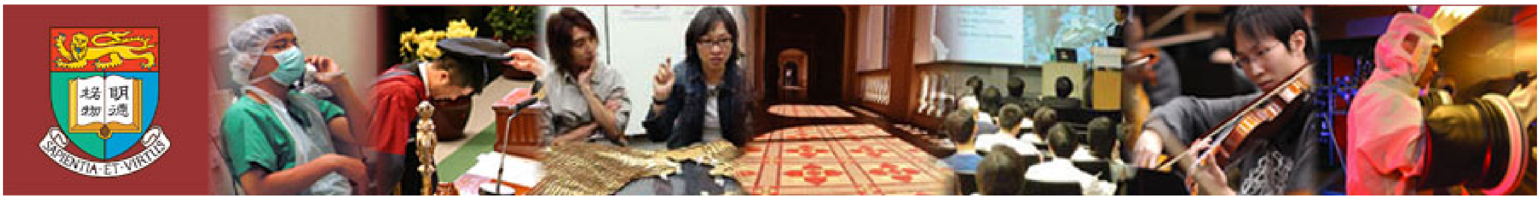

| | |
|---|---|
| Title | Practical aspects of fiber optical parametric amplifiers for optical communication |
| Author(s) | Wong, KKY |
| Citation | The 9th International Conference on Optical Communications and Networks (ICOCN 2010), Nanjing, China, 24-27 October 2010. In Proceedings of the 9th ICOCN, 2010, p. 299-302 |
| Issued Date | 2010 |
| URL | http://hdl.handle.net/10722/135874 |
| Rights | Proceedings of the International Conference on Optical Communications and Networks. Copyright © IEEE. |

**(Invited Paper)**

# PRACTICAL ASPECTS OF FIBER OPTICAL PARAMETRIC AMPLIFIERS FOR OPTICAL COMMUNICATION

**Kenneth Kin-Yip Wong***

* Photonic Systems Research Laboratory, Department of Electrical and Electronic Engineering,
The University of Hong Kong, Pokfulam Road, Hong Kong
E-mail: kywong@eee.hku.hk

**Keywords:** optical amplifiers, parametric amplification, four-wave mixing, wavelength conversion, optical communication, optical fibers, nonlinear optics

## Abstract

Fiber optical parametric amplifiers (OPAs) are based on the third-order nonlinear susceptibility of glass fibers. If two strong pumps and a weak signal are fed into a fiber, an idler is generated. Signal and idler can grow together if pump power is high enough, and phase matching occurs. Until recently, impressive performance of fiber OPAs has been demonstrated in different respects. However, secondary effects should be addressed before OPAs can be utilized in practical applications. Here we report some of these effects, either exploiting them as in the parametric processor such as optical logic gates, inverted and non-inverted wavelength converter, and ultra-wideband monocycle and doublet pulses generator, or suppressing them as in the optical amplifier for WDM systems.

## 1 Introduction

In recent years, impressive performance has been demonstrated by the author's research group and different researchers in fiber OPAs in several respects: 1) Gain in excess of 60-dB has been obtained [1][2]; 2) fiber OPAs can exhibit a large variety of gain spectra: a gain bandwidth of 400-nm or beyond has been demonstrated [3]; tunable narrowband gain regions can also be generated [3]; 3) Noise figure of 3.7-dB [4], limited by other third-order nonlinear process [5]; 4) Polarization-insensitive operation in both one-pump [6] and two-pump configurations [7]; 5) Due to the inverted spectrum of the idler with respect to that of the signal; thus by placing an OPA in the middle of a fiber span one can realize mid-span spectral inversion (MSSI) which counteracts the effect of fiber dispersion and some nonlinear effects [8]. Besides using fiber OPA in continuous-wave regime as in typical systems, pulsed-pump has also been demonstrated to achieve larger bandwidth and higher peak gain by combining with optical filtering technique [9]. Furthermore, by modulating the pump it is possible to modulate signal and/or idler at the output. This can be used to implement a variety of signal processing functions, including: fast signal switching; demultiplexing of time-division-multiplexed signals [10]; retiming and reshaping of waveforms [11]; optical sampling [12][13].

