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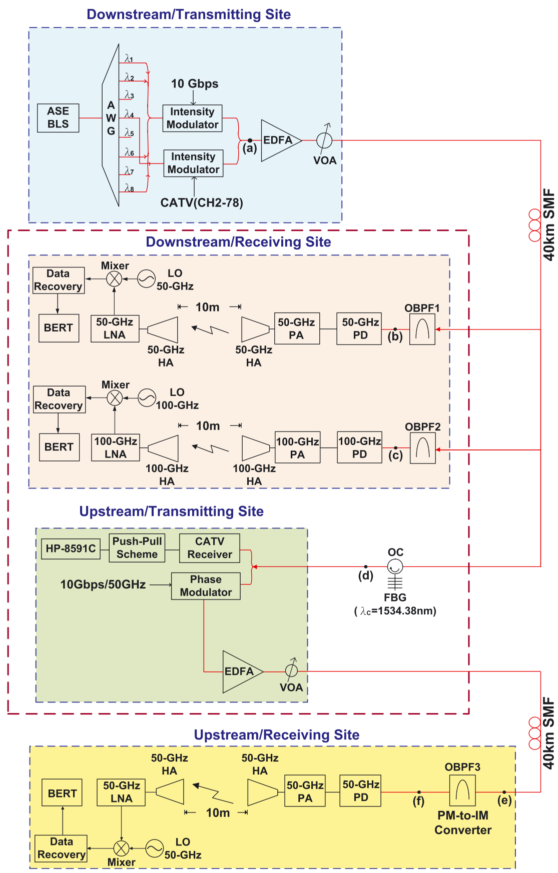

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Progressive and Cost-Effective Bidirectional CATV/Wireless-Over-Fiber Lightwave Transport System

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Abstract: A progressive bidirectional cable television (CATV)/wireless-over-fiber lightwave transmission system based on one broadband light source (BLS), one arrayed waveguide grating, two intensity modulators, and one phase modulator is proposed and experimentally demonstrated. A continuous amplified spontaneous emission BLS is split into eight channels in the C-band with 50-GHz spacing. The multiple equal-space optical spectra exhibit a high optical signal-to-noise ratio ($\geq$ 55 dB) and good flatness ($\leq$ 5 dB). A high-quality comb multicarrier provides a single wavelength and twin millimeter-wave bands for baseband CATV and wireless transport systems. Several measured values (carrier-to-noise ratio $\geq$ 64 dB, composite second order $\geq$ 62 dB, composite triple beat $\geq$ 63 dB, and bit error rate $\leq 10^{-9}$) can be obtained from distortion-reduced and noise-free performance. Moreover, downstream and upstream high-bit-rate wireless transmissions exhibit an interference-eliminating property. Thus, the proposed system does not only offer a future for progressive fiber backbone and CATV/wireless hybrid networks, but also provides a full-duplex interference-free for high-data-rate mobile communication and in-home CATV access networks as well.

Index Terms: Cable television (CATV)/wireless-over-fiber, broadband comb multicarrier, full-duplex interference free.

