Research Article
Vol. 24, No. 20 | 3 Oct 2016 | OPTICS EXPRESS 22573
Optics EXPRESS

Flexible and scalable wavelength multicast of coherent optical OFDM with tolerance against pump phase-noise using reconfigurable coherent multi-carrier pumping

GUO-WEI LU,[1,2,*] TIANWAI BO,[3] TAKAHIDE SAKAMOTO,[1] NAOKATSU YAMAMOTO,[1] AND CALVIN CHUN-KIT CHAN[3]

[1] *National Institute of Information and Communications Technology (NICT), Japan*
[2] *Institute of Innovative Science and Technology, Tokai University, Japan*
[3] *Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China*
[*] *gordon.guoweilu@gmail.com*

Abstract: Recently the ever-growing demand for dynamic and high-capacity services in optical networks has resulted in new challenges that require improved network agility and flexibility in order for network resources to become more "consumable" and dynamic, or elastic, in response to requests from higher network layers. Flexible and scalable wavelength conversion or multicast is one of the most important technologies needed for developing agility in the physical layer. This paper will investigate how, using a reconfigurable coherent multi-carrier as a pump, the multicast scalability and the flexibility in wavelength allocation of the converted signals can be effectively improved. Moreover, the coherence in the multiple carriers prevents the phase noise transformation from the local pump to the converted signals, which is imperative for the phase-noise-sensitive multi-level single- or multi-carrier modulated signal. To verify the feasibility of the proposed scheme, we experimentally demonstrate the wavelength multicast of coherent optical orthogonal frequency division multiplexing (CO-OFDM) signals using a reconfigurable coherent multi-carrier pump, showing flexibility in wavelength allocation, scalability in multicast, and tolerance against pump phase noise. Less than 0.5 dB and 1.8 dB power penalties at a bit-error rate (BER) of 10^{-3} are obtained for the converted CO-OFDM-quadrature phase-shift keying (QPSK) and CO-OFDM-16-ary quadrature amplitude modulation (16QAM) signals, respectively, even when using a distributed feedback laser (DFB) as a pump source. In contrast, with a free-running pumping scheme, the phase noise from DFB pumps severely deteriorates the CO-OFDM signals, resulting in a visible error-floor at a BER of 10^{-2} in the converted CO-OFDM-16QAM signals.

OCIS codes: (060.1660) Coherent communications; (130.7405) Wavelength conversion devices; (060.5060) Phase modulation; (060.1155) All-optical networks.

References and Links

1. N. Charbonneau and V. Vokkarane, "Static routing and wavelength assignment for multicast advance reservation in all-optical wavelength-routed WDM networks," IEEE/ACM Trans. Netw. **20**(1), 1–14 (2012).
2. X. Wang, I. Kim, Q. Zhang, P. Palacharla, and T. Ikeuchi, "Efficient all-optical wavelength converter placement and wavelength assignment in optical networks," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2016), paper W2A.52.
3. Y. B. M'Sallem, Q. T. Le, L. Bramerie, Q. Nguyen, E. Borgne, P. Besnard, A. Shen, F. Lelarge, S. LaRochelle, L. A. Rusch, and J. Simon, "Quantum-dash mode-locked laser as a source for 56-Gb/s DQPSK modulation in WDM multicast applications," IEEE Photonics Technol. Lett. **23**(7), 453–455 (2011).
4. P. Zhu, J. Li, Y. Chen, X. Chen, Z. Wu, D. Ge, Z. Chen, and Y. He, "Experimental demonstration of EON node supporting reconfigurable optical superchannel multicasting," Opt. Express **23**(16), 20495–20504 (2015).
5. G. Lu, T. Sakamoto, and T. Kawanishi, "Coherently-pumped FWM in HNLF for 16QAM wavelength conversion free of phase noise from pumps," in Proc. European Conference of Optical Communications (2014), paper P.1.16.

