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8.375-THz Optical Amplification for Wideband WDM Transmission by Optical Parametric Amplifier Using Cascaded PPLN Modules with Complementary Gain Profiles

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Abstract *We propose a configuration of an optical parametric amplifier using cascaded PPLN modules with different phase-matching characteristics for pump-power-efficient bandwidth extension. We demonstrate 8.375-THz (1548.81–1618.86 nm) inline optical amplification with >15-dB gain using the proposed configuration under a 125-GHz-spaced 67-channel 800-Gbps/λ WDM transmission condition.*

Introduction

Wideband wavelength-division multiplexing (WDM) transmission is a key technology to improve optical fibre throughput. Deployed WDM optical transport networks have typically utilised erbium-doped fibre amplifiers (EDFAs). However, the amplification bandwidth of EDFAs is usually 4 THz in C- or L-bands, and expanding optical amplification bandwidth is an important research topic [1–4]. An optical parametric amplifier (OPA) utilising nonlinear optical effects has attracted research attention due to its wide amplification bandwidth and can amplify various wavelength bands [5–8]. A periodically poled $LiNbO_3$ (PPLN) waveguide as an optical parametric amplification medium has high amplification efficiency without excess unwanted nonlinear effects. Therefore, a PPLN-based OPA is useful for simultaneous amplification of a wideband WDM signal. A 5.125-THz inline-amplified transmission over 3×30 km with a 41-channel 800-Gbps/λ WDM signal using the PPLN-based OPA was demonstrated [9]. In addition, by combining the OPA with forward-pumped distributed Raman amplification, a 6.25-THz inline-amplified transmission over 3×80 km with a 50-channel 1-Tbps/λ WDM signal was demonstrated [10].

In this paper, we propose a configuration of optical parametric amplification using cascaded PPLN modules for extending amplification bandwidth of the OPA without additional pump power. Each PPLN module has different quasi-phase-matching (QPM) condition by waveguide temperature control and amplifies a wideband WDM signal complementarily. Because cascaded PPLN modules share pump light, the amplification bandwidth can be extended with high pump-power efficiency. We show an 8.375-THz effective gain bandwidth with a >15-dB gain and demonstrate the wideband inline amplification of a 125-GHz-grid 67-channel 800-Gbps/λ signal under a 2×30-km WDM transmission condition.

Proposed OPA using cascaded 4-port PPLN modules with complementary gain profiles

The 4-port PPLN module has low-loss integrated pump (de-)combiners using dichroic filters (DFs), and its I/O interfaces are four polarisation maintaining fibre pigtails [11]. Because optical parametric amplification with a PPLN waveguide has polarisation sensitivity, a polarisation-diverse configuration is used in which orthogonal polarisation components of the input signal are amplified separately [5]. Each pump light at a centre wavelength of QPM band, λ_0, is amplified by EDFAs and is converted to second harmonic (SH) light by second-harmonic generation (SHG) with PPLN waveguides. By using different media for SHG and OPA, unwanted nonlinear effects can be suppressed [12]. The SH pump is combined with the signal light and then de-combined after amplification using DFs. The gain bandwidth of a PPLN waveguide depends on its QPM condition, which can be controlled by the waveguide temperature [13,14]. With an optimal temperature for a band around λ_0, a flat gain spectrum is observed around λ_0. By detuning the waveguide temperature, the outside gain increases while the gain around λ_0 decreases, and an effective gain bandwidth can be extended. Wideband inline optical parametric amplification over 5 THz was demonstrated with the temperature detuning [9,10]. However, an

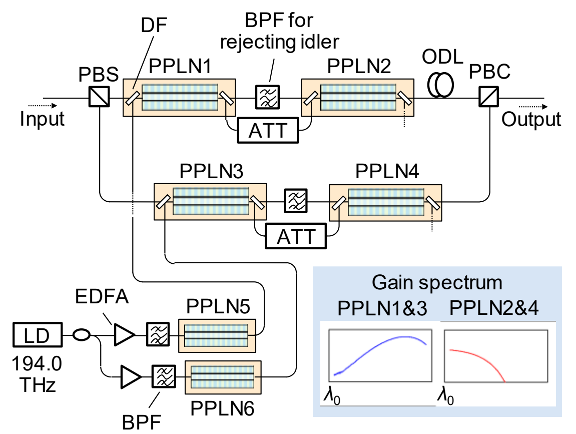

Fig. 1: Configuration of proposed OPA using cascaded 4-port PPLN modules. PBS (PBC): polarization-beam splitter (combiner), DF: dichroic filter, BPF: band-pass filter, ATT: attenuator, ODL: optical delay line.

extension of the effective gain bandwidth is limited by a gain decrease around λ_0.