1. Introduction

At present, the demand of Internet users for high-quality images and mobile broadband services that require wide network bandwidths has increased. Traditional networks that use coaxial cables and twisted pairs as main transmission media can no longer satisfy the demand. With the increasing demand for wireless network bandwidths [1], [2], the required carrier wave frequency must be increased to obtain a wider transmission bandwidth. Recently, 60 GHz technologies have received attention for applications in high-speed wireless local area networks and wireless personal area networks. The main reason for using the spectral range of 57 GHz to 64 GHz is that it is license-free in most countries [3], [4]. Among currently available gigabit wireless approaches, 60 GHz technologies, which have a huge bandwidth, demonstrate considerable potential in terms of capacity and flexibility. The generation of broadband 60 GHz millimeter wave (MMW) by optical heterodyning has been intensively investigated to produce different high-frequency signals and simplify the design of MMW base stations (BSs). Coherent heterodyning is a technique used to generate low phase noise MMW by beating two coherent optical tones [5], [6]. In conventional approaches, coherent optical tone (comb) generation is based on a multiwavelength laser (e.g., mode-locked lasers) or multiple cascaded external modulators [7], [8]. However, conventional 60 GHz coherent optical tones have several disadvantages, such as significant propagation loss, large comb linewidth, poor free spectral range (FSR), large insertion loss of the modulator, and significant modulation instability induced by bias drift. A hybrid wavelength division multiplexing (WDM) lightwave transport system that carries different optical wavelengths to deliver combined multiband signals will be useful in providing telecommunication, gigabit Internet, and big data services [9], [10]. In terms of practicality, fiber cable television (CATV)/wireless integrated lightwave broadband transport systems are attractive in daily life. Hybrid multiband fiber CATV/wireless transport systems with a single coherent optical light source do not only have a simple cost-effective central office but efficiently support different kinds of in-building services as well. In this paper, a hybrid twin band WDM lightwave transport system based on fiber-CATV and fiber-wireless convergences is proposed and experimentally demonstrated. This system consists of one broadband light source (BLS), one arrayed waveguide grating (AWG), two intensity modulators, and one phase modulator. A continuous amplified spontaneous emission BLS (ASE BLS) is spectrally sliced using a 1×8 AWG to demultiplex (DEMUX) eight downstream high-quality comb optical carriers with 50 GHz spacing. Twin MMW bands provide the transmission of 50 GHz and 100 GHz MMW for downstream transmission. The main reason for 50 GHz and 100 GHz propagation loss in the air are considerably lower than 60 GHz. A single wavelength, additionally, is used in baseband frequency downstream (in CATV) and upstream (in 50 GHz MMW) wireless transmissions. This study is the first to use one ASE, one AWG, and one phase modulator in a hybrid WDM lightwave transmission system. The optical signal of downstream transmission was intensity-modulated to generate twin MMW data signals of 10 Gbps/50 GHz, 10 Gbps/100 GHz, and 50–550 MHz CATV. Furthermore, the downloading optical signal successfully phase-remodulated the 10 Gbps/50 GHz MMW data signal of upstream transmission. For the uploading phase signal, we replaced the delay interferometer (DI) with an optical band-pass filter to achieve the mechanism of the most direct optical phase modulation-to-intensity conversion [11]–[13]. Consequently, the optical signals could be detected by a photodiode (PD). The parameter bit error rate (BER) was used to measure and analyze the performance of downstream 10 Gbps/100 GHz and 10 Gbps/50 GHz MMW data signals and upstream 10 Gbps/50 GHz MMW data signal. Meanwhile, the carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB) of the parameters were used to measure and analyze the performance of downstream CATV signal. An in-depth investigation of the hybrid WDM lightwave transport system revealed that BER, CNR, CSO, and CTB performed very well over a 40 km single-mode fiber (SMF) and a 10 m radio-frequency (RF) wireless transport medium. The proposed system not only offers a future for progressive fiber backbone and CATV/wireless hybrid networks but provides an full-duplex interference-free for high data rate mobile communication and in-home digital CATV access network as well.

2. Experimental Setup

The experimental configuration of the high-quality comb source is based on AWG, bidirectional CATV/50 GHz and 100 GHz wireless-over-fiber (CATV/WoF) lightwave transmission systems. The proposed system consists of one ASE BLS, one AWG, two downstream intensity modulators, and one upstream phase modulator, as shown in Fig. 1. The multicarrier head-end site is composed of an ASE BLS, an AWG device, two intensity modulators, an erbium-doped fiber amplifier (EDFA), and a variable optical attenuator (VOA). The major characteristic of AWG, which is utilized as an optical comb band-pass filter, is that it provides sliced equal-space and comb optical sidebands. A continuous ASE BLS (with wavelength ranging from 1526 nm to 1604.9 nm) is employed as a downstream light source at the central office and is spectrally sliced using a 1×8 AWG to generate eight downstream channels $(\lambda_1, \ldots, \lambda_8)$ in the C band with 50 GHz spacing. In this experiment, AWG important parameters are 50 GHz channel