#270381 http://dx.doi.org/10.1364/OE.24.022573
Journal © 2016 Received 12 Jul 2016; revised 16 Aug 2016; accepted 16 Aug 2016; published 20 Sep 2016

6. G. Lu, T. Sakamoto, and T. Kawanishi, "Pump-phase-noise-tolerant wavelength multicasting for QAM signals using flexible coherent multi-carrier pump," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2015), paper M2E.2.
7. W. Shieh, "Maximum-likelihood phase and channel estimation for coherent optical OFDM," IEEE Photonics Technol. Lett. **20**(8), 605–607 (2008).
8. G. Colavolpe, T. Foggi, E. Forestieri, and M. Secondini, "Impact of phase noise and compensation techniques in coherent optical systems," J. Lightwave Technol. **29**(18), 2790–2800 (2011).
9. Z. Dong, J. Yu, H.-C. Chien, L. Chen, and G.-K. Chang, "Wavelength conversion for 1.2Tb/s optical OFDM superchannel based on four-wave mixing in HNLF with digital coherent detection," in Proc. European Conference of Optical Communications (2011), paper Th.11.LeSaleve.5.
10. G. Contestabile, Y. Yoshida, A. Maruta, and K. Kitayama, "Ultra-broad band, low power, highly efficient coherent wavelength conversion in quantum dot SOA," Opt. Express **20**(25), 27902–27907 (2012).
11. X. Wu, W.-R. Peng, V. Arbab, J. Wang, and A. Willner, "Tunable optical wavelength conversion of OFDM signal using a periodically-poled lithium niobate waveguide," Opt. Express **17**(11), 9177–9182 (2009).
12. C. Li, M. Luo, Z. He, H. Li, J. Xu, S. You, Q. Yang, and S. Yu, "Phase noise canceled polarization-insensitive all-optical wavelength conversion of 557-Gb/s PDM-OFDM signal using coherent dual-pump," J. Lightwave Technol. **33**(13), 2848–2854 (2015).
13. G. Lu, T. Bo, and C. Chan, "Pump-phase-noise-tolerant wavelength conversion for coherent optical OFDM using coherent DFB pumping," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2016), paper W3D.3.
14. X. Yi, W. Shieh, and Y. Tang, "Phase estimation for coherent optical OFDM," IEEE Photonics Technol. Lett. **19**(12), 919–921 (2007).
15. G. W. Lu, T. Sakamoto, and T. Kawanishi, "Wavelength conversion of optical 64QAM through FWM in HNLF and its performance optimization by constellation monitoring," Opt. Express **22**(1), 15–22 (2014).

1. Introduction

In next-generation scalable elastic optical networks and data center interconnect networks, it is crucial to realize flexible allocation and efficient utilization of the spectral resources [1]. However, in most of the deployed mesh optical networks, network utilization could only reach approximately 30%–40% [2], which is mainly because of severe wavelength contention among optical circuits competing for the continuous wavelength/spectrum slots along their paths, i.e., wavelength continuity constraints. Wavelength conversion or multicast, with flexible wavelength allocation and multicast scalability, is helpful to avoid wavelength contention, improve the utilization efficiency, and efficiently manage the network resources [3,4]. Moreover, with the deployment of advanced multi-level modulation formats in optical networks, it is highly desirable to avoid the introduction of extra phase noise from pumps to the converted signals when performing wavelength conversion or multicast. Recently, we proposed and experimentally demonstrated wavelength conversion [5] and multicast [6] with tolerance against pump-phase-noise for single-carrier multi-level modulation formats using the coherent pumping scheme. As another promising candidate to realize spectrum efficient transmission in future optical networks, coherent optical orthogonal frequency division multiplexing (CO-OFDM) exhibits more sensitivity to phase noise compared with single-carrier formats [7,8]. When performing wavelength conversion or multicast of CO-OFDM, narrow linewidth external-cavity lasers are usually deployed as pumps to avoid the extra phase noise from pumps [9–11]. However, this increases the implementation cost. Similarly, by applying the coherent pumping scheme, pump-phase-noise-tolerant wavelength conversion for multi-carrier CO-OFDM has also been experimentally demonstrated [12,13].