However, secondary effects should be addressed in order for fiber OPAs to be useful in communication applications. In multi-wavelength systems, these are: four-wave mixing (FWM), cross-phase modulation (XPM); and cross-gain modulation (XGM) between signals [14]. Furthermore, the pump-to-signal relative intensity noise (RIN) transfer and frequency/phase modulation (FM/PM) to signal intensity conversion are also potential challenges for practical fiber OPAs [15]. In particular the signal crosstalk due to the FWM and XGM effects, which have shown to be the constraints of using fiber OPAs in wavelength-division multiplexing (WDM) systems [14]. On the other hand, one can leverage on the peculiar performance of fiber OPAs by achieving some optical signal processing functionalities with appropriate designs as shown in this paper.

## 2 Suppression of secondary effects

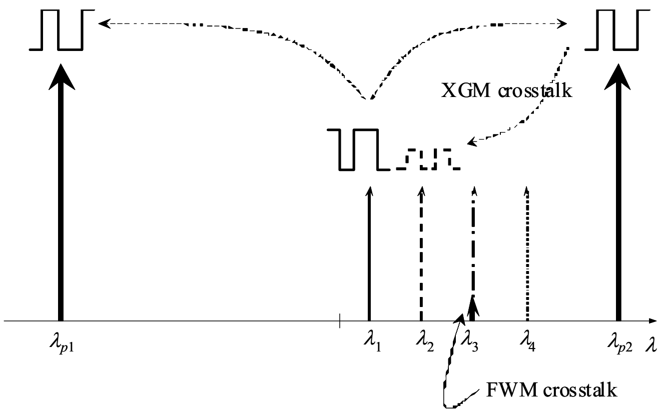


Fig. 1 Illustration of the signal quality degradation of WDM system due to XGM and FWM effects in a 2P-OPA. [19].

Previous work has shown that this kind of degradation is already severe even with only three WDM channels in one-pump OPA (1P-OPA) system [14]. It was also shown that unequal channel spacing slightly improves the degradation. However, the XGM effect still provides a basic detrimental effect when using OPA in WDM systems, mediated through the depletion of the pump(s) as shown in Fig. 1. Only channel #1 ($\lambda_1$) is shown with intensity-modulation (IM) for clarity. Also note that the corresponding idlers for all four channels ($\lambda_1 - \lambda_4$) have not been shown here for simplicity. The signal ($\lambda_1$) is amplified by the parametric gain (with pump wavelengths at $\lambda_{p1}$ and $\lambda_{p2}$). As it grows, it draws power away from the pump(s), because the total optical power remains constant. As a result, the pump power itself now has IM and all channels #2 – #4 will exhibit slightly different gains at different times, depending on whether they travel with a depleted part of the pump, or an undepleted one. As a result, the amplified channels #2 – #4 will themselves exhibit IM, which constitutes crosstalk. If we now consider that channels #2 – #4 are replaced by independent modulation signals, it is clear that their amplitudes will experience fluctuations due to XGM crosstalk induced by the first channel and vice versa, which will lead to deterioration of their qualities. Furthermore, the spurious FWM also lead to extra signal quality degradation. Similar signal degradation can also be observed in two-pump OPA (2P-OPA), which provides an extra degree of freedom, such that a flattened gain spectrum can be achieved by trading with the gain bandwidth [16].

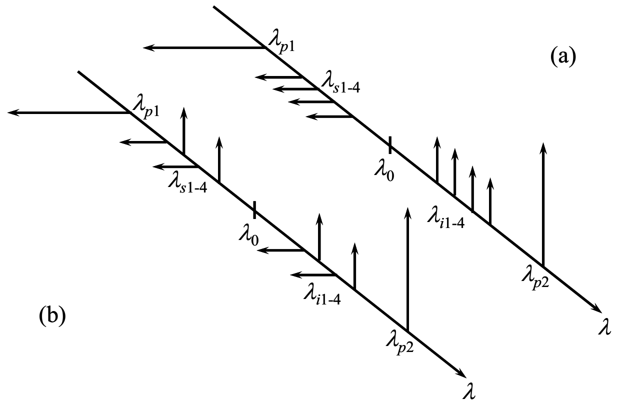


Fig. 2 Schematics of (a) Co-polarized (COPO); (b) polarization-interleaving (POIN) 2OP-OPA system [18].

In addition to the flattened gain spectrum can be achieved by 2P-OPA, the two-orthogonal-pump OPA (2OP-OPA) has been demonstrated to be polarization-independent [7]. Preliminary results have also been confirmed that it is effective in suppressing nonlinear crosstalks with co-polarized (COPO) WDM channels [17] with the configuration as shown in Fig. 2(a). Furthermore, by using polarization-interleaving (POIN) WDM channels as shown in Fig. 2(b), the signal quality can further be improved [18].