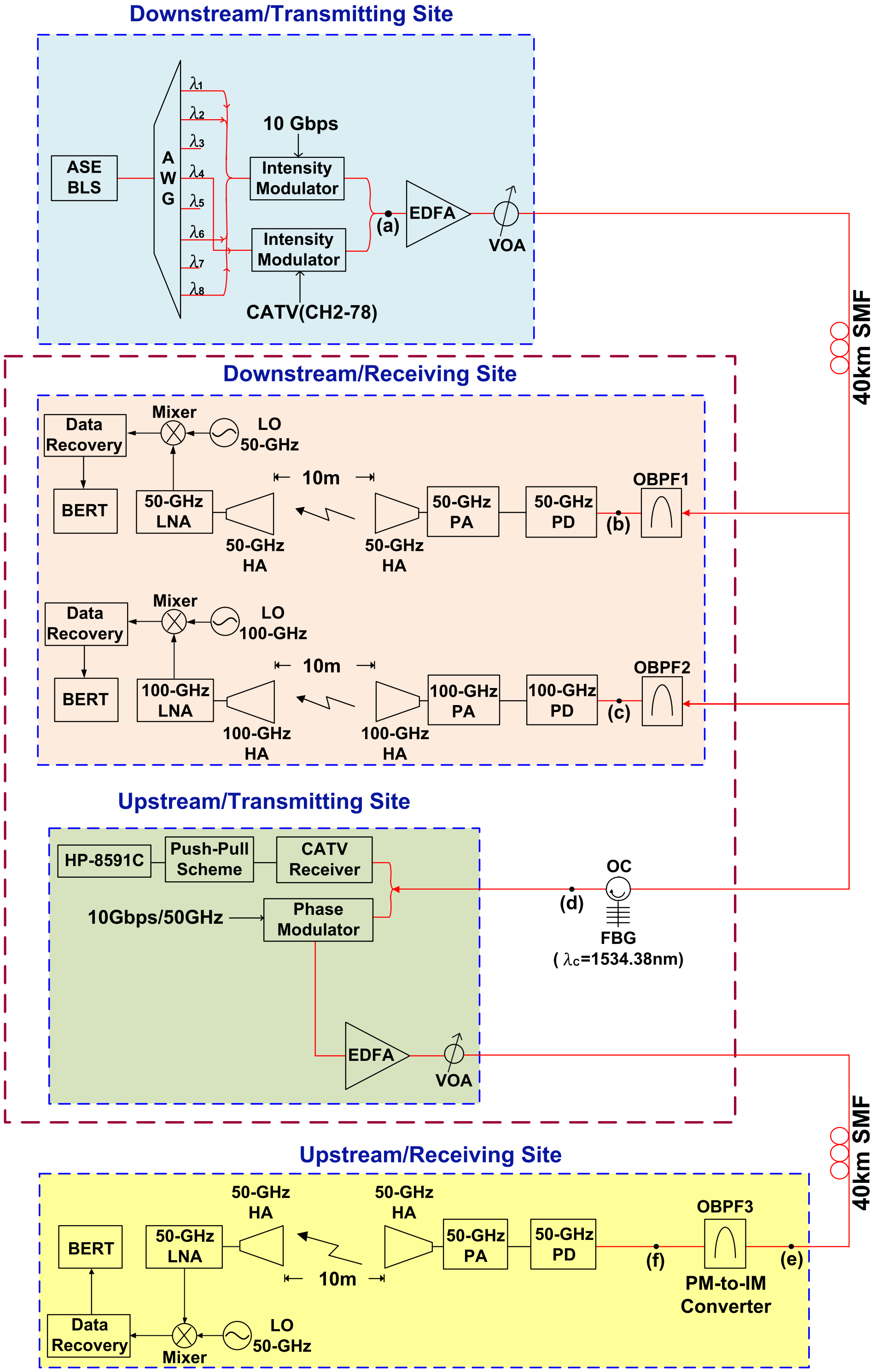

Fig. 1. Experimental configuration of the proposed bidirectional CATV/50 GHz and 100 GHz CATV/WoF lightwave transmission system.

spacing, insertion loss ≤ 5.5 dB, ripple ≤ 0.5 dB, and isolation ≥ 50 dB (adjacent channel and non- adjacent channel), respectively. The comb optical signal employs AWG to DEMUX three groups of phase-coherent optical tones with frequency spacings of 50 GHz (two phase coherent optical tones λ_1 and λ_2 are selected, with a frequency spacing of 50 GHz between the two optical tones) and 100 GHz (λ_6, and λ_8) and a baseband (λ_4) among the optical channels.

