C+L-band Transmission Using Hybrid Lumped Repeater with High-gain PPLN-based Optical Phase Conjugators and EDFAs

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Abstract *We propose a C+L-band lumped repeater with over-15-dB-gain PPLN-based optical phase conjugators and EDFAs to mitigate gain saturation in parametric amplification. The proposed repeater achieves ~7-dB NF and uniformizes the SNR variation of 84-channel 640-Gbps signals within 1 dB after 1120-km G.652.D fibre transmission.*

Introduction

Multiband wavelength-division multiplexing (WDM) transmission using C- and L-bands can improve optical fibre throughput [1–3]. Optical power transition through stimulated Raman scattering (SRS) from the shorter band to the longer band is one of the main challenges in the design of multiband systems. Spectrum pre-emphasis has often been used to achieve uniform linear noise performance over multiband, but nonlinear signal distortion caused by optical Kerr effect in the emphasized short-wavelength channels restricts the total fibre-launched power. Numerical optimization techniques for the launched channel powers considering the fibre nonlinearities have thus been studied [4].

The optical parametric amplifier (OPA) has attracted attention because of its wide-gain bandwidth [5–8]. When amplifying a signal, the OPA generates phase-conjugated light (idler light) with an inverted spectrum at a band symmetric to the centre wavelength of the gain band λ_c. Utilizing the idler light, an OPA can function as an optical phase conjugator (OPC) and a wavelength converter [9–13]. The optical phase conjugation is performed at optical repeater sections to mitigate fibre nonlinearities and chromatic dispersion (CD). In addition, wideband spectral inversion can mitigate the differences in the transmission performance between the bands—for example, those induced by the SRS [14,15]. OPC typically requires a reserve band for idler light, but a complementary spectrally inversed (CSI) configuration using two OPCs in parallel has been proposed [9–11]. Another challenge is that an OPC with low-conversion efficiency causes excessive linear noise. A phase-conjugation system without the linear noise penalty was demonstrated by combining a loss-less CSI-OPC using high-efficiency periodically poled $LiNbO_3$ (PPLN) waveguides with distributed Raman amplification in the C-band [16]. Recently, we developed a PPLN-based OPA capable of amplifying a wideband signal with high gain and demonstrated WDM transmission over 14 THz [17]. In the high-gain region of the OPA, idler light is generated at the same optical power as the signal light [8], so the wideband OPC with a higher-conversion gain can also be achieved. However, a challenge in both the OPA and OPC is the gain saturation, which causes nonlinear signal distortion and restricts the output power [18].

In this paper, we propose a C+L-band hybrid optical lumped repeater cascaded PPLN-based CSI-OPC and erbium-doped fibre amplifiers (EDFAs). The conversion gain of the PPLN-based OPC is utilized as a part of the repeater gain, and thus, the linear noise penalty can be suppressed. The low noise figure (NF) of the PPLN-based OPA regardless of wavelength [19] and the effect of the OPC on averaging the impact of SRS are what enable the uniform transmission performance over C+L-band to be achieved. Moreover, by using EDFAs as post-amplifiers, a high-output power can be obtained without excess distortion. We apply the proposed repeater with over-15-dB-gain PPLN-based CSI-OPC to C+L-band transmission in an 80-km-span G.652.D single-mode fibre (SMF) link and confirm the uniform transmission performance in the 84-channel 640-Gbps WDM signal after 1120-km transmission.

Proposed repeater configuration

Figure 1 shows our proposed repeater using the PPLN-based CSI-OPC which consists of polarization-diverse OPAs [7] and EDFAs. The WDM signal is divided into C- and L-bands with a WDM coupler and then input to the OPCs. In addition to converting the input signal to phase-conjugated light, the high-gain OPC also serves as a pre-amplifier in the repeater. The λ_c in the OPCs is allocated at the border between the C- and L-bands, and the idler light is generated in the other band (i.e., not the input band) by means

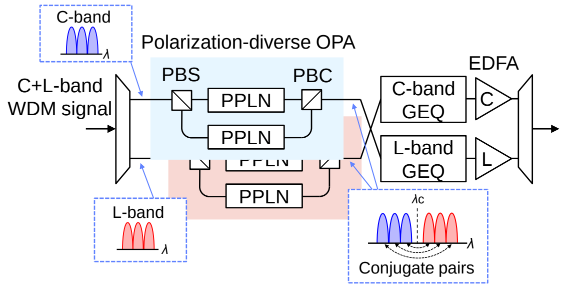

Fig. 1: Proposed repeater configuration.

