal during the fiber transmission.

Fig. 7 shows the BER for the transmission of a 58.32-GHz mmW signal at 1.25 Gbps or 2.5 Gbps as a function of the received optical power with simultaneous transmission of a wireline signal. It can be seen that the receiver sensitivity for the 58.32-GHz mmW signal at 2.5 Gbps with simultaneous transmission of a 10-Gbps wireline signal is -11.3 dBm. Note that there is no power penalty induced by the wireline signal, since the wireline data is modulated on the optical carrier and the wireless mmW signal is carried by the two sidebands. Since the optical carrier and the two sidebands are well separated, the wireline signal has no impact on the mmW signal even the polarizations of the two optical signals are not perfectly orthogonally polarized.

IV. Simultaneous Transmission of a Broadband MMW, an IR-UWB and a Wireline Signal

In Section III, the simultaneous transmission of a wireline and a wireless mmW signal over a WDM-PON was evaluated. Considering that an IR-UWB signal occupies a spectrum from 3.1 to 10.6 GHz, which will not overlap with the spectrum of an mmW signal. Thus, it is feasible to transmit simultaneously an mmW, an IR-UWB, and a wireline signal over a single fiber. In this Section, simultaneous transmission of an mmW signal, an IR-UWB signal, and a wireline signal over a colorless WDM-PON is experimentally investigated.

A. Experimental Setup

Fig. 8 shows the configuration of the experimental setup. Similar to the configuration in Fig. 3, an optical carrier and two optical sidebands are generated by the PolM, PC2 and PBS1. The wireline signal is modulated on the optical carrier and the mmW and the IR-UWB wireless signals are modulated on the two optical sidebands. At the CS, a 1.25-Gbps PRBS NRZ signal with a word length of 2^{14} for mmW data modulation and a 1.25-Gbps bi-phase modulated (BPM) IR-UWB signal are generated by the AWG with a sampling rate of 10 GS/s and are combined by an electrical power divider. The IR-UWB signal has a pulse shape of a doublet. The sequences of the NRZ signal and IR-UWB signal are pre-generated by a Matlab program and are then loaded to the AWG to physically generate the sequences. Since the spectrum of the IR-UWB signal is within 3.1 to 10.6 GHz, a 1.25-GHz low-pass filter and a 3-GHz high-pass filter are applied in the Matlab program, respectively, to the NRZ signal and IR-UWB signal to avoid spectral overlap of the two signals. The combined NRZ signal and IR-UWB signal are applied to MZM2. The two optical sidebands are modulated by the combined NRZ and IR-UWB signal. Instead of using an AWG to generate the IR-UWB signal, for real implementation a simple, low cost and low power consumption IR-UWB generator can be employed. Similar to the configuration shown in Fig. 3, the wireless signal (the mmW and the UWB signal) and the wireline signal are orthogonally polarized. At the BS, the optical carrier carrying the wireline signal and the two optical sidebands carrying the wireless signal are separated by PBS2. The electrical wireline signal is generated by direct detection at the PD. For the broadband mmW and IR-UWB signals, the two optical sidebands are divided into two paths by OC2. One is sent to a 100-GHz PD to generate 1.25-Gbps mmW signal at 58.32 GHz. Since the NRZ signal and the IR-UWB signal are intensity modulated on both the two sidebands, an electrical filter at the mmW band is employed to filter out the up-converted IR-UWB signal. Since a bandpass filter at 60 GHz band is not available at the time of experiment, the 1.25-Gbps 58.32-GHz signal is firstly down-converted to the baseband by an external mixer and a low-pass filter (LPF), and is then used to extract the NRZ signal. The other is sent to a 20-GHz PD to generate the IR-UWB signal. The IR-UWB is amplified by a 40-dB electrical amplifier and sent to a high-pass filter (HPF). The HPF is employed to filter out the 1.25-Gbps NRZ mmW signal.

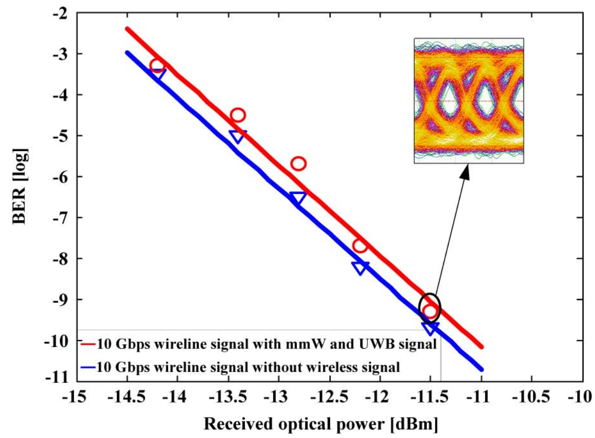

Fig. 9. BER for the transmission of a10-Gbps wireline signal with or without simultaneous transmission of a broadband mmW and a UWB signal. Inset: eye-diagram of the 10-Gbps baseband signal with simultaneous transmission of a 1.25-Gbps mmW and a 1.25-Gbps IR-UWB signals.