Both 50 GHz and 100 GHz twin MMW bands are intensity-modulated with a 10 Gbps amplitude-shift keying (ASK) data stream via one intensity modulator. The single wavelength λ_4 is also intensity-modulated with baseband analog RF 77 channels (CH 2–78; 50–550 MHz) from a CATV multichannel signal generator through the other intensity modulator. Two optical signal paths are then combined by a 2×1 optical combiner [point (a) in Fig. 1] and amplified by EDFA. The output power and noise figure of EDFA are 1.8 dBm and 3.81 dB, respectively, at an input power of −16 dBm. The VOA is cascaded after EDFA. A low optical power launched into the fiber corresponds to few distortions transported to later receivers. Transmitted over a 40 km SMF link, the hybrid signals are split by a 1×3 optical coupler, passed through two optical band-pass filters (OBPFs), that is, OBPF1 and OBPF2, one Bragg fiber grating (FBG) to select the appropriate optical wavelength, detected by two photodiodes (PDs) (50 GHz ($\text{BW} = 50$ GHz, data rate $= 40$ Gbps) and 100 GHz ($\text{BW} = 100$ GHz, data rate $= 100$ Gbps)), and an analog optical receiver. In the first path, the 10 Gbps/50 GHz MMW data signal is optically filtered using OBPF1. OBPF1, with a 3 dB bandwidth of 0.83 nm, is utilized to remove unwanted optical sidebands [point (b) of Fig. 1]. The 10 Gbps/50 GHz MMW data electrical signal is then detected by a 50 GHz PD, boosted by a 50 GHz power amplifier (PA), and wirelessly transmitted by a 50 GHz horn antenna (HA). When transmitted over a 10 m RF wireless transmission, the 10 Gbps/50 GHz MMW data signal is received by a 50 GHz HA, amplified by a 50 GHz low-noise amplifier (LNA) with a noise figure of approximately 3.2 dB, and down-converted by a heterodyne receiver, which is composed of a 30 GHz local oscillator (LO) and a mixer. In the scheme, the horn antennas 50 GHz HA and 100 GHz HA gain are 20 dB and 25 dB, respectively. The power amplifiers 50 GHz PA and 100 GHz PA output power are 24 dBm and 17 dBm, respectively. The LNA is a device that is placed at the front end of a receiver. Both 50 GHz and 100 GHz LNAs, in the experiment, are provided to high gain ($\geq$14 dB) and low noise figure ($\leq$ 3.4 dB). High bit rate digital data are recovered using a data recovery scheme. In this scheme, the receiving site generates a clock from an approximate frequency reference, phase-aligns to the transitions in the data stream, and regenerates the data stream. The transmission procedure in the second path (10 Gbps/100 GHz MMW data signal) is the same as that in the first path. The 10 Gbps/100 GHz MMW optical signal is shown as [point (c) of Fig. 1]. For the third path, the specific wavelength λ_c is selected by an optical circulator (OC) and combined with a FBG ($\lambda_c = 1534.38$ nm). The single-wavelength optical signal [point (d) of Fig. 1] is split by a 1×2 optical splitter and launched into a CATV receiver and a phase modulator. After reaching the CATV receiver, the CATV signal is supplied into a push-pull scheme for even-order distortion elimination and fed into an HP-8591C CATV analyzer for CNR, CSO, and CTB performance analyses. For upstream transmission, the received 10 Gbps/50 GHz MMW data signal is fed into a phase modulator for phase remodulation, amplified by EDFA, attenuated by VOA, and delivered by another 40 km SMF link. Over this SMF link, the optical signal passes through OBPF3, which plays the role of a phase modulation-to-intensity modulation (PM-to-IM) converter. The upstream phase-modulated signal is converted into intensity-modulated signal, which can be detected by a 50 GHz PD, boosted by a 50 GHz PA, and wirelessly transmitted by a 50 GHz HA. Over a 10 m RF wireless transmission, the 10 Gbps/50 GHz MW data signal is received by a 50 GHz HA, amplified by a 50 GHz LNA with a noise figure of approximately 3.4 dB, and down-converted by a heterodyne receiver, which is composed of a 50 GHz LO and a mixer. Data are recovered by a data recovery scheme and fed into a bit error rate tester (BERT) to estimate BER performance.

3. Experimental Results and Discussion

The continuous ASE BLS is split into eight channels in the C band with 50 GHz spacing by a 1×8 AWG. The sliced eight optical spectra of the scheme are shown in Fig. 2. The multiple equal-space optical spectra exhibit both high optical signal-to-noise ratio ($\text{OSNR} \geq 55$ dB) and

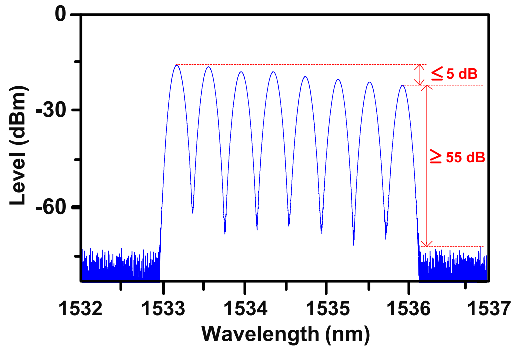

Fig. 2. Eight comb optical spectra of the generated BLS after AWG.