In our proposed scheme as shown in Fig. 1, two 4-port PPLN modules are cascaded in one polarisation-diverse arm. The second PPLN modules (PPLN2&4) amplify the small gain band of the first PPLN modules (PPLN1&3) around λ_0. By this complementary amplification, further temperature detuning of the first modules becomes available, and an extension of the effective gain bandwidth is achieved. The gain of the second PPLN module is set to a narrow bandwidth around λ_0 by detuning the waveguide temperature opposite to that of the first PPLN module. The signal amplified by the first PPLN module is passed through a band-pass filter (BPF) to reject idler light and then is re-combined with the SH pump light in the second module. The de-combined pump light in the first PPLN module is input to the second PPLN module, resulting in an extended the effective gain bandwidth without increasing power consumption. By narrowing the QPM bandwidth of the second modules, reuse of the pump light is acceptable with little effect of gain saturation because the pump light is not consumed for outside-band components.

When the OPA amplifies the entire band of a WDM signal with a large gain, the wavelength dependence of the noise figure (NF) is negligible [5,11]. However, in the proposed configuration, that dependence becomes apparent because the first PPLN module has a large gain gradient. Assuming that the NF spectrum of the conventional OPA is the reference, the NF penalty in the proposed OPA is expressed as

$$\Delta\alpha(f) \approx 1 + \frac{1}{\alpha_{\mathrm{ref}}(f)}\left(\frac{1}{G_{\mathrm{1st}}(f)} - \frac{1}{G_{\mathrm{ref}}(f)}\right) + \frac{\alpha_{\mathrm{2nd}}(f)}{\alpha_{\mathrm{ref}}(f)\cdot l_{\mathrm{filter}}(f)\cdot G_{\mathrm{1st}}(f)}, \qquad (1)$$

where $l_{\mathrm{filter}}(f)$ is the loss spectrum of the idler filter, $\alpha_{\mathrm{ref}}(f)$ is the reference NF, $G_{\mathrm{1st}}(f)$ and $G_{\mathrm{ref}}(f)$ are the gain spectra of the first PPLN module in the proposed OPA and conventional OPA, respectively, and $\alpha_{\mathrm{2nd}}(f)$ is the NF of the second PPLN module in the proposed OPA.

Figure 2 compares the gain and NF spectra of the conventional PPLN-based OPA and proposed OPA. The gain and NF spectra were measured by sweeping CW light at −15-dBm input. The λ_0 of PPLN waveguides was 1545.32 nm (= 194.0 THz). The loss of the BPF for idler rejection was <1 dB. The power of the SH pump was ~1.6 W. In the conventional OPA, the waveguide temperature was detuned so that the 15-dB gain bandwidth was the widest, and a ~7.8-THz effective gain bandwidth from λ_0 was achieved. In the proposed OPA, the first modules (PPLN1&3) were detuned to increase the outside gain while the gain around λ_0 was decreased by ~10 dB. The second modules (PPLN2&4) consisted of low-loss PPLN waveguides fabricated with mechanical sculpturing [15] to suppress gain reduction in the outside-band components and had a gain only in the band around λ_0. Thus, a ~8.7-THz effective gain bandwidth with a >15-dB gain was achieved. The input power of the SH pump to the second module was ~0.6 W. The maximum NF penalty was 1.4 dB, and was in good agreement with the

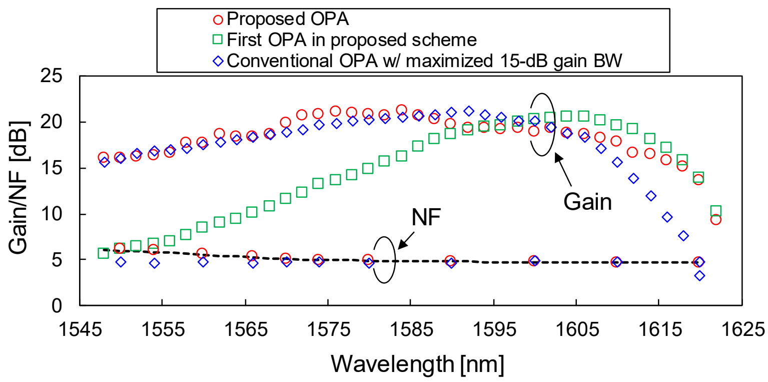

Fig. 2: Comparison of gain/NF spectrum. Dashed line indicates theoretical NF spectrum of proposed OPA.