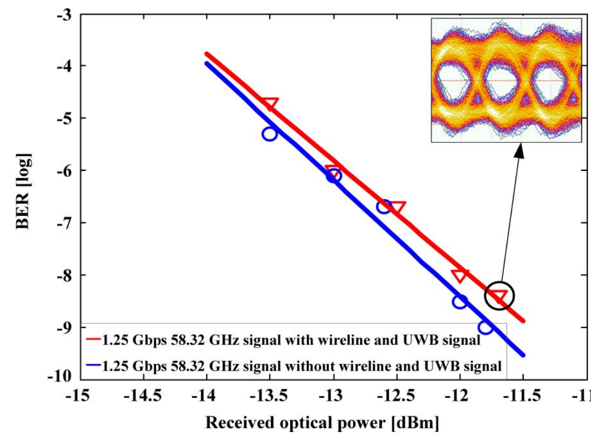

Fig. 10. BER for the transmission of a 1.25-Gbps 58.32-GHz mmW signal with or without simultaneous transmission of a 10-Gbps wireline signal and a 1.25-Gbps IR-UWB signal. Inset: eyediagram of the down-converted 1.25-Gbps 58.32 mmW with simultaneous transmission of a 10-Gbps wireline signal and a 1.25-Gbps IR-UWB signal.

B. Experimental Results

Fig. 9 shows the BER for the transmission of a 10-Gbps baseband signal as a function of the received optical power with or without simultaneous transmission of a wireless signal (mmW and UWB). The receiver sensitivity for the transmission of the 10-Gbps wireline signal with simultaneous transmission of a 1.25-Gbps 58.32-GHz mmW and a 1.25-Gbps IR-UWB signal is -11.5 dBm . Comparing the BER measurements with or without the wireless transmission, it can be seen that a power penalty as low as 0.3 dB is again resulted thanks to the orthogonal polarization of the two signals.

Fig. 10 shows the BER for the 1.25-Gbps 58.32-GHz mmW signal as a function of the received optical power with or without simultaneous transmission of a 10-Gbps wireline signal and a 1.25-Gbps IR-UWB signal. It can be seen that the receiver sensitivity for the 1.25-Gbps 58.32-GHz mmW signal with a 10-Gbps wireline and a 1.25-Gbps IR-UWB signal is -11.5 dBm. Comparing the BER measurements with or without a wireline and an IR-UWB signal, it can be seen that a power penalty of 0.3 dB is resulted. Note that this power penalty is mainly caused by the IR-UWB signal, since the wireline data is modulated on the optical carrier, which has negligible impact on the mmW transmission.

Fig. 11 shows the BER for the transmission of a 1.25-Gbps IR-UWB signal as a function of the received optical power with or without simultaneous transmission of a 10-Gbps wireline signal and a 1.25-Gbps mmW signal. It can be seen that the receiver sensitivity for the 1.25-Gbps IR-UWB mmW signal with a 10-Gbps wireline and a 1.25-Gbps mmW signal is -13.3 dBm. Comparing the BER measurement (red line in Fig. 11) of the IR-UWB signal with a wireline and an mmW signal and the BER measurement (black curve in Fig. 11) of the IR-UWB signal with only an mmW signal, a power penalty of 0.2 dB is resulted. This power penalty is caused by the wireline signal. Comparing the BER measurement (black curve in Fig. 11) of the IR-UWB signal with only an mmW signal and the BER measurements (blue line in Fig. 11) without a wireline and an mmW transmission, a power penalty of 0.7 dB is resulted. This power penalty is resulted due to the mmW transmission. Since the optical wireline signal is perfectly orthogonal to the optical wireless signal, the cross talk between the wireline and wireless is smaller than the impact due to the imperfect high-pass filtering.