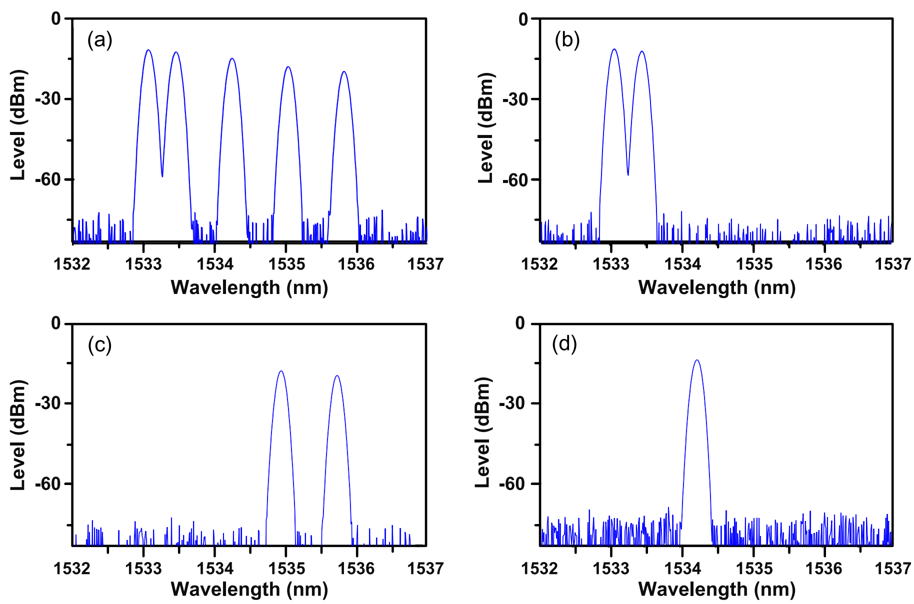

Fig. 3. (a)–(d). Optical spectra of different optical signals at four points in the optical path [insert (a)–(d) of Fig. 1].

good flatness $\leq$ 5 dB. Fig. 3 shows the spectra of different optical signals from points (a) to (d), as shown in Fig. 1. For downstream transmission, the measured point (a) is merged with the aforementioned three band optical signals into a single hybrid optical signal, as shown in Fig. 3(a). Over a 40 km SMF link, the hybrid signal is split by a 1 $\times$ 3 optical splitter. By utilizing OBPF1, the first wireless transmission measured point (b), which is shown in Fig. 3(b), is removed by an outer sideband, except for two wavelengths with a spacing of 0.4 nm (50 GHz), i.e., λ_1, and λ_2. The mixed 10 Gbps/50 GHz MMW data electrical signal is then detected by a 50 GHz PD. Similarly, the second wireless transmission presented in Fig. 3(c) shows two wavelength spacing of 0.8 nm (100 GHz), i.e., λ_6 and λ_8. For the third CATV transmission, a single optical wavelength is selected by an OC combined with an FBG ($\lambda_c = 1534.38$ nm), as shown in Fig. 3(d). Additionally, the brilliant measured RF spectra of 10 Gbps/50 GHz and 10 Gbps/100 GHz MMW data signals after 50-GHz PD and 100-GHz PD, are shown in Fig. 4(a) and Fig. 4(b), respectively. Thus, the hybrid three-band optical signals can simultaneously provide bidirectional wireless mobile/CATV to countless clients.

For the CATV transmission path, the cascaded push-pull scheme is utilized during the elimination of even-order harmonic distortions. In particular, CATV picture quality is mainly degraded

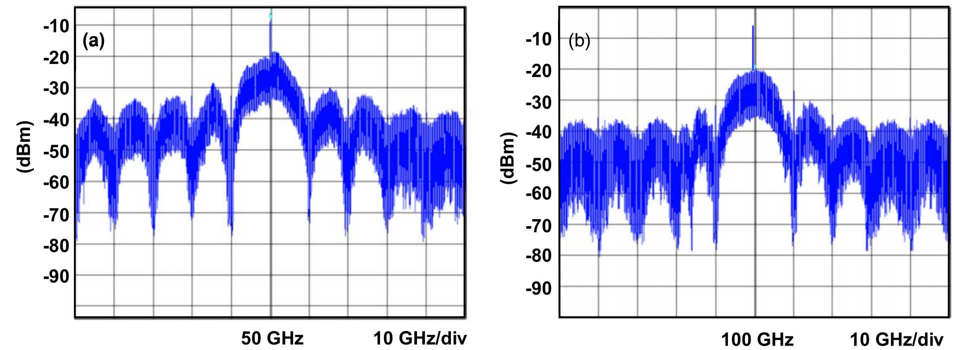

Fig. 4. (a) Measured RF spectrum of the 10 Gbps/50 GHz MMW data signal after 50-GHz PD. (b) Measured RF spectrum of the 10 Gbps/100 GHz MMW data signal after 100-GHz PD.

