Self-seeded 1-to-60 Multicasting in a Two-pump Parametric Mixer

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Abstract: We demonstrate a new multicasting scheme requiring only two CW tones to deliver spectrally-distinct copies of the input channel. 1-to-60 multicasting operation was achieved with 28 mW per-copy power efficiency and sensitivity penalty of 0.18 dB.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (060.4255) Networks, multicast

1. Introduction

The recent trends in broadband multimedia content broadcast over passive (PON) and short-reach optical networks have induced a significant interest in all-optical multicasting technologies. An ideal multicasting strategy should not increase complexity of the network architecture, induce minimal energy overhead, and more importantly, maintain the integrity to the multicast traffic, regardless of its modulation format. These requirements mandate that multicasting device is capable of delivering high copy count with minimal dissipation, while strictly preserving channel format and quality.

Previously, multicasting in the physical layer has been implemented passively with optical power splitter to deliver signal to multiple nodes. The signal quality is not preserved with such schemes due to the significant power loss induced by the power splitter elements. Worse, passive multicast is a *frequency-degenerate scheme* that cannot change the input wavelength, and is inherently incompatible with widely adopted wavelength-division multiplexed (WDM) PON systems. Consequently, all-optical WDM multicasting schemes have been actively investigated for their potential to deliver multiple, spectrally-distinct copies with insignificant penalty to the delivered channel. Previous demonstrations using various platforms [1-3] have shown low-penalty performance with high copy count. Most of these approaches are crippled by the requirement to use multiple lasers in the multicasting block, drastically increasing the cost, complexity and the dissipation of the network. Recognizing this limitation, an energy-efficient multicasting device can be constructed using a two-pump parametric mixer, which circumvents the need for multiple pumps via higher-order light generation [4].

In this paper, we demonstrate a new multicast architecture to generate a large number of spectrally-distinct channel copies in a self-seeded parametric device. High copy count is achieved by engineering of wide parametric bandwidth relying on high-order mixing enhancement in multisectional, dispersion-managed mixer. The device possessed physical bandwidth of 140 nm, allowing for highly efficient, 1-to-60 multicasting operation while consuming only 28 mW per channel copy. The measured performance, demonstrates, to the best of our knowledge, the record performance of WDM multicasting to date.

2. Self-seeded Multicasting by Extensive Higher-order FWM

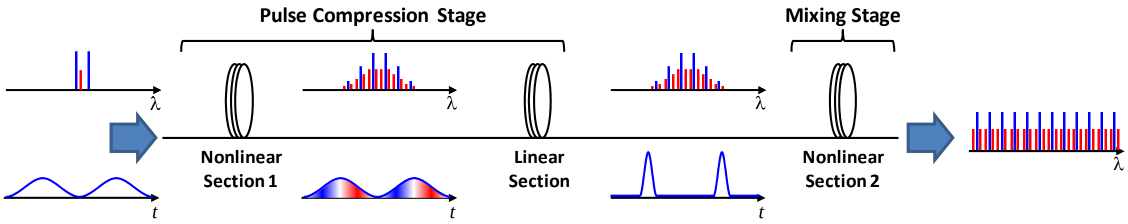

Fig. 1. Principle of higher-order mixing based multicasting. Upper and lower row correspond to spectral and temporal evolution of the optical field along the mixer.

The proposed multicasting device comprises two functional stages, as illustrated in Fig. 1. In the pulse compression stage, two intense pump waves mix in a nonlinear fiber section and generate new tones through four-photon mixing (FPM) process. Temporally, this process is equivalent to nonlinear frequency chirping of the beat pattern formed by the two pump waves due to self-phase modulation (SPM) of the optical field. When the chirped optical field propagates in the second fiber section possessing a positive chromatic dispersion and negligible nonlinearity, the frequency chirp translate into a linear temporal compression of the beat pattern and thereby generates intense pulses

[5]. The formation of intense pulses subsequently leads to extensive spectral spanning in the mixing stage comprising a nonlinear fiber with low dispersion [6]. Since the repetition rate of the pulses equals to the frequency difference between the two pump lasers, spectral broadening of pulses in the second stage is then equivalent to generation of higher-order light in equidistant frequency spacing. In the presence of a weak signal positioned in spectral proximity to the original pumps, the pump-signal mixing processes are duplicated by each higher-order pumps. Consequently, the signal is multicast to spectrally-distinct copies, with the number of copies equal to twice the number of higher-order pumps generated.