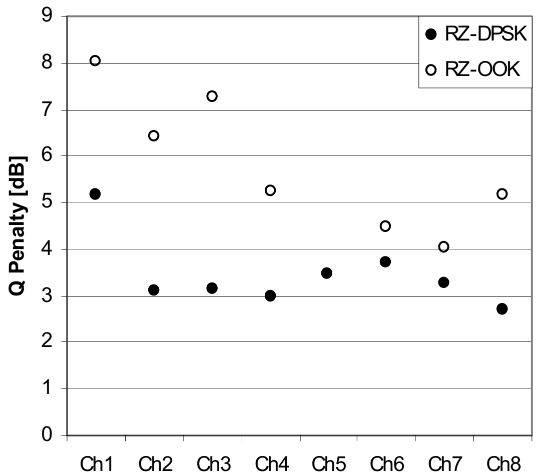


Fig. 3 Q-factor penalty of RZ-DPSK and RZ-OOK signals at different channel [19].

Besides pursuing pumps configuration to suppress nonlinear crosstalk, reduction by using different modulation formats has also been shown to be effective. For example, return-to-zero differential phase-shift keying (RZ-DPSK) modulation format, which the signal power level is constant, should be effective in suppressing XGM-induced crosstalk. We demonstrated substantial crosstalk suppression in one-pump OPA by using RZ-DPSK modulation format, of which its pattern independent amplitude and sub-unity duty cycle would be effective in reducing XGM and FWM effects significantly. By using RZ-DPSK format with eight 10 Gb/s channel, 100 GHz channel spacing, Q-factor penalty of RZ-DPSK signal was reduced by 2.4 dB (on average) comparing to RZ-OOK counterparts as shown in Fig. 2 [19].

## 3 Utilization of secondary effects

Turns out some of the detrimental second-order effects in fiber OPA are like the double-edge sword, which can be utilized for optical signal processing functionalities that are not available by conventional techniques. For example, pulsed-pump OPA has been utilized to generate 40-GHz pulse (or even higher speed) [20], as clock generators [13]. Some of the research efforts pursued by our research group will be described here as follows.

Firstly, all-optical XOR-, OR-, NOT-, and AND-gate were demonstrated for 10 Gb/s RZ-OOK signals using a single experimental setup. Typical results are shown in Fig. 4. The operating principles of these logic gates based on pump depletion (XGM) and FWM. This setup can be set to generate different logic by altering input power, state-of-polarization, center frequencies of input optical signals, and/or input bitstreams. Full-width at half-maximum (FWHM) pulsewidth of the input and the output signals were less than 5.1 ps in all cases showing a possibility of higher data rate operation at 80 Gb/s or beyond [21].

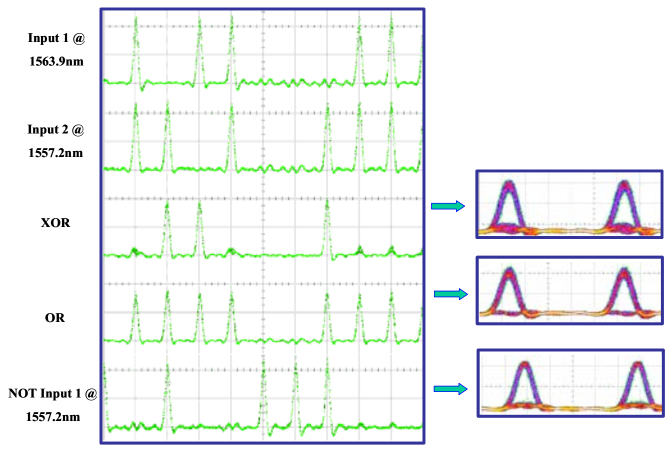


Fig. 4 Bit patterns for the inputs and outputs of XOR-, OR-, and NOT-gates [21].

In addition, we proposed another scheme, using a two-pump OPA (2P-OPA), to achieve both inverted and non-inverted all-optical wavelength conversion [22]. The operating principle is again based on the utilization of the XGM of the pump as before. Experiments have confirmed that the signal at 1554 nm could be flexibly converted to the C-band (1532–

1556 nm) with an extinction ratio (ER) between 7 and 14 dB. Noted that the similar scheme can be extended to all-optical wavelength conversion and multicasting for a 10 Gb/s NRZ system with 100 GHz channel spacing. Multicasting is another potentially useful networking function. It involves routing the same data stream from a single node to several destinations, commonly implemented via IP digital routers in electrical domain [23]. Another group has pursued different approach but similar idea in 2P-OPA for multicasting [24].

