Wavelength reuse in a bidirectional radio-over-fiber link based on cross-gain and cross-polarization modulation in a semiconductor optical amplifier

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Wavelength reuse in a bidirectional radio-over-fiber link is proposed and demonstrated based on the cross-gain modulation (XGM) and the cross-polarization modulation in a semiconductor optical amplifier (SOA). With a polarization beam splitter placed at the remote antenna unit, the polarization-modulated signal generated at the SOA is converted into noninverted and inverted intensity-modulated signals. The noninverted signal is used to cancel the inverted XGM-induced intensity-modulated signal to form a clean optical carrier for wavelength reuse in upstream signal transmission, while the inverted intensity-modulated signal is combined constructively to enhance the XGM-induced signal, providing robust downlink service. A bidirectional transmission of 5 GHz RF signal carrying a 50 MBaud 16 quadrature amplitude modulation baseband signal is experimentally implemented. The error vector magnitude degradation due to the fiber transmission for both the downlink and uplink signal is about 0.2%.

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Radio-over-fiber (RoF) has been extensively studied for wireless communications, antenna remoting, and radio-astronomy systems [1,2]. In a RoF link, high-frequency and wideband RF signals can be distributed from a center office (CO) to several remote antenna units (RAUs), by which all the complex, high-power consumption and high-cost signal processing functions in the RAUs can be centralized in a shared location [3]. For future wireless communications, due to the increasing demand for seamless services, more and more RAUs are required to provide sufficient network coverage [4]. Thus, it is highly desirable that the capital and operational costs of every RAU could be minimized. To this end, one can rely on bidirectional RoF links with centralized light sources at the CO and wavelength reuse schemes at the RAUs, so that no expensive light sources are required at the user site [5]. This method is extremely attractive if the radio signals are distributed over wavelength-division multiplexing networks since the RAUs are wavelength independent, demanding no wavelength management. Among the many examples of wavelength reuse schemes, the gain saturation effect in a semiconductor optical amplifier (SOA) is widely used to erase the information in the downlink optical signal so that the optical carrier can be remodulated to carry an uplink information in the RAU [6–8]. However, to effectively remove the downlink information, the injected optical signal to the SOA should have a very low extinction ratio (typically less than 3 dB), which is power inefficient.

In this paper, wavelength reuse in a bidirectional RoF link based on the cross-gain modulation (XGM) and the cross-polarization modulation (XPolM) in a single SOA placed at the CO is proposed and experimentally demonstrated. By inserting a polarization beam splitter (PBS) in the RAU, one port of the PBS can output an enhanced downstream signal, while the other provides an optical carrier with all the downstream information erased. The clean carrier is then used to remodulate an upstream RF signal for the uplink service. A bidirectional RoF link is thus realized.

Figure 1 shows the schematic diagram of the proposed bidirectional RoF link. A weak continuous-wave probe light and a strong pump light are counterdirectionally fed into an SOA via its two optical ports. The pump light is modulated by a microwave signal, which is generated by modulating the optical carrier by a quadrature amplitude modulation (QAM) RF signal at a Mach–Zehnder modulator (MZM). In the SOA, the strong pump light would induce XGM, by which the information carried by the pump light is transferred to the probe light with amplitude inversion. Meanwhile, the carrier density changes caused by the pump light for the transverse-electric (TE) mode and transverse-magnetic (TM) mode are different, so the TE and TM modes of the probe signal would experience different refractive indices. XPolM effect is thus formed [9–11]. If a PBS is connected after the SOA, the two modes are coherently combined, which can produce an inverted or noninverted signal at the two output ports

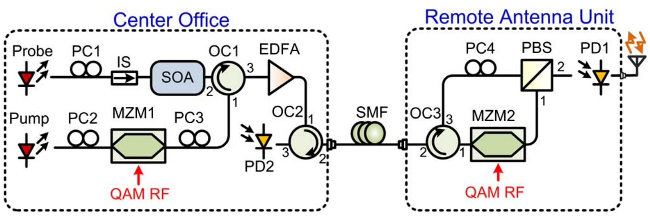

Fig. 1. Schematic diagram of the proposed bidirectional RoF link.