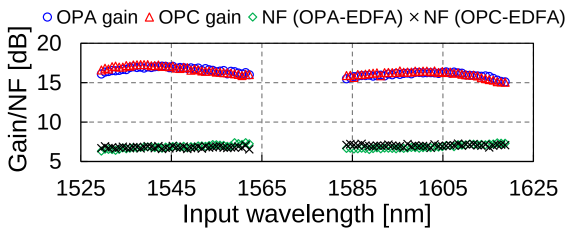

Fig. 2: Amplification and conversion gain spectrum of PPLN-based OPA and total NF of proposed repeater.

of spectral inversion. The output of the OPCs consists of both original and phase-conjugated components. The gain equalizers (GEQs) extract only the phase-conjugated light while equalizing the spectra. The phase-conjugated signals are amplified with C- or L-band EDFA as a post-amplifier. Our PPLN-based OPA and OPC provide a flat NF spectrum around 5 dB even in the L-band and other bands [19]. The NF of the optical repeater strongly depends on that of the pre-amplifier, and thus, the high-gain OPC provides a flat linear noise performance over the C- and L-bands. We measured the conversion gain of the OPC and the total NF of the proposed repeater. The λ_c in our PPLN waveguides was 1572.9 nm (190.6 THz) [19]. The post-EDFA for the L-band was the phosphorus-co-doped EDFA [20]. Input probe light containing 50-GHz-bandwidth frequency bins with 100-GHz spacing was generated using amplified spontaneous emission (ASE) and a wavelength-selective switch (WSS). The input power was 2 dBm and a programmable GEQ with the ~6-dB insertion loss was implemented so that the output spectrum was flattened. We also measured a case where OPA was not operating as OPC (OPA-EDFA case). Figure 2 shows the measurement results, where we can see that a >15-dB conversion gain and the flat repeater NF of 6.3–7.4 dB were obtained within 1529.1–1619.6 nm regardless of C- or L-band. There was no difference in total NF between the OPA-EDFA and OPC-EDFA cases, indicating that there is no linear noise penalty from the application of OPC.

Experimental setup for WDM transmission

We conducted WDM transmission using the proposed repeater with the experimental setup

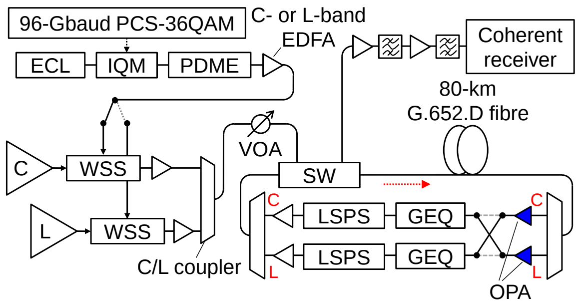

Fig. 3: Experimental setup. ECL: external cavity laser, IQM: I/Q modulator, PDME: polarization-division-multiplexing emulator, VOA: variable optical attenuator, SW: switch.

shown in Fig. 3. The channel under test (CUT) was modulated with 96-Gbaud probabilistically constellation shaped (PCS-) 36QAM [7]. Its entropy after polarization-division multiplexing was 8.87 bits. Interference WDM signal with 100-GHz spacing was emulated using ASE from C- and L-band EDFAs. The bandwidth of the WDM signal was up to 4.2 THz (42 ch.) per band (1529.16–1562.64 nm and 1583.69–1619.62 nm). The interference channels were spectrally shaped and combined with the CUT using a WSS. The transmission line was an 80-km G.652.D SMF. In the proposed repeater, loop-synchronous polarization scramblers (LSPSs) were implemented, and thus, the repeater NF was slightly degraded compared to the measured values in the previous section. The OPA-EDFA and OPC-EDFA cases can be changed by swapping the paths from the OPAs to the GEQs. The CUT was demodulated by offline digital signal processing (DSP) based on an 8 × 2 adaptive equalizer with periodically inserted pilot symbols [21]. A normalized generalized mutual information (NGMI) and signal-to-noise ratio (SNR) were calculated from the demodulated signal. The net data rate of the signal was 640 Gbps/ch. with an NGMI threshold of 0.857 assuming a 1.64% pilot rate according to Ref. [7].

Transmission results

First, we compared the proposed repeater with the OPA-cascaded configuration in terms of power tolerance including the gain saturation of the OPA. The tested signal was an only-C-band 42-channel WDM signal, and the CUT was the centre channel at 1545.3 nm. The OPA was not operated as an OPC, but just as a pre-amplifier. Figure 4(a) shows the fibre-launched power characteristics of the SNR after 1120-km transmission. As the input power increased, the signal was degraded due to not only fibre nonlinearities but also the gain saturation in the OPA. This was particularly evident in the OPA-OPA case, where the high-power signal input to the post-OPA resulted in a degraded power

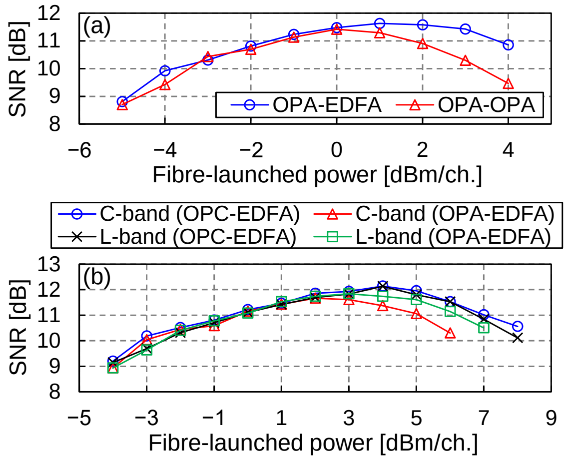

Fig. 4: SNR after 1120 km transmission as function of fibre-launched power. (a) 42-ch. only C-band transmission. (b) 14-ch. C+L-band configuration.