Another interesting application of fiber OPA in microwave photonics is generating ultra-wideband (UWB) monocycle or doublet pulse using XGM in a single experimental setup [25]. The high-speed optical parametric process realizes the signal amplification, idler generation, and pump depletion simultaneously within femtosecond response time in the HNL-DSF. After the combination of the three lightwaves with a suitable time delay between them, UWB pulse is obtained. A selective generation of monocycle or doublet pulse can be made by altering the optical attenuators without changing the wavelengths or the powers of the pump and the signal. In our experiment, high-quality UWB monocycle and doublet pulses with a fractional bandwidth of 115% and 126% were generated, as shown in [25] and [26]. The similar concept can be extended into millimeter-wave UWB signal generation via frequency up-conversion [26].

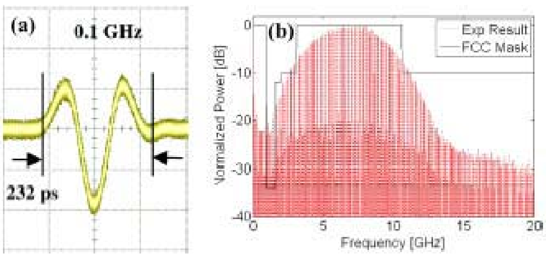


Fig. 5 UWB doublet pulse generation with repetition rate of 0.1 GHz. (a) Waveform of generated doublet pulse. (b) Power spectrum of the corresponding generated doublet pulse [25].

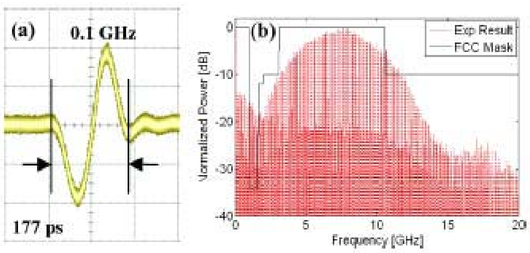


Fig. 6 UWB monocycle pulse generation with repetition rate of 0.1 GHz. (a) Waveform of generated monocycle pulse. (b) Power spectrum of the corresponding generated monocycle pulse [25].

In addition, we demonstrated a novel receiver sensitivity improvement scheme for 10-Gb/s RZ-OOK signal using constructive superposition of signals and idlers in OPA for WDM systems by dual-end detection. The principle of preamplifier based on OPA is shown in Fig. 7 [27]. By launching a weak signal together with a strong pump into nonlinear medium, both the amplification of weak signal and generation of new component called idler will occur by extracting power from the strong pump. As a result, the pattern on signal can be transcribed to idler, while the pump will be depleted simultaneously. By feeding both the amplified signal and idler into a photodiode (PD), constructive superposition can enhance the amplitude of signal. Therefore, an output electrical signal with higher voltage swing is obtained. Implementing this dual-end detection scheme in each channel of WDM systems, extra amplification can be obtained. Receiver sensitivity down to -42 dBm was realized and power penalties were improved by more than 3 dB in all channels compared to the single-end counterpart through signal swing enhancement as show in Fig. 8. The results showed that the proposed preamplifier can obtain comparable performance under single-channel and multi-channels cases. This scheme would be useful for improving performance of OPA-assisted receivers in WDM systems.

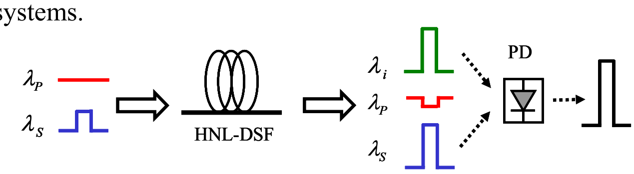


Fig. 7 Principle of proposed preamplifier [27].