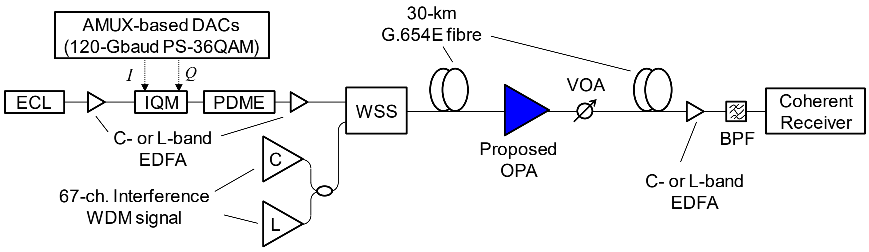

Fig. 3: Experimental setup for 2×30-km transmission using proposed OPA. ECL: external cavity laser, IQM: I/Q modulator, PDME: polarization-division multiplexing emulator, WSS: wavelength selective switch, and VOA: variable optical attenuator.

theoretical value calculated with Eq. (1). Note that, 193.6–194.0 THz was a guard band due to an edge of the idler filter.

8.375-THz optical inline amplification for 2×30-km WDM transmission

Figure 3 shows the experimental setup for the 2×30-km transmission of a 125-GHz-spaced 67-channel 800-Gbps/λ WDM signal using the proposed OPA. The OPA was used for an inline amplifier of the 8.375-THz WDM signal. In the transmitter side, a Nyquist-pulse-shaped 120-Gbaud probabilistically shaped (PS-) 36QAM signal was generated using an I/Q modulator driven by analogue-multiplexer-based high-speed digital-to-analogue convertors (AMUX-based DACs) [16]. The information rate of the polarization-division-multiplexed (PDM) PS-36QAM signal was 8.87 bit per 4D symbol. The interference WDM channels were emulated using amplified spontaneous emission (ASE) light from C- and L-band optical amplifiers [17]. The interference WDM signal was spectrally shaped and combined with the channel under test (CUT) using a wavelength selective switch (WSS), and

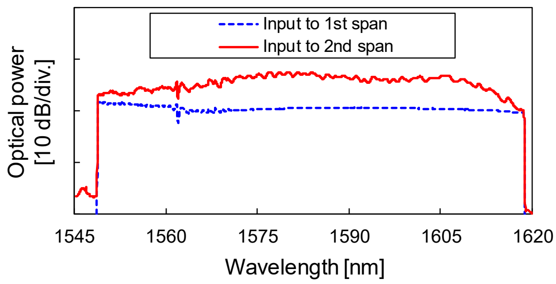

Fig. 4: Spectra of input to first span and second span.

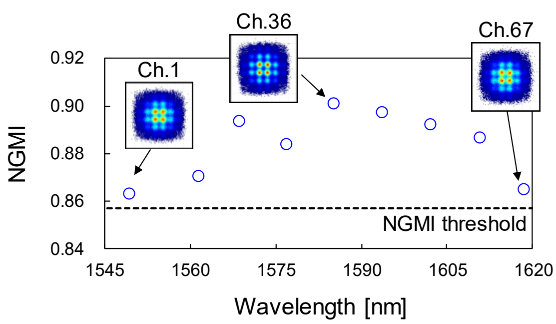

Fig. 5: NGMI spectrum of PDM-PS-36QAM signals.

an 8.375-THz WDM signal from 1548.81 nm to 1618.86 nm was generated. The interference WDM signal was rectangularly hollowed out around the wavelength of the CUT with a 125-GHz bandwidth in the WSS. The transmission lines were 30-km G.654E SMFs with a ~6-dB propagation loss. The average fibre-launched optical power was −16.5 dBm/ch. The total input power to the proposed OPA was −5.0 dBm. The output power from the OPA was 14.7 dBm. After transmission, the CUT was pre-amplified by a C- or L-band EDFA, extracted by a BPF, and received by a coherent receiver. The received CUT was digitised using a digital storage oscilloscope operating with 256 GS/s and was demodulated by offline digital signal processing on the basis of a complex 8×2 MIMO equalizer in the frequency domain [18]. A normalized generalized mutual information (NGMI) was calculated from the demodulated signal. Assuming a code rate of 0.826 defined in accordance with the DVB-S2 and 1.64% pilot-signal insertion, the net data rate per channel was 800 Gbps with a NGMI threshold of 0.857 [9].