In this paper, previous work [13] will be extended to demonstrate a flexible and scalable wavelength multicast for CO-OFDM signals through four-wave mixing (FWM) in highly nonlinear fibers (HNLFs) using a reconfigurable coherent multi-carrier pump. It shows flexibility in wavelength allocation, scalability in multicast, and tolerance against pump phase noise. Moreover, benefiting from the phase-noise cancellation effect of coherent pumping, even a low-cost distributed feedback (DFB) laser can be used as a pump source without introducing extra phase noise in the converted signals. This effectively reduces the implementation cost and ensures superior performance in terms of phase noise tolerance. Here, flexible wavelength multicasts of CO-OFDM with subcarrier modulations of 16 quadrature amplitude modulation (16QAM) and quadrature phase-shift keying (QPSK) are experimentally demonstrated with tunabilities in channel spacing (25 GHz or 50 GHz) and multicast scale (1-to-3 or 1-to-7). Owing to the tolerance against pump phase noise, less than 0.5 dB and 1.8 dB power penalties are obtained for all of the converted CO-OFDM-QPSK and CO-OFDM-16QAM signals, respectively, in comparison with the input signals at a bit-error rate (BER) of 10^{-3}. In contrast, with free-running DFB pumps, the converted signals are significantly distorted due to severe phase noise from pumps. Especially for the converted CO-OFDM-16QAM signals with free-running pumps, an error floor at a BER of ~$1\mathrm{x}10^{-2}$ is observed. By using reconfigurable coherent multi-carrier pump, in addition to the flexibility and scalability in multicast [4], the proposed scheme exhibits high tolerance against phase noise from pump, especially suitable for OFDM with multi-level QAM like CO-OFDM-16QAM.

2. Operation principle

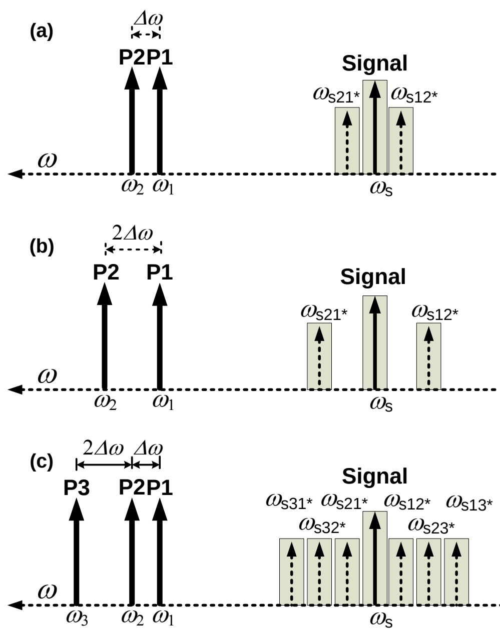

Fig. 1. Flexible and scalable wavelength multicast with tolerance against pump phase noise using a coherent multi-carrier pump.

Figure 1 shows the operation principle of the proposed flexible pump-phase-noise-tolerant wavelength multicast based on FWM in an HNLF. A reconfigurable multi-carrier pump is deployed as the pump in FWM for wavelength multicast. After FWM, the replicas are generated uniformly and symmetrically with respect to the input signal. As shown in Figs. 1(a) and 1(b), when a 2-carrier pump with pump spacing of $\Delta\omega$ and $2\Delta\omega$ is deployed, wavelength multicasts with a multicast scale of 1-to-3 and channel intervals of $\Delta\omega$ and $2\Delta\omega$ respectively, are achieved. Using a 3-carrier pump with non-uniform pump spacing, a 1-to-7 wavelength multicast with channel interval of $\Delta\omega$ is obtained, as shown in Fig. 1(c). By flexibly changing the number and interval of the pump carriers, replicas with different channel spacing and multicast scales can be obtained, which is essential for scalable elastic optical networks [4].

Importantly, multi-carrier CO-OFDM is sensitive to phase noise especially when subcarriers are modulated using multi-level QAM like 16QAM. The extra phase noise in multicast should be suppressed to avoid the performance deterioration of the converted signals. The generated spurious components alongside the input signal are non-degenerate