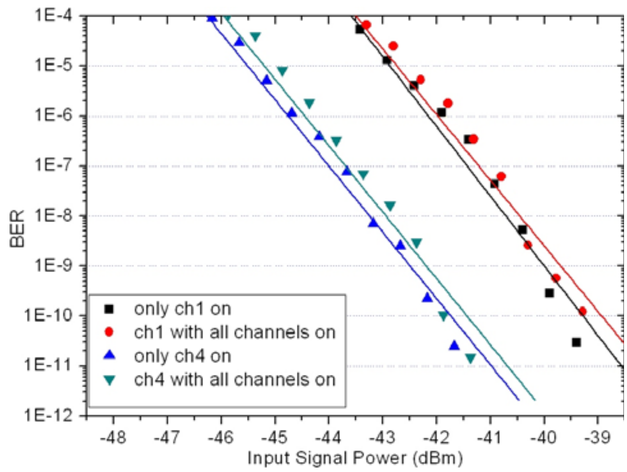


Fig. 8 BER of comparison of channel 1 and 4 with other channels on and off.

## 4 Conclusion

Substantial progress has been made in recent years with the development of fiber OPAs. However, second-order effects should be addressed before OPAs can be practical. Here we report some of these effects, either exploiting them as in the parametric processor such as optical logic gates, inverted and non-inverted wavelength converter, and ultra-wideband monocycle and doublet pulses generator, or suppressing them as in the optical amplifier for WDM systems. We anticipate that further progress with high-power pumps, highly-nonlinear fibers with tailored dispersion properties, and SBS suppression techniques, fiber OPAs and related devices will find practical applications in areas such as high-power wavelength conversion, optical communications, optical signal processing, etc.

## Acknowledgments

The work described in this paper was partially supported by grants from the research Grants Council of the Hong Kong

Special Administrative Region, China (Project No. HKU 7179/08E and HKU 7183/09E).

## References


[1] K. K. Y. Wong, K. Shimizu, K. Uesaka, G. Kalogerakis, M. E. Marhic, and L. G. Kazovsky, "Continuouswave fiber OPA with 60 dB gain using a novel two-segment design," *IEEE Photon. Technol. Lett*., **15**, pp. 1707-1709, 2003.

[2] T. Torounidis, P. A. Andrekson and B. E. Olsson, "Fiber-optical parametric amplifier with 70-dB gain," *IEEE Photon. Technol. Lett.*, **18**, pp. 1194-1196, 2006.

[3] M. E. Marhic, K. K. Y. Wong, and L. G. Kazovsky, "Wideband tuning of the gain spectra of one-pump fiber optical parametric amplifiers," *IEEE J. of Selected Topics in Quantum Electron.*, **10**, pp. 1133-1141, 2004.

[4] J. L. Blows and S. E. French, "Low-noise-figure optical parametric amplifier with a continuous-wave frequency-modulated pump," *Opt. Lett.,* **27**, pp. 491-493, 2002.

[5] P. L. Voss and P. Kumar, "Raman-noise-induced noise-figure limit for $\chi^{(3)}$ parametric amplifiers," *Opt. Lett*., **29**, pp. 445-446, 2004.

[6] K. K. Y. Wong, M. E. Marhic, K. Uesaka, and L. G. Kazovsky, "Polarization-independent one-pump fiber optical parametric amplifier," *IEEE Photon. Technol. Lett.,* **14**, pp. 1506-1508, 2002.

[7] K. K. Y. Wong, M. E. Marhic, K. Uesaka, and L. G. Kazovsky, "Polarization-independent two-pump fiber optical parametric amplifier," *IEEE Photon. Technol. Lett.,* **14**, pp. 911-913, 2002.

[8] S. Radic, C. McKinstrie, and R. Jopson, "Polarization dependent parametric gain in amplifiers with orthogonally multiplexed optical pumps," OFC'03, paper ThK3.

[9] G. Kalogerakis, K. Shimizu, M. E. Marhic, K. K. Y. Wong, K. Uesaka, and L. G. Kazovsky, "High repetition-rate pulsed-pump fiber optical parametric amplifier for amplifications of communication signals," *IEEE/OSA J. Lightwave Technol.*, **24**, pp. 3021-3027, 2006.

[10] J. Hansryd and P. A. Andrekson, "O-TDM demultiplexer with 40-dB gain based on a fiber optical parametric amplifier," *IEEE Photon. Technol. Lett*., **13**, pp. 732-734, 2001.

[11] Y. Su, L. Wang, A. Agrawal, and P. Kumar, "Simultaneous 3R regeneration and wavelength conversion using a fiber-parametric limiting," OFC'01, paper MG4.