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of the PBS. This phenomenon was previously used to implement both inverted and noninverted wavelength conversion in an optical communication system [9]. By carefully adjusting the powers and the polarization states of the probe and pump lights, the noninverted signal produced by the XPolM and the inverted signal generated by the XGM are complementary. As a result, in one port of the PBS, an optical signal with no power variation would be obtained, i.e., the information is erased; in the other port, the inverted signal generated by the XPolM would combine constructively with the XGM-generated signal, thus greatly enhancing the XGM-generated signal, resulting in a signal with high modulation depth.

The wavelength reuse scheme based on XPolM and XGM in an SOA can be directly employed in a RoF link for duplex communications. The SOA is placed at the CO to generate the downlink optical signal, which is transmitted through a length of single-mode fiber (SMF) to the RAU. At the RAU, the downlink signal is sent to a PBS. One port of the PBS outputs an intensity-modulated signal, which is used to provide the downlink services, while the other port provides an optical carrier with all the downstream information suppressed. This optical carrier is then remodulated by an uplink signal, and transmitted back to the CO for providing the upstream services. Because of the wavelength reuse based on the SOA, the RAU is simple and colorless.

Note that although, in Fig. 1, two laser sources are used in the CO, in a practical RoF system, the pump laser source can be shared by other transmitters connected to different RAUs. Adaptive polarization controlling should be required in the RAU if the transmission distance is large, which is currently complex but would possibly be simplified due to the fast development in the polarization devices for optical communications [12].

A proof-of-concept experiment is carried out. The probe and pump lights are generated by two tunable laser sources (Agilent N7714A). The wavelengths of the two lights are tuned at 1552.524 and 1550.000 nm with the powers at −2.02 and 4.02 dBm, respectively. A 5 GHz RF signal carrying a 50 MBaud 16 QAM (Agilent E8267D) data is used to modulate the pump light at MZM1 (Fujitsu FTM7921ER), which has a bandwidth of 10 GHz and a half-wave voltage of 4.0 V. The SOA (Kamelian SOA-NL-L1-C-FA) is biased at 186.71 mA. Due to the XPolM and XGM in the SOA, the probe signal undergoes both polarization modulation and intensity modulation. Figure 2 shows the electrical spectrum of the probe signal after optical to electrical conversion at a 20 GHz photodetector (PD) at the output of the transmitter, which is measured by a 43 GHz signal analyzer (Agilent N9030A). As can be seen, the 50 MBaud 16 QAM signal is modulated on the 5 GHz microwave carrier. This signal is transmitted to the RAU via a 2 km SMF. At one output port of the PBS (port 1), a clean optical carrier is generated, which is sent to MZM2 (Fujitsu FTM7937EZ, bandwidth 40 GHz and half-wave voltage 1.8 V), to which an uplink signal is applied. At the other output port of the PBS (port 2), an enhanced intensity-modulated signal is generated which is applied to PD1 to perform optical to electrical conversion. To avoid the reflections from the optical connectors, the uplink signal is transmitted to the CO via another 3 km SMF.

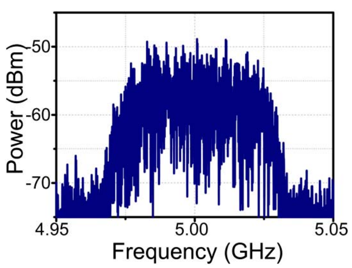

Fig. 2. Electrical spectrum of the downlink signal at the output of the transmitter.