Optics EXPRESS

FWM products with frequencies of ω_{sij^*}, where i, $j \in$ [1–3], $i \neq j$ and * represents the conjugate operation. The corresponding phase could be expressed as:

$$\theta_{sij^*} = \theta_s \pm (\Delta\theta_i - \Delta\theta_j) + C \tag{1}$$

where θ_s, $\Delta\theta_i$, $\Delta\theta_j$ and C are the phase of input signal, the phase noise from pumps i and j, and a constant term, respectively. It is obvious that, if the pumps are coherent in phase, the phase noise from pumps could be cancelled out in the resultant phase of the converted signals. A coherent multi-carrier pump could be simply generated by an optical comb followed by a programmable optical processor (POP), which inherently ensures the phase coherence of the carriers. By using a coherent multi-carrier, the proposed multicast scheme for multi-level CO-OFDM features high pump-phase-noise tolerance, multicast scalability and flexibility in wavelength allocation. As discussed in [4] and [12], the parallel pump scheme inherently supports the wavelength multicast of polarization-division multiplexed signals. Here, limited by the available components in the laboratory, the proof-of-concept experiment is demonstrated for single-polarization OFDM signals.

3. Experiment and results

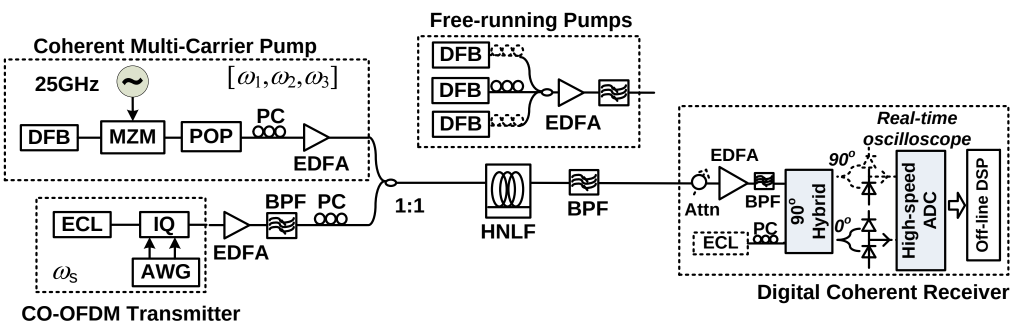

Fig. 2. Experimental setup of flexible and scalable wavelength multicast.

Figure 2 illustrates the experimental setup. CW light from an external cavity laser (ECL) at 1548.6 nm is modulated by an in-phase/quadrature (IQ) modulator, which is driven by signals from an arbitrary waveform generator (AWG). The generated CO-OFDM signal is constructed by 256 subcarriers, where 104 subcarriers are data-modulated and 8 pilot subcarriers are used for phase noise estimation [14]. Inverse fast Fourier transform (IFFT) with a size of 256 is used to convert the signal to the time domain. The cyclic prefix length is 8. With the AWG operated at 25 GSamples/s and subcarriers modulated in 16QAM and QPSK, the bit rates of the synthesized CO-OFDM-16QAM and CO-OFDM-QPSK are approximately 40 Gbps and 20 Gbps, respectively.

To generate the coherent multi-carrier pump, an optical comb with a carrier spacing of 25 GHz is firstly synthesized using a DFB laser at 1546 nm as the light source and a dual-drive Mach-Zehnder modulator (MZM) driven by 25 GHz RF clocks. After the MZM, an optical comb with around 10 lines and uniform power distribution is obtained. A POP based on liquid crystal on silicon (LCoS) technology is used to manipulate the configuration of the multi-carrier pump. As shown in Fig. 3, two carriers with a 25 GHz or 50 GHz interval, and three carriers with 25 GHz and 50 GHz intervals are obtained with >50 dB extinction ratio. After separate power amplifications, the pump and input CO-OFDM-16QAM signals are combined and fed to a piece of HNLF, which is 150 m long and has a nonlinear coefficient of 18 W/km, an attenuation coefficient of 0.9 dB/km, a zero-dispersion wavelength of 1548 nm, and a dispersion slope of 0.02 ps/nm^2/km. Note that, different from [13], a piece of HNLF with shorter length is deployed here, which is helpful to suppress the stimulated Brillouin scattering (SBS) effect, thus improving the system performance. The converted signals after multicast are filtered out and detected by a digital coherent receiver, which consists of a 100 kHz-linewidth ECL laser as the local oscillator, an optical 90-degree hybrid, and two balanced photo-detectors (PDs). After digitization by a digital storage oscilloscope at 50 GSamples/s, the data is processed off-line through digital signal processing, including carrier frequency estimation and synchronization, fast Fourier transform (FFT), channel estimation, phase noise estimation, constellation decision, and BER calculations. Approximately 1.5 million bits are used for BER calculation. For performance comparison, wavelength multicasts with free-running pumps are also conducted by using independent DFB lasers as pumps. The DFB lasers used in the experiment have a laser linewidth of ~3.5 MHz.