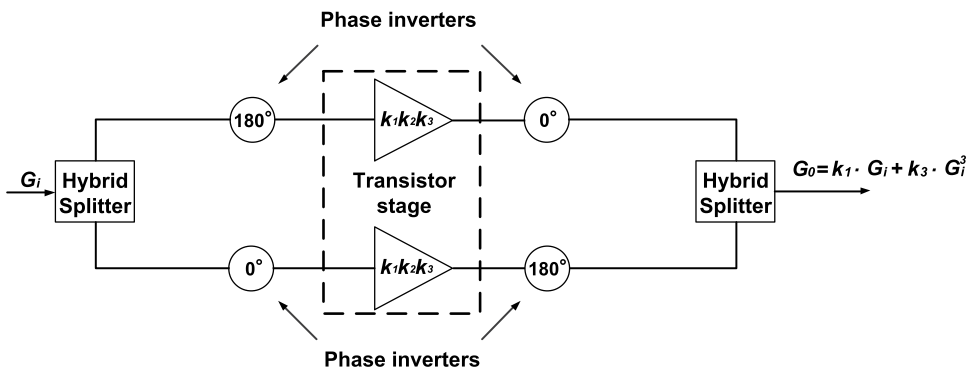

Fig. 5. Push–pull amplifier circuit block diagram.

from second-order harmonic products. The interfering beat pattern will appear as vertical lines on the CATV screen when the second-order harmonic frequency is closed to the horizontal line frequency or when the second-order beat product has sufficient amplitude. Fig. 5 shows the push-pull amplifier circuit has symmetric phase inverters in order to cancel second-order harmonic distortion components. The transistor stage can provide 20 dB of gain. The entire block diagram has an overall gain of 23 dB under the practical measurement. The second-order harmonic distortions of the push-pull section will be about –75 dB at push-pull scheme output. Therefore, the push-pull block scheme can remove second-order harmonic distortions completely. The push-pull scheme output modus is given by the following formula [14], [15]:

$$G_o = k_1 \cdot G_i + k_3 \cdot G_i^3 \tag{1}$$

where G_o is the push-pull scheme output gain, G_i is the push-pull scheme input gain, and both k_1, and k_3 are the characterizing amplitude coefficients of the fundamental and third-order harmonic distortions in transistor stage, respectively. The expression of the output power CATV receiver is as follows:

$$P_o = n_1 \cdot P_i + n_2 \cdot P_i^2 + n_3 \cdot P_i^3 \tag{2}$$

where P_o is the output power of a system detected from the CATV receiver; P_i is the input of the receiver; and n_1, n_2, and n_3 are the amplitude coefficients of the fundamental, second-order, and third-order nonlinear distortions, respectively. The CATV signal is fed into a push-pull scheme, that is,

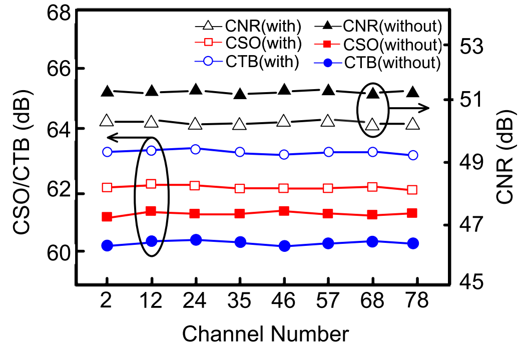

Fig. 6. Measured CNR/CSO/CTB values with and without the push–pull amplifier scheme.

$P_o = G_i$. Substituting (2) into (1) and disregarding high-order nonlinear terms approximation result in the following:

$$G_o = (k_1 \cdot n_1)P_i + (k_1 \cdot n_2)P_i^2 + (k_1 \cdot n_3 + k_3 \cdot n_1^3)P_i^3. \tag{3}$$

We choose $k_1 = -k_3 n_1^3/n_3$, and the third-order nonlinearity component is eliminated in the push-pull scheme output. Finally, (3) can be rewritten as follows:

$$G_o = (k_1 \cdot n_1)P_i + (k_1 \cdot n_2)P_i^2. \tag{4}$$

The indices of CSO and CTB are important to CATV performance measurements; these indices can be defined logarithmically and mathematically as follows [16]:

$$\text{CNR} = \left(\text{CNR}_{\text{RIN}}^{-1} + \left(\text{CNR}_{\text{th}}^{-1} + \text{CNR}_{\text{shot}}^{-1}\right)\right)^{-1} \tag{5}$$

$$\text{CNR(dB)} = -10\log\left[10^{\frac{\text{CNR}_{\text{RIN}}}{10}} + 10^{\frac{\text{CNRth}}{10}} + 10^{\frac{\text{CNR}_{\text{shot}}}{10}}\right] \tag{6}$$

where CNR_{RIN} results from the intensity-modulated noise, and both CNR_{th} and CNR_{shot} are related to the received amplifier noises.