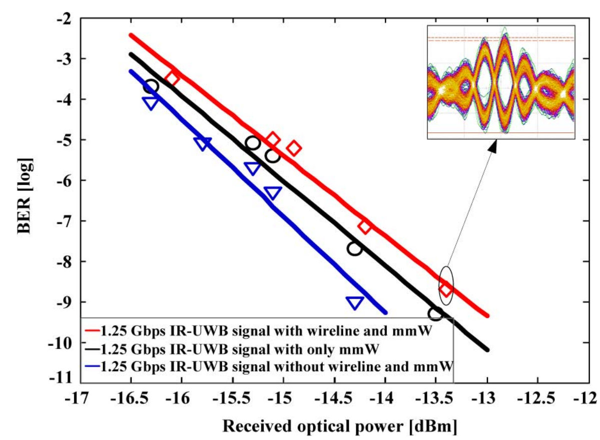

Fig. 11. BER for transmission of a 1.25-Gbps IR-UWB signal with or without simultaneous transmission of a 10-Gbps wireline signal and 1.25-Gbps 58.32-GHz mmW signal. Inset: eyediagram of the 1.25-Gbps IR-UWB signal.

C. Wireless Transmission of the IR-UWB Signal

The wireless transmission of a BPM IR-UWB signal is also tested. To do so, the IR-UWB signal at the BS is radiated to free space via a UWB antenna, as shown in Fig. 12. The radiated signal is then received by another UWB antenna. The wireless distance is set to 2 cm and the gain of the antenna is 4.4 dBi at 4.5 GHz. After amplification by a 20-dB electrical amplifier to compensate for the loss of the wireless link, the IR-UWB signal is sent to a DSO or a BERT to evaluate the transmission performance.

Fig. 13 shows the PSD of the emitted IR-UWB signal, measured at the output of the high-pass filter. It can be seen that the PSD of the emitted IR-UWB signal is well under the spectral mask defined by the FCC except for the spectral range from 0.96 GHz to 1.61 GHz. This is due to the imperfect high-pass filtering and can be improved by using a HPF with better out-of-band

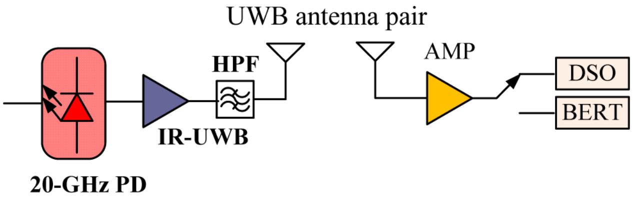

Fig. 12. Wireless transmission of an IR-UWB signal via a UWB antenna pair.

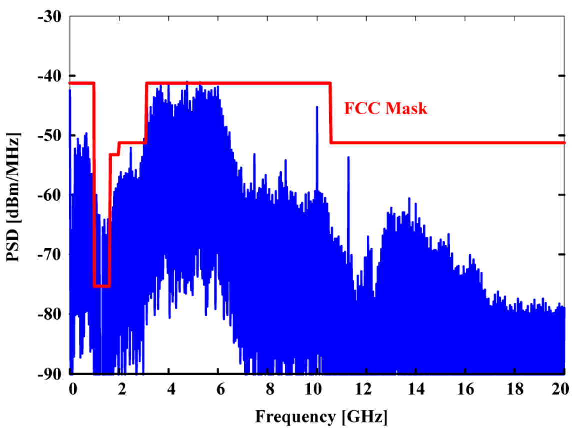

Fig. 13. PSD of the IR-UWB signal at the output of the high-pass filter.

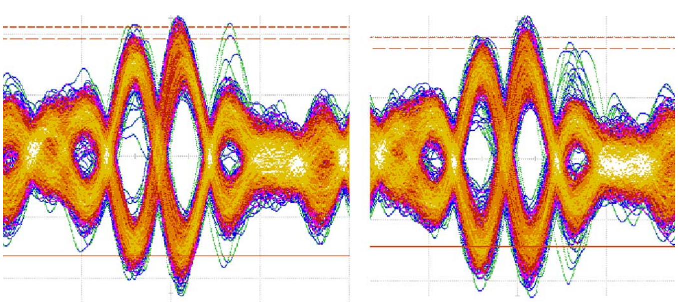

Fig. 14. Eyediagrams of the received IR-UWB signal. (a) The IR-UWB signal without simultaneous transmission of an mmW signal and a wireline signal. (b) The IR-UWB signal with simultaneous transmission of an mmW signal and a wireline signal.

rejection. Moreover, the PSD of the emitted IR-UWB signal at the output of the antenna may be altered due to the specific gain spectrum of the antenna. To ensure the PSD of the emitted IR-UWB signal is still compliant with the FCC mask, in the design of the IR-UWB pulse the gain spectrum of the antenna can be considered.Fig. 14 shows the eye diagrams of the received IR-UWB signal without or with simultaneous transmission of an mmW signal and a wireline signal. As can be seen the eyes of the received IR-UWB signal are well open. Comparing Fig. 14(b) with Fig. 14(a) we can see that there is no significant degradation in the eyediagram in Fig. 14(b).