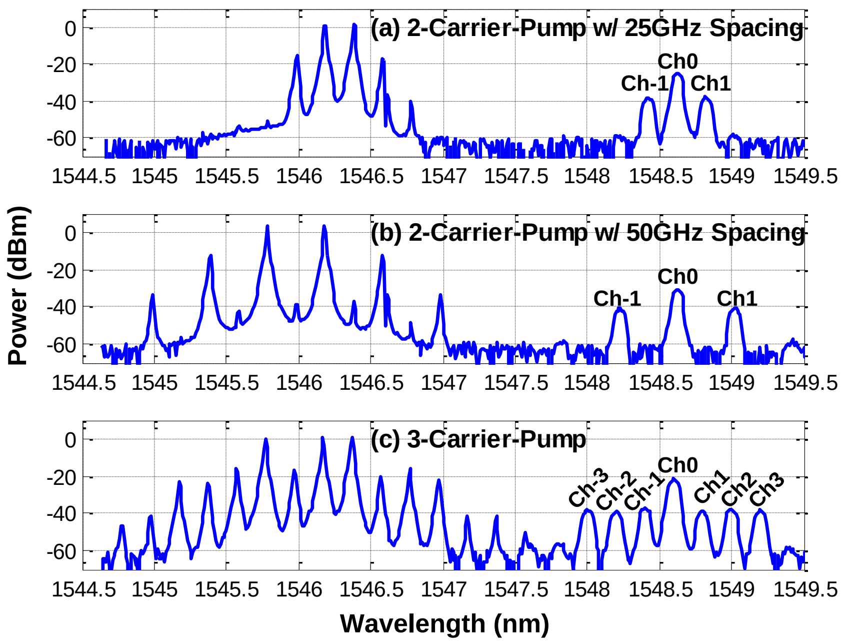

Fig. 3. Measured optical spectra after HNLF with (a) 2-carrier 25 GHz-spaced pump, (b) 2-carrier 50 GHz-spaced pump and (c) 3-carrier pump.

Figure 3 shows the measured optical spectra after HNLF with a coherent 2-carrier pump with 25 GHz/50 GHz spacing or a 3-carrier pump to achieve 1-to-3 or 1-to-7 multicast, respectively. The converted signals are denoted as "Ch *i*", where $i \in [0, \pm 1, \pm 2, \pm 3]$. The wavelength allocation and the multicast scale could be changed simply by tuning the carrier spacing and carrier number of the coherent pump using POP, respectively. It confirms the flexibility in wavelength allocation and the scalability in multicast of the proposed scheme. In the following sections, the performance of the converted CO-OFDM-QPSK and CO-OFDM-QPSK signals with multicast scales of 1-to-3 and 1-to-7 and channel intervals of 25 GHz and 50 GHz, respectively, are experimentally investigated.

Optics EXPRESS

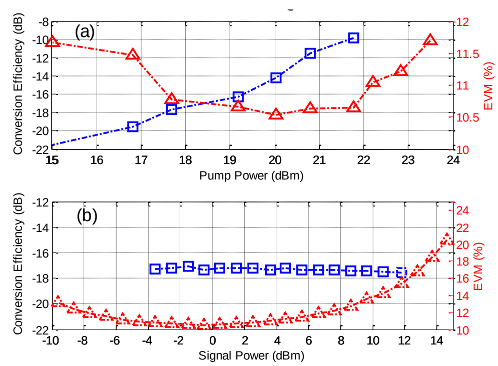

Fig. 4. Measured EVM and conversion efficiency when tuning pump and signal power launched to HNLF in the 1-to-7 multicast of CO-OFDM-QPSK: (a) signal power: −4.4dBm, pump power: 15~24dBm; (b) single power: −10~14.5dBm, pump power: 22.2dBm.