$$\text{CSO} = 10\log\frac{\text{video carrier level}}{\text{second - order distortion level}} \tag{7}$$

$$\text{CTB} = 10\log\frac{\text{video carrier level}}{\text{third - order distortion level}}. \tag{8}$$

As shown in (7) and (8), when second-order and third-order distortion levels are low, the CSO and CTB measured values are high (good).

The measured CNR/CSO/CTB values under NTSC channel number (CH 2–78; 550.25–740.25 MHz) with and without a push-pull scheme are shown in Fig. 6. The CNR value of the system with a push-pull scheme is deteriorated slightly by approximately 1 dB compared with the system without a push-pull scheme. This slight deterioration in CNR measured using a CATV analyzer (HP-8591C) is attributed to the increase in received amplifier noises with the push-pull scheme. Nevertheless, the value of CNR (≥ 64 dB) in the system with a push-pull scheme still agrees with the smallest CATV CNR demand at the receiving node (≥ 50 dB). By comparison, the values of CSO and CTB in the system with a push-pull scheme are significantly improved. The CTB value improved by approximately ≥ 4 dB. The CSO and CTB values in the system with a push-pull scheme are higher than 62 dB and 63 dB, respectively, and satisfy the CATV CSO/CTB requirements at the receiving-end node (≥ 60/60 dB). These improvements can be attributed to the use of the push-pull amplifier scheme to eliminate nonlinear distortions.

For the twin MMW bands WoF transmission paths, Fig. 7(a) shows the measured BER curves of the 10 Gbps/50 GHz hybrid MMW data signal with and without, i.e., back-to-back (BTB),

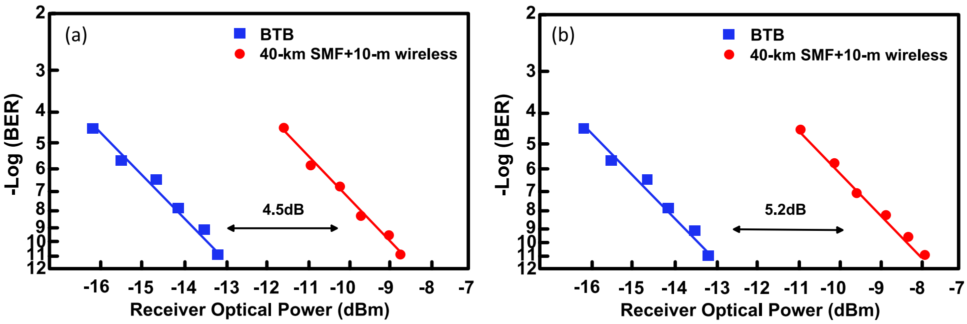

Fig. 7. (a) Measured BER curves of the 10 Gbps/50 GHz MMW data signal for BTB, as well as 40 km SMF and 10 m RF wireless transport scenes. (b) Measured BER curves of the 10 Gbps/100 GHz MMW data signal for BTB and 40 km SMF and 10 m RF wireless transport scenes.

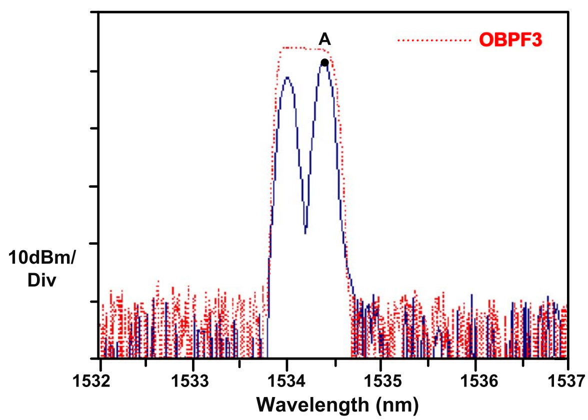

Fig. 8. Spectrum of the OBPF3 (BW = 0.83 nm) utilized as a PM-to-IM conversion in the proposed experiment.

