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High Conversion Efficiency, Mid-Infrared Pulses Generated via Burst-Mode Fiber Laser Pumped Optical Parametric Oscillator

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ABSTRACT We present a mid-infrared optical parametric oscillator (OPO) with a high pump-to-idler conversion efficiency from 1.06 μm to 3.8 μm, which was quasi-synchronously pumped by a burst-mode fiber laser. The pump pulse was specially designed with a rectangular profile in temporal, which was composed of hundreds of ultrashort sub-pulses. By applying the quasi-synchronous pumping scheme, the buildup time of the parametric signal pulse could be minimized. No back-conversion effect was observed when the pump peak power was increased. A maximum pump-to-idler conversion efficiency of 19.6% was achieved when the number of intra-burst sub-pulses was set to be 240. By increasing the number of intra-burst sub-pulses to be about 480, the maximum average output power of 7.9 W at 3.8 μm was realized under pump power of 45.3 W. The corresponding pump-to-idler conversion efficiency was computed to be about 17.5%. The experimental results show an improvement of 40% in pump-to-idler conversion efficiency for this quasi-synchronously pumped OPO when compared with the conventional long laser pulse pumped OPO.

INDEX TERMS Mid-infrared, optical parametric oscillator, quasi-synchronously pumped, burst-mode fiber laser.

I. INTRODUCTION

High power mid-infrared (mid-IR) lasers working around 3 to 5 μm have been widely used in many fields, such as environmental monitoring, medical diagnostics, and infrared countermeasurement [1]–[3]. Optical parametric oscillator (OPO) is an effective technique to convert the wavelength of mature near-IR lasers into the mid-IR region, where a pair of signal and idler photons are generated from one pump photon. For OPO system, the pump-to-idler conversion efficiency is theoretically limited by the quantum efficiency which is decided by the frequency ratio between pump and idler photon. In practice, because of optical absorption, thermal effects, crystal quality, spatial beam profile, and other experimental difficulties, the conversion efficiency is much lower, approximately half of the theoretical limit[4]. Ignoring these inevitable effects, many techniques for improving conversion efficiency of OPO have been employed [5]–[8].

The buildup time and the back-conversion are two major factors related to the temporal dynamics of the conversion process [9], which can greatly reduce the conversion efficiency in the normal long pulse OPO. The buildup time is achieved when the signal and idler waves are initialed from quantum noise and then amplified to detectable level. The more time it takes the signal and idler waves to buildup, the lower pump power can be used in parametric conversion process, which means the pump-to-idler conversion will be less efficient. The back-conversion process happens when the intensity of signal and idler waves are very high and then the signal and idler waves are back converted into the pump wave. Obviously, the back-conversion process is detrimental to improving the pump-to-idler conversion efficiency. In order

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to raise the conversion efficiency, both buildup time and back-conversion process should be minimized. We have previously investigated several OPO systems for high efficiency mid-IR laser output by using techniques to minimize these two effects in the parametric conversion process [10]–[12].

One of the most important methods is based on controlling the temporal shape of the pump pulse. Compared to the pulse with Gaussian shape, the rectangular and double rectangular pulse provide a significant improvement in the conversion efficiency, which has been theoretically and experimentally proved to improve the OPO's performance [9], [13]–[15]. We have previously reported a high efficiency mid-IR OPO system, which was pumped by a gain-switched fiber laser with "figure-of-h" pulse shape [16]. High power mid-IR emission was generated with average output power of 5.15 W at 3.8 μm and 8.54 W at 3.3 μm under the pump power of 45 W. By reducing the buildup time and back-conversion process, experimental results illustrated an obvious improvement to pump-to-idler conversion efficiency by using the "figure-of-h" pulses over simple pedestal-free pulses. Another method for improving the conversion efficiency is based on a special designed nonlinear crystal with quasi-periodically poled structure. Different from a periodically poled structure, which can effectively afford one reciprocal vector to compensate the phase mismatch in nonlinear conversion, quasi-periodically poled structure can afford more reciprocal vectors to compensate several phase mismatches simultaneously [17]. Therefore, an additional nonlinear difference frequency generation (DFG) process that converts the signal to the idler further is phase matched simultaneously by a quasi-periodically poled nonlinear crystal. Thus, the DFG process can reduce the signal intensity and lead to suppressing of back-conversion. Hence, improvement in the pump-to-idler conversion efficiency can be obtained. In this aspect, we have already investigated an efficient OPO with high parametric conversion from 1.064 to 3.8 μm [18], [19]. A quasi-periodically poled magnesium oxide doped lithium niobate wafer was designed and fabricated as the nonlinear crystal of the OPO. When compared with a periodically poled channel fabricated on the same wafer, an improvement of 32% in conversion efficiency was realized for the pump-to-idler conversion [19].