Figures 3(a) and 3(b) show the electrical spectra measured at the two output ports of the PBS without fiber transmission. The optical powers at the two ports are 8.20 and 4.72 dBm, respectively. No signal is observed in Fig. 3(a), showing that the information in the downlink signal is effectively erased. On the other hand, a strong signal is presented in Fig. 3(b). As compared with the electrical spectrum obtained before the PBS shown in Fig. 2, the optical power is about 0.94 dB lower, but the electrical information is more than 10 dB stronger, indicating the significant signal enhancement by converting the polarization modulation in the downlink signal into the intensity modulation. Figures 3(c) and 3(d) show the case when 2 km SMF is inserted into the downlink. By carefully adjusting the PC placed before the PBS, the information in the downlink signal is largely suppressed. The small remaining signal in Fig. 3(c) is generated because of the dispersion of the SMF, which converts some polarization modulation into the intensity modulation. Then, another 5 GHz RF signal with 50 Mbaud, 16 QAM data is generated and used as an uplink signal, which is applied to MZM2 to modulate the clean optical carrier. Figure 3(e) shows the electrical spectrum of the modulated uplink signal. The uplink signal is transmitted through a 3 km SMF to the CO; the electrical spectrum at the output of the 3 km SMF is shown in Fig. 3(f). Although there is some power degradation due to the insertion loss of the optical fiber, the transmission does not change the shape of the spectrum. The extinction ratio is generally larger than 20 dB.

Figures 4(a) and 4(b) show the constellation diagrams of the received downlink signal without and with the

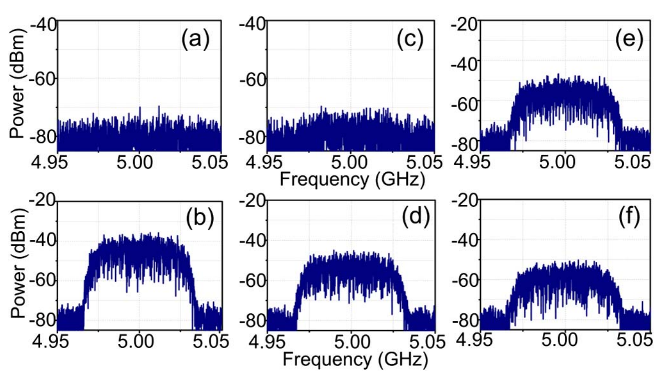

Fig. 3. Electrical spectra measured at the two output ports of the PBS, (a), (b) without fiber transmission, (c), (d) with 2 km SMF transmission, and the electrical spectra of the optical uplink signal (e) without and (f) with 3 km SMF transission.

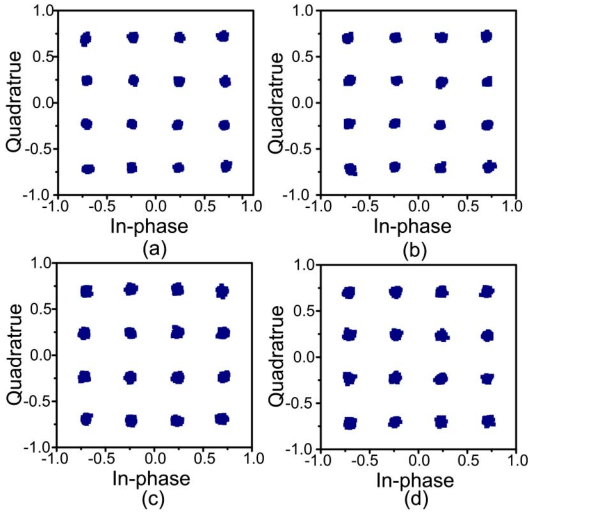

Fig. 4. Constellation diagrams of the downlink signal measured at the port 2 of the PBS (a) without and (b) with 2 km SMF transmission. The constellation diagrams of the uplink signal (c) at the output of MZM2 and (d) at the CO with 3 km SMF transmission.