tolerance. In contrast, in the proposed configuration (OPA-EDFA), since the high-output power was provided by the post-EDFA, the power tolerance was improved by ~1.5 dB. Next, we tested the C+L-band transmission of seven channels per band (1542.5–1548.1 nm and 1598.4–1604.4 nm) to verify the mitigation effect of the proposed repeater for the fibre nonlinearity. The power tolerance was compared between using the OPA as an OPC and just as a pre-amplifier. Figure 4(b) shows the SNR after 1120-km transmission at the centre channels in the C- and L-bands. In the OPC-EDFA case, the power tolerance was improved by ~2 dB compared to the OPA-EDFA case, which indicates that the adjustable range of the channel power in the pre-emphasis can be extended. The SNR was also improved by ~0.5 dB for the C-band signal and by ~0.3 dB for the L-band signal. There was no linear noise penalty due to the OPC since the SNRs were matched in the low-power region.

Finally, we conducted 84-channel C+L-band WDM transmission. Figure 5 shows the spectrum of the WDM signal at the input and output of the transmission fibre. We pre-emphasized the optical spectrum of the WDM signal so that the fibre-output spectrum was flattened over the C- and L-bands considering SRS. The total fibre-launched power was restricted to 21.5 dBm in this setup. Figure 6 shows the transmission distance dependence of the NGMI for representative channels allocated at both ends and in the centre of each band. In the OPA-EDFA case, ch. 1 was affected by fibre nonlinearities due to high-input power with pre-emphasis. In the OPC-EDFA case, all channels showed almost the same characteristics. The achievable transmission distance of ch. 1 was improved by about 1.5 times by averaging out the performance with ch. 84. In addition, the CD was mitigated by the OPC

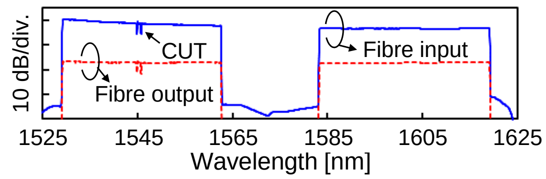

Fig. 5: Optical spectra of 84-ch. WDM signal at input and output of transmission fibre (0.1-nm resolution).

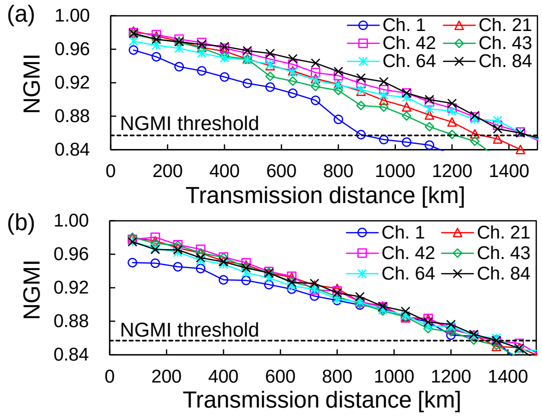

Fig. 6: Transmission distance characteristics of NGMI for ch. 1 (1529.5 nm), ch. 21 (1545.3 nm), ch. 42 (1562.2 nm), ch. 43 (1583.7 nm), 1601.4 nm), and ch. 84 (1618.7 nm). (a) in OPA-EDFA case. (b) in OPC-EDFA case.

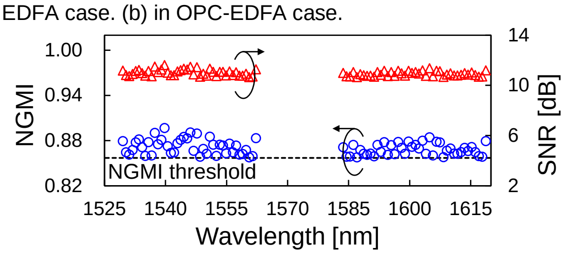

Fig. 7: NGMI of all 84 channels after 1120 km transmission.

from ~24600 ps/nm to ~4120 ps/nm after 1120-km transmission for ch. 84 (the longest wavelength channel). Nonlinear mitigation effects could not be clearly identified due to the low-channel power in the full-WDM configuration. Figure 7 shows the measurement result of all 84 channels after 1120-km transmission. As we can see, NGMIs of all channels were better than the threshold, and 53.76-Tbps transmission was successfully demonstrated. The SNRs were uniform within 1 dB thanks to the flat NF spectrum and equalization effect of the transmission performance between the C- and L-bands.

Conclusion

We proposed a C+L-band lumped repeater with high-gain wideband PPLN-based CSI-OPC and EDFAs. By mitigating fibre nonlinearities and gain saturation in the OPA, the improvement in power tolerance was shown. We also demonstrated C+L-band WDM transmission over 1120 km with a uniform transmission performance within 1-dB SNR variation over 8.4 THz by averaging the effect of SRS.

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