To achieve optimal performance, different from the previous work in [13], the operation condition of pump and signal power is optimized according to the measured error-vector magnitudes (EVMs) and the corresponding conversion efficiencies of the converted signals in the experiment. when the launched power of the pump and signal are adjusted. As an example, Fig. 4 shows the measured EVMs and conversion efficiencies of the converted CO-OFDM-QPSK signals at “Ch-1” in 1-to-7 multicast. The increase in the launched pump power improves the EVM of the converted signal up to ~22 dBm because of the improved conversion efficiency and OSNR, but further increase in the pump power results in the increase of EVM due to the distortion caused by the stimulated Brillouin scattering or cross-phase modulation from the pump [15]. On the other hand, the measured EVM reaches its minimum when the signal power is increased to 0 dBm owing to the improved OSNR, but further increase in the signal power causes self-phase modulation of the converted signal, which deteriorates the EVM of the signal [15]. Therefore, according to the measured EVMs, the optimal launched power of the pump and signal are obtained at 20 dBm and 0 dBm, respectively.

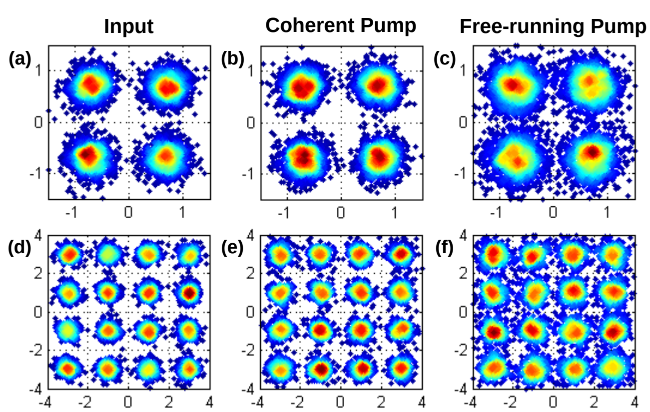

Fig. 5. Measured constellations of (a) (d) the input, and the converted signal (b) (e) with coherent pump and (c) (f) with free-running pump. (a)-(c): CO-OFDM-QPSK at OSNR = 7 dB, and (d)-(f): CO-OFDM-16QAM at OSNR = 16 dB.

To assess the pump phase noise tolerance of the proposed scheme, the constellations of the input and the converted CO-OFDM-16QAM (at OSNR = 16 dB) and CO-OFDM-QPSK (at OSNR = 7 dB) signals with different pumping schemes in 1-to-7 multicast are plotted in Fig. 5. Even using a DFB laser as the pump source, with a coherent 3-carrier pump, clear constellation (EVM = 31% for CO-OFDM-QPSK and EVM = 15% for CO-OFDM-16QAM) could be observed with a slight increase in EVM compared with those of input (EVM = 30% for CO-OFDM-QPSK, EVM = 14% for CO-OFDM-16QAM). On the other hand, with free-running DFB pumps, the severe phase noise introduced from pumps deteriorates the constellation with increased EVMs (EVM = 40% for CO-OFDM-QPSK, EVM = 18% for CO-OFDM-16QAM).

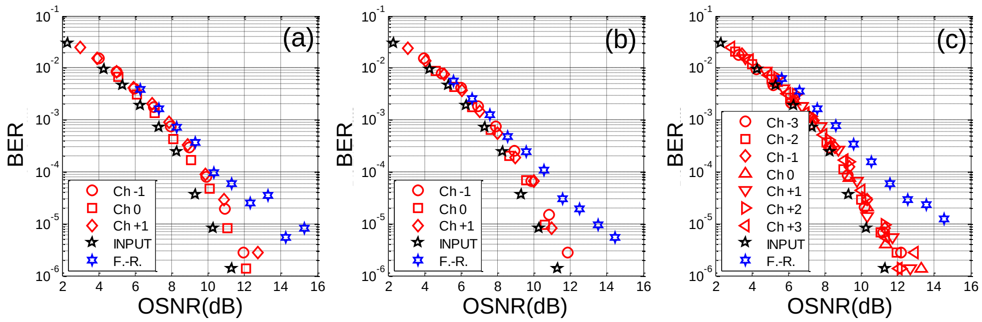

Fig. 6. Measured BER vs. OSNR of the input and converted CO-OFDM-QPSK signals with coherent pumping and free-running pumping in 1-to-3 multicast with (a) 25 GHz spacing and (b) 50 GHz spacing, and (c) 1-to-7 multicast.