2 km SMF transmission. The error vector magnitudes (EVMs) are 2.4058% and 2.5443%, respectively. The signal degradation induced by fiber transmission is very small. The constellation diagrams of the received uplink signal without and with the 3 km SMF transmission are shown in Figs. 4(c) and 4(d). The EVMs are 2.6836% and 2.8887%, respectively. The EVM degradation is only around 0.2%, showing again the high performance of the bidirectional RoF system. Because the downlink signal has a small EVM degradation after 2 km SMF transmission, and the wavelength-reused signal can tolerate 3 km SMF transmission, the distance between the CO and RAU can be more than 2 km.

It should be noted that the proposed RoF link is colorless and transparent to various wireless services because no wavelength-dependent devices are used in the system. Figure 5(a) shows the optical powers at the two outputs of the PBS as a function of the wavelength of the probe light. For the probe wavelength ranging over 30 nm, a clean optical carrier and an enhanced downlink signal are always obtained. The power variation is smaller than 2.5 dB. Figure 5(b) shows the case when the frequency of the RF signal is changed from 2 to 10 GHz. Again, a clean optical carrier and an enhanced downlink signal are generated. The power variation is less than 1 dB.

In conclusion, a novel wavelength reuse scheme in a bidirectional RoF link based on XPolM and XGM in an SOA was proposed and demonstrated. By using of centralized optical sources and an SOA in the CO,

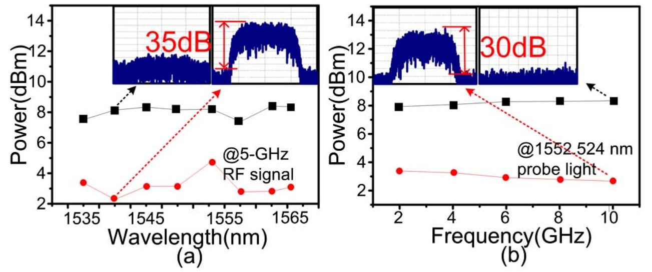

Fig. 5. Optical powers at the outputs of the PBS as a function of (a) the wavelength of the probe light and (b) the frequency of the RF signal.

symmetrical colorless RoF services were provided with no active optical devices in the RAU. The performance of the link in terms of EVM was experimentally evaluated. The results showed that, for both downlink and uplink transmission, degradation in EVM was as small as 0.2%, which confirmed the high transmission performance of the proposed system.

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References

1. J. Yao, J. Lightwave Technol. **27**, 314 (2009).
2. C. Lim, A. Nirmalathas, M. Bakaul, P. Gamage, and K. L. Lee, J. Lightwave Technol. **28**, 390 (2010).
3. E. Sackinger, *Broadband Circuits for Optical Fiber Communication* (Wiley, 2005).
4. C. W. Chow, L. Xu, C. H. Yeh, C. H. Wang, and F. Y. Shi, J. Lightwave Technol. **27**, 4773 (2009).
5. Z. Jia, J. Yu, G. Ellinas, and G. K. Chang, J. Lightwave Technol. **25**, 3452 (2007).
6. E. Conforti, C. M. Gallep, S. H. Ho, A. C. Bordonalli, and S. M. Kang, IEEE Trans. Microwave Theor. Tech. **50**, 77 (2002).
7. W. Lee, M. Y. Park, S. H. Cho, J. Lee, and C. Kim, IEEE Photon. Technol. Lett. **17**, 2460 (2005).
8. Y. Y. Won, H. C. Kwon, and S. K. Han, J. Lightwave Technol. **25**, 3472 (2007).
9. Y. Liu, M. Hill, E. Tangdiongga, H. De Waardt, and N. Calabretta, IEEE Photon. Technol. Lett. **15**, 90 (2003).
10. H. Soto, D. Erasme, and G. Guekos, IEEE Photon. Technol. Lett. **11**, 970 (1999).
11. R. Manning, A. Antonopoulos, R. Le Roux, and A. Kelly, Electron. Lett. **37**, 229 (2001).
12. X. S. Yao, X. J. Chen, and T. G. Liu, Opt. Express **18**, 6667 (2010).