[12] J. Li, J. Hansryd, P. O. Hedekvist, P. A. Andrekson, and S. N. Knudsen, "300-Gb/s eye-diagram measurement by optical sampling using fiber-based parametric amplification," *IEEE Photon. Technol. Lett*., **13**, pp. 987-989, 2001.

[13] J. Hansryd, P. A. Andrekson*,* M. Westlund, J. Li, and P.-O. Hedekvist, "Fiber-Based Optical Parametric Amplifiers and Their Applications," *IEEE J. of Selected Topics in Quantum Electron.*, **8**, pp. 506-520, 2002.

[14] T. Torounidis, H. Sunnerud, P. Hedekvist and P. A. Andrekson, "Amplification of WDM signals in fiber-based optical parametric amplifiers," *IEEE Photon. Technol. Lett.*, **15**, pp. 1061-1063, 2003.

[15] M. E. Marhic, G. Kalogerakis, K. K. Y. Wong, and L. G. Kazovsky, "Pump-to-signal transfer of low-frequency intensity modulation in fiber optical parametric amplifiers," *IEEE/OSA J. Lightwave Technol*., **23**, pp. 1049-1055, 2005.

[16] M. E. Marhic, Y. Park, F. S. Yang, and L. G. Kazovsky, "Broadboad fiber-optical parametric amplifiers and wavelength converters with low-rippled Chebyshev gain spectra," *Opt. Lett.*, **21**, pp. 1354-1356, 1996.

[17] K. K. Y. Wong, G.-W. Lui, and L.-K. Chen, "Experimental study of the WDM signal crosstalk in two-pump fiber optical parametric amplifiers," *Optics Comm.,* **270**, pp. 429-432, 2007.

[18] K. K. Y. Wong, G. W. Lu and L. K. Chen, "Polarization-interleaved WDM signals in a fiber optical parametric amplifier with orthogonal pumps," *Opt. Express*, **15**, pp. 56-61, 2007.

[19] B. P. P. Kuo, P. C. Chui, and K. K. Y. Wong, "A Comprehensive Study on Crosstalk Suppression Techniques in Fiber Optical Parametric Amplifier by Modulation Format," *IEEE J. of Selected Topics in Quantum Electron.*, **14**, pp. 659-665, 2008.

[20] J. Hansryd and P.A. Andrekson, "Wavelength tunable 40GHz pulse source based on fibre optical parametric amplifier," *IEE Electron. Lett.*, **37**, pp. 584-585, 2001.

[21] D. M. F. Lai, C. H. Kwok, and K. K. Y. Wong, "All-Optical Picoseconds Logic Gates based on a Fiber Optical Parametric Amplifier," *OSA Opt. Express*, **16**, pp. 18362-18370, 2008.

[22] K. K. Y. Wong, G.-W. Lui, and L.-K. Chen, "Simultaneous all-optical inverted and non-inverted wavelength conversion using a single-stage fiber optical parametric amplifier," *IEEE Photon. Technol. Lett.*, **18**, pp. 1442-1444, 2006.

[23] K. K. Y. Wong, G.-W. Lui, K.-C. Lau, P. K. A. Wai, and L.-K. Chen, "All-Optical Wavelength Conversion and Multicasting by Cross-Gain Modulation in a Single-Stage Fiber Optical Parametric Amplifier," OFC2007.

[24] Q. Lin, R. Jiang, C. F. Marki, C. J. McKinstrie, R. Jopson, J. Ford, G. P. Agrawal, and S. Radic, "40-Gb/s Optical Switching and Wavelength Multicasting in A Two-Pump Parametric Device," *IEEE Photon. Technol. Lett.*, **17**, pp. 2376-2378, 2005.

[25] J. Li, B. P. P. Kuo, and K. K. Y. Wong, "Ultra-wideband Pulse Generation based on Cross-gain Modulation in Fiber Optical Parametric Amplifier", *IEEE Photon. Technol. Lett*. **21**, pp. 212-214, 2009.

[26] J. Li, Y. Liang, and K. K. Y. Wong, "Millimeter-wave UWB Signal Generation via Frequency Up-conversion Using Fiber Optical Parametric Amplifier", *IEEE Photon. Technol. Lett*., **21**, pp. 1172-1174, 2009.

[27] Y. Liang, J. Li, P. C. Chui, and K. K. Y. Wong, "Receiver Sensitivity Improvement for WDM Systems using an Optical Parametric Amplifier," *IEEE Photon. Technol. Lett.*, **21**, pp. 1562–1564, 2009.