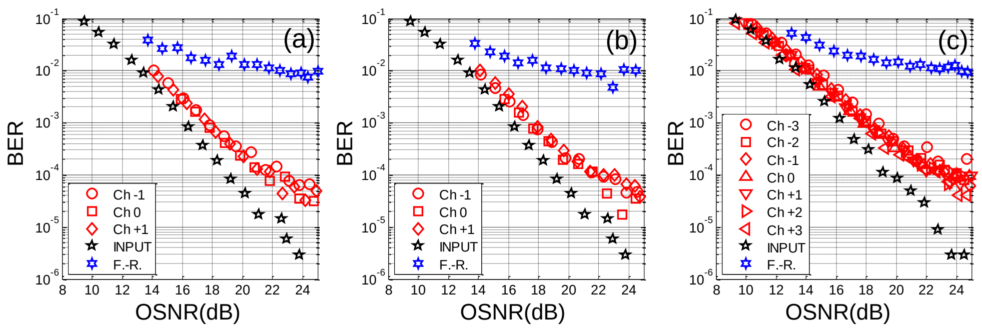

Fig. 7. Measured BER vs. OSNR of the input and converted CO-OFDM-16QAM signals with coherent pumping and free-running pumping in 1-to-3 multicast with (a) 25 GHz spacing and (b) 50 GHz spacing, and (c) 1-to-7 multicast.

To confirm the observation in constellations, BERs are also measured for the input and converted signals with different pumping schemes. The BER results for CO-OFDM-QPSK are shown in Fig. 6. By using coherent pumping with DFB as the pump source, with respect to the input signal, less than 0.5 dB power penalty is observed at a BER of 10^{-3} for all of the replicas either in a 1-to-3 multicast with 25 GHz or 50 GHz spacing, or in a 1-to-7 multicast. The low penalty is maintained at a BER of up to ~10^{-5}. However, with free-running DFB pumps, although a less than 1 dB power penalty is obtained at a BER of 10^{-3} as well, the penalty is increased to ~4 dB at a BER of 10^{-5}. It verifies the feasibility of the proposed scheme, and shows the advantage of the coherent pumping over free-running pumping. Moreover, the use of DFB as the pump source makes the scheme cost-effective. Figure 7 depicts the BER results of CO-OFDM-16QAM signals. As shown in Figs. 7(a)-7(c), a power penalty less than 1.8 dB is observed at a BER of 10^{-3} for the converted CO-OFDM-16QAM signals using coherent pumping with different multicast scales (1-to-3 or 1-to-7) and different wavelength allocations (25 GHz or 50 GHz spacing). On the other hand, error floors are observed at a BER of 10^{-2} for the converted CO-OFDM-16QAM signals when pumping using free-running DFB pumps. Since higher order multi-level subcarrier modulation becomes more sensitive to the phase noise, the proposed coherent pumping scheme is more

Optics EXPRESS

beneficial for the multicast of CO-OFDM-16QAM signals. This further verifies the feasibility and the advantage of the proposed scheme in terms of the phase-noise tolerance.

4. Conclusions

We have experimentally demonstrated a flexible and scalable wavelength multicast of CO-OFDM signals using a reconfigurable coherent multi-carrier pump. The re-configurability of the multi-carrier pump enabled by the programmable optical processor offers flexibility in wavelength allocation of the converted signals and scalability of multicast. Moreover, the phase coherence of the multi-carrier pump ensures the replicas are free of phase noise from pumps, and enables the deployment of low-cost DFB lasers as pump sources. The experimental results show less than 0.5 dB and 1.8 dB power penalties for all of the converted CO-OFDM-QPSK and CO-OFDM-16QAM signals, respectively, with different multicast scales and wavelength allocations.

Funding

JSPS Grant-in-Aid for Scientific Research (C) of Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan (15K06033).