Figure 4 shows the optical spectra input to the first or second fibre spans. The optical attenuation before the second span was set so that the input power to each span at a wavelength with the lowest gain was the same. Figure 5 shows the NGMI of representative channels. All measured channels were better than the NGMI threshold. The wavelength dependence of the NGMI was based on the gain spectrum of the OPA, and excessive signal distortion caused by the proposed configuration was not confirmed.

Conclusion

We proposed a configuration of an OPA using cascaded PPLN modules with complementary gain profiles to pump-power-efficiently extend the effective gain bandwidth. A 0.9-THz (8-nm) bandwidth extension was achieved in comparison with a conventional PPLN-based OPA. We demonstrated 8.375-THz optical inline amplification using the proposed OPA under a 2×30-km WDM transmission condition.

References

[1] F. Hamaoka, M. Nakamura, S. Okamoto, K. Minoguchi, T. Sasai, A. Matsushita, E. Yamazaki, and Y. Kisaka, "Ultra-Wideband WDM transmission in S-, C-, and L-Bands Using Signal Power Optimization Scheme," *IEEE Journal of Lightwave Technology*, vol. 37, no. 8, pp. 1764–1771, 2019, DOI: 10.1109/JLT.2019.2894827.

[2] J. Renaudier, A. Meseguer, A. Ghazisaeidi, P. Tran, R. Muller, R. Brenot, A. Verdier, F. Blache, K. Mekhazni, B. Duval, H. Debregeas, M. Achouche, A. Boutin, F. Morin, L. Letteron, N. Fontaine, Y. Frignac, and G. Charlet, "First 100-nm Continuous-Band WDM Transmission System with 115Tb/s Transport over 100km Using Novel Ultra-Wideband Semiconductor Optical Amplifiers," in *Proceedings of European Conference on Optical Communication (ECOC)*, Th.PDP.A.2, 2017, DOI: 10.1109/ECOC.2017.8346084.

[3] L. Galdino, A. Edwards, W. Yi, E. Sillekens, Y. Wakayama, T. Gerard, W. S. Pelouch, S. Barnes, T. Tsuritani, R. I. Killey, D. Lavery, and P. Bayvel, "Optical Fibre Capacity Optimisation via Continuous Bandwidth Amplification and Geometric Shaping," *IEEE Photonics Technology Letters*, vol. 32, no. 17, pp. 1021–1024, 2020, DOI: 10.1109/LPT.2020.3007591.

[4] M. A. Iqbal, L. Krzczanowicz, I. Phillips, P. Harper, and W. Forysiak, "150nm SCL-Band Transmission through 70km SMF using Ultra-wideband Dual-stage Discrete Raman Amplifier," in *Proceedings of Optical Fiber Communication Conference (OFC)*, W3E.4, 2020, DOI: 10.1364/OFC.2020.W3E.4.

[5] S. Shimizu, T. Kobayashi, T. Kazama, T. Umeki, M. Nakamura, K. Enbutsu, T. Kashiwazaki, R. Kasahara, K. Watanabe, and Y. Miyamoto, "PPLN-based Optical Parametric Amplification for Wideband WDM Transmission," *IEEE Journal of Lightwave Technology*, (Early Access), 2022, DOI: 10.1109/JLT.2022.3142749.

[6] T. Kato, S. Watanabe, T. Yamauchi, G. Nakagawa, H. Muranaka, Y. Tanaka, Y. Akiyama, and T. Hoshida, "Real-time transmission of 240×200-Gb/s signal in S+C+L triple-band WDM without S- or L-band transceivers," in *Proceeding European Conference on Optical Communication (ECOC)*, PD1.7, 2019, DOI: 10.1049/cp.2019.1021.

[7] C. B. Gaur, V. Gordienko, A. A.I. Ali, P. Hazarika, A. Ellis, and N. J. Doran, "Polarization-insensitive fibre optic parametric amplifier with gain bandwidth of 35 nm in L-band," in *Proceedings of European Conference on Optical Communication (ECOC)*, Tu2A.4, 2021, DOI: 10.1109/ECOC52684.2021.9605891.

[8] C. B. Gaur, V. Gordienko, P. Hazarika, and N. J. Doran, "Polarization Insensitive Fiber Optic Parametric Amplifier With a Gain Bandwidth of 22 nm in S-Band," in *Proceedings of Optical Fiber Communication Conference (OFC)*, W4J.1, 2022, DOI: 10.1364/OFC.2022.W4J.1.