In this paper, we designed a totally new pump pulse shape for compact but efficient OPO conversion. The OPO system applied a burst-mode fiber laser as the pump source, which was called as quasi-synchronously pumping scheme. The pump pulse was specially designed with a rectangular profile in temporal, which was composed of several ultrashort sub-pulses. By applying the quasi-synchronously pumping scheme, the buildup time could be minimized and no back-conversion effect was observed when the pump peak power increased. The maximum pump-to-idler conversion efficiency of 19.6% was achieved when the number of intra-burst sub-pulses was set to be 240. By increasing the number of intra-burst pump pulses to be about 480, the maximum average power output of 7.9 W at 3.8 μm was realized under pump power of 45.3 W. The corresponding pump-to-idler conversion efficiency was computed to be about 17.5%. Compared to the normal OPO pumped by long pulse lasers, our quasi-synchronously pumped OPO show an improvement of 40% in pump-to-idler conversion efficiency.

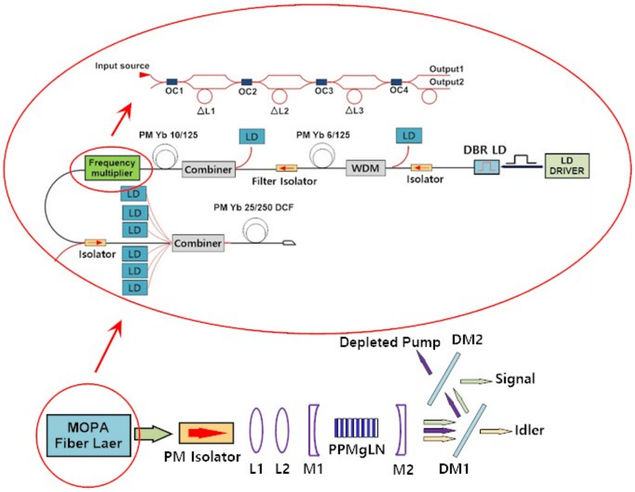

FIGURE 1. Experimental setup for fiber laser pumped Mid-infrared OPO system.

II. EXPERIMENTAL SETUP

To investigate the improvement of conversion efficiency in the parametric conversion process, a single-pass single-resonant (SPSR) linear cavity was utilized. The experimental setup of the fiber laser pumped mid-infrared OPO system is illustrated in Fig. 1, which is similar to that described in [10]. The pump source was a master oscillator power amplifier (MOPA) structured linearly polarized fiber laser, which was composed of three amplifier stages. A gain-switched distributed Bragg reflector (DBR) laser diode was applied as the seed laser, which was directly modulated into burst-mode operation with a single sub-pulse duration of 200 ps. After two pre-amplifier stage, a specially designed frequency multiplier component, which was composed of four cascaded 3-dB fiber optical couples (OCs), was used to increase the intra-burst pulse repetition rate to be about 1.1 GHz. Such a GHz high frequency is especially beneficial for the synchronously pumped OPO since the cavity length of the OPO can be greatly shortened to make the OPO compact. The preamplified pulse burst passing through a high-power three-port isolator was then amplified in the final amplifier stage. The burst-mode pulses from the final power amplifier stage was directed to pump the PPMgLN-based OPO. By using a couple of convex lens L1 and L2, the pump laser beam through the isolator was loosely focused into the center of the PPMgLN crystal with a spot diameter of about 250 μm. The PPMgLN was home-fabricated with a domain period of 29.4 μm and size of 50 x10 x1 (mm). The PPMgLN crystal was mounted on a heat sink. Both end surfaces of the crystal were finely polished and antireflection (AR) coated at wavelengths of 1.06 μm, 1.4 to 1.7 μm, and 3.5 to 4.2 μm. Both the input mirror M1 and the output coupler M2 were concave