3. Experiment

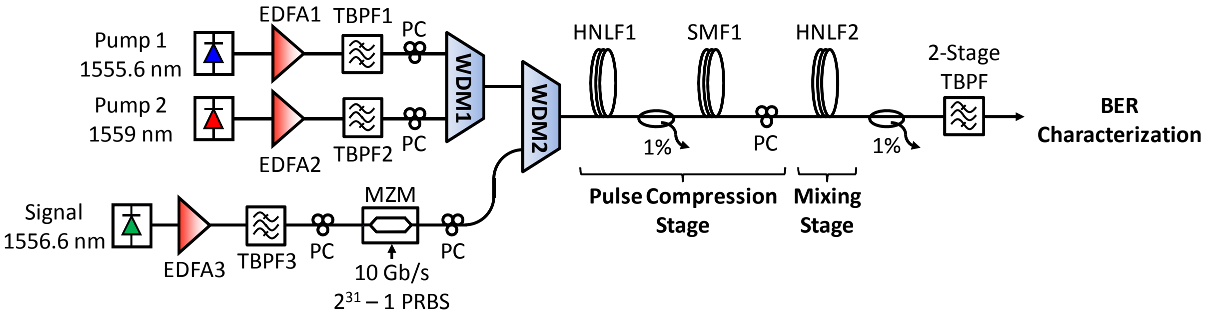

Fig. 2. Experimental setup for self-seeded multicasting.

The self-seeded multicasting mixer is based on a two-pump architecture, as shown in Fig. 2. Output waves from two external cavity lasers emitting at 1555.6 and 1559 nm are amplified and filtered to generate pump waves with optical signal-to-noise ratio (OSNR) exceeding 60 dB. The pump powers after WDM couplers (WDM1 & 2) are 29.6 and 29 dBm for the blue and red pumps respectively. After combining the pump and the signal at 1556.6 nm, all waves are launched into a three-section fiber span for higher-order light generation and multicasting. The first section (HNLF1) is a 100-m highly-nonlinear fiber (HNLF) for initial mixing of the pump and signal waves. The fiber is characterized to have a zero-dispersion wavelength (ZDW) of 1552 nm, dispersion slope of 0.028 ps/nm^2/km and nonlinear coefficient of 12 W^{-1}km^{-1}. Differential straining along the fiber is applied to raise the stimulated Brillouin scattering threshold beyond 30 dBm [7], thus eliminate the need for pump phase dithering. Immediately after acquiring nonlinear chirp, the output field from the first section undergoes a linear temporal compression in a section of standard single-mode fiber (SSMF). The total length of SSMF, including pigtails of all components and the fiber spool (SMF1), is 7 m. Extensive higher-order mixing then takes place in the subsequent HNLF section (HNLF2). The 200-m dispersion flattened HNLF used in this section is characterized to possess low dispersion (< 1 ps/nm/km) over 1500 – 1650 nm band. Maximal multicasting efficiency is attained by aligning the polarizations of pumps and signal through in-path polarization controllers (PC). The multicast copies are selected by a two-stage tunable band-pass filters (TBPF) with 0.25 nm bandwidth, and characterized by bit-error rate (BER) measurement.

4. Results and Discussions

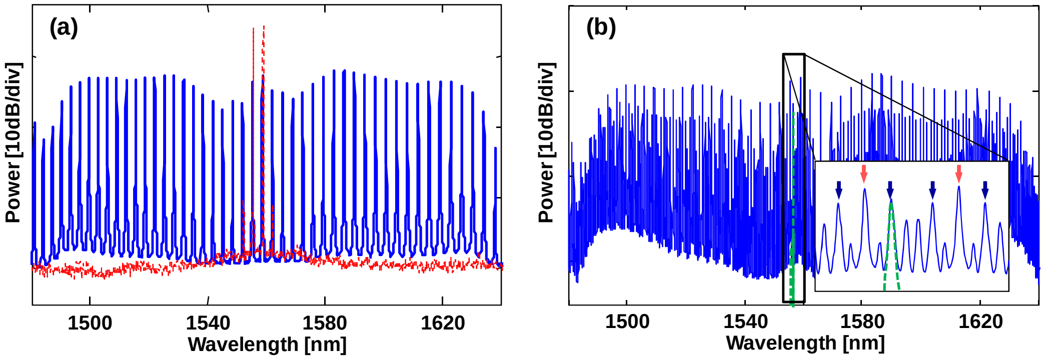

Fig. 3. Mixer output spectra (a) with pumps only, and (b) with pumps and signal. Inset in (b) shows a zoom-in view of the spectrum in 1554 – 1561 nm, with pumps and multicast copies indicated by red and blue arrows respectively. Input pump and signal are indicated by red and green dashed lines in (a) and (b) respectively.