Table I shows the optical receiver sensitivity for the wireless transmission of an IR-UWB signal with or without other services. The sensitivity here is defined as the optical power required achieving a BER of 10^{-9} over a wireless link. The optical receiver sensitivity for the wireless transmission of a 1.25-Gbps IR-UWB signal with simultaneous transmission of a 10-Gbps wireline and a 1.25-Gbps mmW signal is -10.5 dBm. Comparing the receiver sensitivity for the IR-UWB signal transmission with or without other signal transmission, a power penalty of 0.8 dB is resulted.

TABLE I
RECEIVER SENSITIVITIES

	IR-UWB signal with a wireline and an mmW signal	IR-UWB signal with only an mmW signal	IR-UWB signal without a wireline and an mmW signal
Receiver sensitivity [dBm]	-10.5	-10.8	-11.3

V. DISCUSSION

As it is shown in Figs. 9–11, the receiver sensitivities for the transmission of a 10-Gbps baseband wireline signal, a 1.25-Gbps 58.32-GHz mmW signal and a 1.25-Gbps BPM IR-UWB signal are -11.5 dBm, -11.5 dBm and -13.3 dBm, respectively. Thus, the optical power required at each ONU to ensure error free transmission of the three signals is

$$P_{ONU} = S_{baseband} + S_{UWB} + S_{mmW} \approx -7.2\,\text{dBm} \quad (5)$$

where P_{ONU} is the optical power required at each ONU to ensure error-free transmission of the three signals, $S_{baseband}$, S_{mmW} and S_{UWB} are the sensitivities of the wireline, mmW and IR-UWB receiver, respectively. In the optical link shown as Fig. 1, the insertion loss for a 25-km optical link (IL_{Link}), and the loss of the WDM DEMUX (IL_{DEMUX}) are 5 dB, and 1 dB, respectively. As a result, the emission power of a 100-GHz spaced WDM channel (P_{Tx}) in an OLT for error free transmission is

$$P_{Tx} = P_{ONU} + IL_{Link} + IL_{DEMUX} = -1.2\,\text{dBm}. \quad (6)$$

From (6), it can be seen that an output power of -1.2 dBm is required for each 100-GHz spaced WDM channel at the OLT to ensure simultaneous error-free transmission of a 1.25-Gbps 58.32-GHz mmW, a 1.25-Gbps IR-UWB and a 10-Gbps wireline signal.

Considering that the output power of an EDFA should be maintained to be within a 10 dBm to ensure no nonlinearity in the fiber link [22], the proposed broadband mmW, UWB over WDM-PON architecture can support 13 users. The typical number of channels for a WDM-PON is 16, 32 or 64, although no standard is released. Note that the sensitivity of the BERT is 50 mV. It can be expected that the use of an additional LNA before the BERT can significantly improve the sensitivities of the receivers, so that the proposed UWB, mmW over WDM-PON architecture can support more users to meet the requirement for fiber-to-the-home (FTTH) applications.

VI. Conclusion

We have proposed a novel approach to achieving simultaneous transmission of a broadband mmW, an IR-UWB signal and a wireline signal over a colorless WDM-PON. Simultaneous error-free transmission of a 1.25-Gbps 58.32-GHz mmW signal, a 1.25-Gbps IR-UWB signal, and a 10-Gbps wireline signal were achieved over a single 100-GHz WDM-PON channel to increase the spectral efficiency of the WDM-PON network. The first contribution of the approach was the use of the PolM in the CS, which was functioning, in conjunction with a PC and a PBS, to generate two optical sidebands and an optical carrier, which were physically separated at the outputs of the PBS. The wireline signal was modulated on the optical carrier and the wireless signal (mmW and UWB) was modulated on the two optical sidebands. The second contribution of the approach is the employment of polarization multiplexing for multiservice over a WDM-PON. Since the wireline signal and wireless signal were orthogonally polarized, no cross talk between the wireline signal and wireless signal was resulted. At the BS, the wireless and the wireline signal were separated by another PBS. Since no optical filters were employed to separate the different services in the entire network (in both the OLT and ONU), the proposed configuration is compliant with a colorless WDM-PON architecture and it can reduce the complexity and the cost of the overall system. The proposed approach was experimentally evaluated. In the experiment, the power penalty due to the interference between the wireline signal and wireless signal was as small as 0.3 dB. Based on the measured sensitivities for the 10-Gbps wireline signal, the 1.25-Gbps mmW, and the 1.25-Gbps IR-UWB signal, the number of ONUs that could be supported by the system was estimated. For the experimented system, 13 ONUs could be supported if the optical power applied to the 25-km SMF link is 10 dBm. More number of users can be supported if the electrical receivers with higher sensitivities are employed.

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