media, respectively. The measured BER curves between BTB and a 40 km SMF wire line, as well as a 10 m RF wireless transmission, has a large power penalty of 4.5 dB at BER of 10^{-9}. Similarly, Fig. 7(b) shows the measured BER curves of the 10 Gbps/100 GHz hybrid MMW data signal for BTB and over a 40 km SMF as well as a 10 m RF wireless transmission. The measured BER curves between BTB and the 40 km SMF wire line as well as the 10 m MMW wireless transmission has a power penalty of 5.2 dB at a BER of 10^{-9}. Fiber dispersion degrades transmission performance because of the natural characteristics of the two optical sidebands passing over a 40 km SMF transmission. Moreover, when passing over a 10 m MMW wireless transmission, the fading effect leads to amplitude and phase fluctuations in the received signal and degraded the results in BER. The LNA is a key component that is placed at the front end of a receiver. By using these good specification LNAs, the low noise figure effect of noise from subsequent stages of the receive chain are reduced, while the noises of the LNAs themselves are fed directly into the received signal. LNAs high gain property are able to boost the desired signal power while adding minimum noise and distortion. When low noise amplification and data recovery are cascaded simultaneously, noise-free and error-free transmissions are achieved to demonstrate the excellent performance of the established hybrid WoF transport system.

Apart from the FBG selected optical signal, $\lambda_4 = \lambda_c = 1534.38$ nm is passed toward the downstream transmission of the CATV receiver to measure CNR/CSO/CTB values. The remaining downstream optical signals pass through the upstream phase modulator to reuse the single wavelength λ_4. For upstream transmission, a mixed 10 Gbps/50 GHz MMW data signal is fed into the phase modulator. The modulation index is related to the variations in phase of the

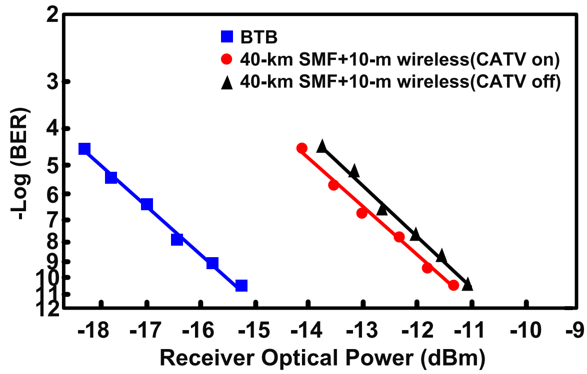

Fig. 9. Measured BER curves of the 10 Gbps/50 GHz MW data signal for BTB and 40 km SMF and 10 m MMW wireless transport scenes.

IM-based downstream signal, instead of the ratio of the level of the modulated MMW signal to the level of the IM-based downstream signal. The upstream receiving site can be obtained from both obvious distortion suppression and high robustness against fiber nonlinearity when passing over a 40 km SMF and a 10 m MMW wireless transmission. Conventionally, the PM-scheme phase-class signal is converted into an intensity-class signal by utilizing an expensive delay interferometer (DI). In our proposed methodology, we adopt the cost-effective OBPF to play the role of a PM-to-IM converter. As illustrated in Fig. 8, the central wavelengths of OBPF3 (with a bandwidth of 0.83 nm) and the phase-modulated upstream double-sided optical signal are 1533.98 nm and 1534.38 nm, respectively. The wavelength of position A is 1534.38 nm. The phase-modulated upper sideband (1534.38 nm) is removed by OBPF3. The lower sideband (1533.98 nm) is reserved. PM-to-IM conversion can be achieved successfully. The optical signal of intensity can be correctly detected by a PD. To evaluate between downstream intensity-modulated CATV signal and upstream phase-remodulated 10 Gbps/50 GHz MMW data signal interference, we turn the CATV downstream signal on/off. The MMW wireless BER values exhibits a slight power penalty of approximately 0.2 dB, as shown in Fig. 9. Minimal interference occurs between the CATV and bidirectional MMW wireless transport system.

4. Conclusion

A progressive bidirectional CATV/WoF lightwave transmission system based on one BLS, one AWG, two intensity modulators, and one phase modulator is proposed and experimentally demonstrated. Several brilliant measured values (CNR $\geq$ 64 dB/CSO $\geq$ 62 dB/CTB $\geq$ 63 dB/BER $\leq 10^{-9}$) can be obtained from both distortion-reduced and noise-free performances. Moreover, downstream CATV/MMW and upstream high bit rate wireless transmissions exhibit an interference-reducing property. Thus, the proposed system does not only offer a future for progressive cost-effective fiber backbone/wireless hybrid networks, but also provides a full-duplex interference free for high data rate mobile communication and in-home digital CATV access network in the future.

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