The spectral response of the multicast mixer is shown in Fig. 3(a). Seeded by only two CW pumps, an efficient higher order mixing resulted in generation of a flat frequency comb covering a spectral span of 140 nm with less than 10-dB power ripple. *The measurement represents the widest continuous-wave optical frequency comb generated to date, to the best of our knowledge*. The optical signal-to-noise ratio (OSNR) exceeded 40 dB for all generated tones within the 140 nm band. The wide bandwidth and noise-preserving mixing process thus enabled high copy count self-seeded multicasting. The input signal was then multicast through generation of sidebands around each newly generated (high-order) pump tone. To demonstrate the fidelity of the scheme, a 10 Gb/s on-off keying (OOK) signal carrying $2^{31} - 1$ pseudo-random binary sequence (PRBS) was inserted into the multicaster. The mixer output spectrum with an input signal power of 10 dBm is shown in Fig. 3(b). Close-up examination of the spectrum reveals the fine structure of the parametric generation with multiple tones, with each pump spawning two frequency sidebands. At this 10dBm input signal power level, generation of spurious FWM products (crosstalk) was evident. However, this crosstalk is easily avoided *for any input power level* by selecting the wavelengths of the seeding pump tones so that the spurious tones do not overlap with newly generated channel copies. This property represents a fundamental advantage over the multiple seed schemes [3], in which FWM crosstalk cannot be circumvented even at moderate signal powers.

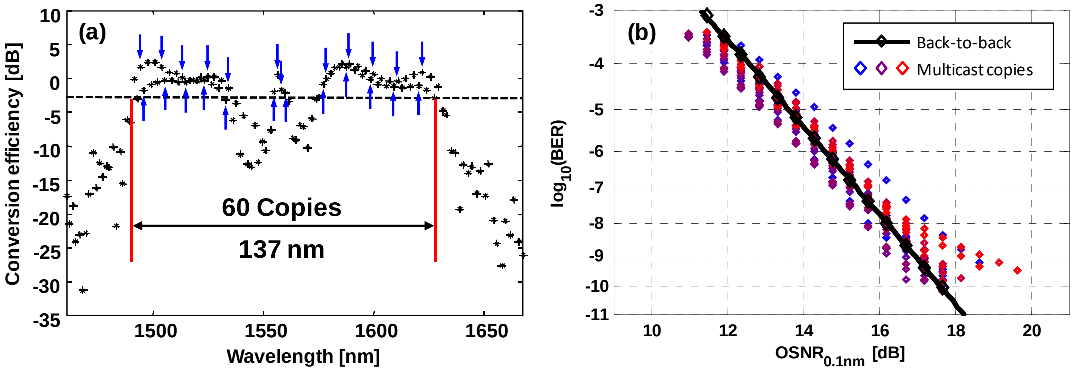

Fig. 4. (a) Measured conversion gain of the multicast copies; (b) BER curves of the input signal and selected multicast copies. Spectral positions of selected copies with BER performance shown are marked by arrows in (a).

The multicast efficiency, measured with respect to the power of the input channel is plotted in Fig. 4(a). 60 copies with conversion efficiency exceeding -3 dB were obtained, with net-gain observed at most of the newly generated frequencies. Finally, the quality of all outputs was characterized using input noise-loading method [8], where BER was measured against the OSNR of the input signal. To preserve the figure clarity, BER of 24 copies covering the entire mixer bandwidth, as indicated in Fig. 4(a), are plotted in Fig. 4(b). The receiver sensitivity, defined as the minimum input OSNR necessitated to reach BER of 10^{-9}, was degraded by only 0.18 dB on average for all measured copies as compared to the input signal. The sensitivity penalty of the worst copy was 1.68 dB, whereas an improvement by as much as 0.67 dB is observable with the best created channel copy. The sensitivity improvement can be accounted by mark-level noise reduction due to gain saturation effect in the parametric mixer [9]. In general, the sensitivity degrades as the spectral position of the copy progressed farther away from the input signal due to a gradual reduction in the OSNR of pumps of the higher order. The higher-order pump OSNR fading can be reduced by using a lower-noise gain block design, thereby eliminating the sensitivity degradation.

5. Conclusion

We reported a new WDM multicast architecture and experimental demonstration of the scheme based on high-efficiency higher-order generation in a two-pump fiber parametric mixer. The result was achieved by precise dispersion management of multisegmented mixer capable of wide-band parametric generation of higher-order pump tones. The multicast scheme enabled 1-to-60 multicasting operation with negligible signal degradation for the first time. Operated at a power efficiency of 28 mW per generated channel copy, the reported scheme also represents a new class of energy-efficient multicasting devices.

6. Acknowledgment

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7. References

[1] J. Pleumeekers et al., in Proc. OFC 2002, pp. 596 – 597.
[2] B. Zsigri et al., Photon. Technol. Lett. **18**, 2290 (2006).
[3] C.-S. Brès et al., J. Lightwave Technol. **27**, 356 (2009).
[4] C.-S. Brès et al., Photon. Technol. Lett. **21**, 1002 (2009).
[5] T. Inoue et al., J. Lightwave Technol. **24**, 2510 (2006).
[6] F. Parmigiani et al., Opt. Express **14**, 7617 (2006).
[7] A. Wada et al., IEICE Trans. Commun. **E76-B**, 345 (1993).
[8] N. Alic et al., Opt. Express **15**, 8997 (2007).
[9] K. Inoue et al., J. Lightwave Technol. **20**, 969 (2002).