[9] T. Kobayashi, S. Shimizu, M. Nakamura, T. Umeki, T. Kazama, R. Kasahara, F. Hamaoka, M. Nagatani, H. Yamazaki, H. Nosaka, and Y. Miyamoto, "Wide-Band Inline-Amplified WDM Transmission Using PPLN-Based Optical Parametric Amplifier", *IEEE Journal of Lightwave Technology*, vol. 39, no. 3, pp. 787–794, 2021, DOI: 10.1109/JLT.2020.3039192.

[10] T. Kobayashi, S. Shimizu, M. Nakamura, T. Umeki, T. Kazama, J. Yoshida, S. Takasaka, T. Tatamida, H. Kawakami, F. Hamaoka, M. Nagatani, H. Yamazaki, K. Watanabe, T. Saida, and Y. Miyamoto, "50-Tb/s (1 Tb/s × 50 ch) WDM Transmission on Two 6.25- THz Bands Using Hybrid Inline Repeater of PPLN-based OPAs and Incoherent-forward-pumped DRA," in *Proceedings of Optical Fiber Communication Conference (OFC)*, Th4A.8, 2022, DOI: 10.1364/OFC.2022.Th4A.8.

[11] T. Kazama, T. Umeki, S. Shimizu, T. Kashiwazaki, K. Enbutsu, R. Kasahara, Y. Miyamoto, and K. Watanabe, "Over-30-dB Gain and 1-dB Noise Figure Phase-Sensitive Amplification Using Pump-Combiner-Integrated Fiber I/O PPLN Module", *Optics Express*, vol. 29, no. 18, pp. 28824–28834, 2021, DOI: 10.1364/OE.434601.

[12] T. Kazama, T. Umeki, M. Abe, K. Enbutsu, Y. Miyamoto, and H. Takenouchi, "Low-Parametric-Crosstalk Phase-Sensitive Amplifier for Guard-Band-Less DWDM Signal Using PPLN Waveguides," *IEEE Journal of Lightwave Technology*, vol. 35, no. 4, pp. 755–761, 2016, DOI: 10.1109/JLT.2016.2603186.

[13] D. H. Jundt, "Temperature-dependent Sellmeier equation for the index of refraction, n_e, in congruent lithium niobate," *Optics Letters*, vol. 22, no. 20, pp. 1553–1555, 1997, DOI: 10.1364/OL.22.001553.

[14] X. Tang, Z. Wu, and P. Urquhart, "Temperature Optimization for Broad-Band Quasi-Phase-Matched Difference Frequency Generation," *IEEE Journal of Lightwave Technology*, vol. 22, no. 6, pp. 1622–1627, 2004, DOI: 10.1109/JLT.2004.827658.

[15] T. Kashiwazaki, T. Yamashima, N. Takanashi, A. Inoue, T. Umeki, and A. Furusawa, "Fabrication of low-loss quasi-single-mode PPLN waveguide and its application to a modularized broadband high-level squeezer," *Applied Physics Letters*, vol. 119, 251104, 2021, DOI: 10.1063/5.0063118.

[16] F. Hamaoka, M. Nakamura, M. Nagatani, T. Kobayashi, A. Matsushita, H. Wakita, H. Yamazaki, H. Nosaka, and Y. Miyamoto, "120-GBaud 32QAM Signal Generation Using Ultra-Broadband Electrical Bandwidth Doubler," in *Proceedings of Optical Fiber Communication Conference (OFC)*, M2H.6, 2019, DOI: 10.1364/OFC.2019.M2H.6.

[17] D. J. Elson, G. Saavedra, K. Shi, D. Semrau, L. Galdino, R. Killey, B. C. Thomsen, and P. Bayvel, "Investigation of bandwidth loading in optical fibre transmission using amplified spontaneous emission noise," *Optics Express*, vol. 25, no. 16, pp. 19529–19537, 2017, DOI: 10.1364/OE.25.019529.

[18] M. Nakamura, T. Kobayashi, F. Hamaoka, and Y. Miyamoto, "High Information Rate of 128-GBaud 1.8-Tb/s and 64-GBaud 1.03-Tb/s Signal Generation and Detection Using Frequency-Domain 8×2 MIMO Equalization," in *Proceedings of Optical Fiber Communication Conference (OFC)*, M3H.1, 2022, DOI: 10.1364/OFC.2022.M3H.1.