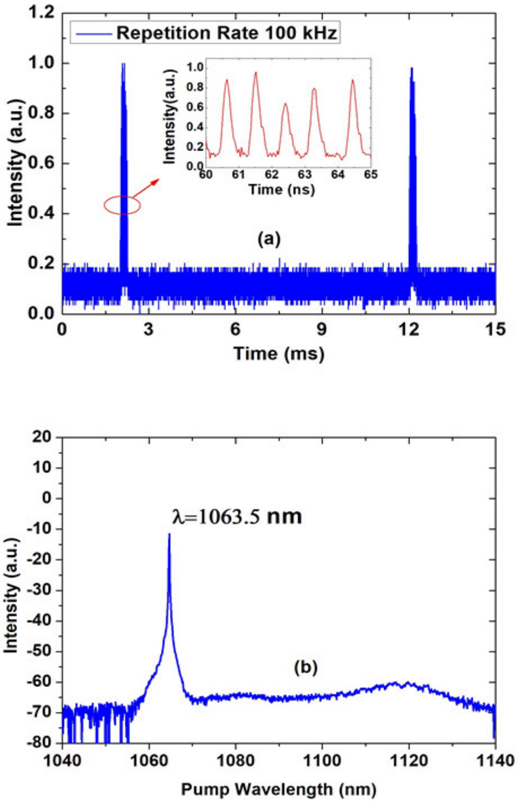

FIGURE 2. Measured (a) burst-mode pulse trains. Inset: Details of the intra-burst pulses. (b) spectrum of the pump fiber laser.

mirrors with a radius of curvature 200 mm and coated with anti-reflective at 1.06 μm and 3 to 5 μm while high reflective from 1.4 to 1.7 μm. The cavity length of the OPO, which was finely tuned to ensure the synchronously pumping and to optimize the parametric conversion, was about 60 mm including 50 mm of the PPMgLN wafer. A dichroic mirror (DM1) with high transmission at the idler wavelength and high reflection at the pump and signal wavelengths was inserted for the idler power measurement. Another dichroic mirror (DM2) was used to separate the pump and signal waves.

III. RESULTS AND DISCUSSION

The pump source of the OPO system was a burst-mode operated fiber laser, which was composed of a DBR laser diode and three amplifier chains. The DBR laser diode was directly modulated for burst-mode operation, and the burst repetition rate was fixed to 100 kHz. Each burst contained the same number of pulses, and the intra-burst repetition rate was set to be about 138 MHz, depending on the specially designed home-made DBR laser driver. As seen in the inset of Fig. 1, a frequency multiplier was employed, which was composed of four cascaded 3-dB fiber optical couplers (OCs). When one signal pulse passes through the first 3-dB OC, it splits into two identical sub-pulses. The two arms are set to different fiber lengths. When these two pulses are combined together by the second coupler, one pulse will be delayed with respect to the other. By choosing the arm length of every OC carefully, frequency multiplied burst-mode pulses can be obtained by generally modulating the intra-burst repetition rate of the seed signal. Therefore, the intra-burst repetition rate and the number of intra-burst sub-pulses were both multiplied by a factor of 8. A maximum output power of 61.2 W was obtained from the burst-mode fiber laser. The slope efficiency was computed to be about 63.2%. After a polarization maintaining isolator (PM ISO), the maximum pump power for OPO was reduced to 45.3 W due to the 1.8 dB loss of the PM ISO. Figure 2(a) shows the measured burst-mode pulse trains from the fiber laser under burst repetition rate of 100 kHz. Due to the use of the OCs, the pulse to pulse stablitly was indeed poor, and the fluctuation of the pulses was calculated to be less than 20%. The wavelength of the pump fiber laser was at 1063.5 nm, as shown in Figure 2(b). The pulse duration of every intra-burst single pulse was measured to be about 200 ps. By increasing the number of intra-burst pump pulses, the pulse energy and pump peak power could be adjusted correspondingly. Actually, the quasi-synchronously pumping scheme is a variant of synchronous pumping technique. For conventional synchronously pumping, the pump pulses are identical and generated uniformly in time, and the period of the pulses should be strictly equal to the round-trip time of the OPO cavity so that the synchronous pumping conditions are matched all the time. In this paper, the pump pulse shape was quite different. It had a rectangular profile in temporal, which was composed of hundreds of ultrashort sub-pulses, as shown in figure 5. Within each rectangular profile, the synchronously pumping conditions were continuously satisfied.

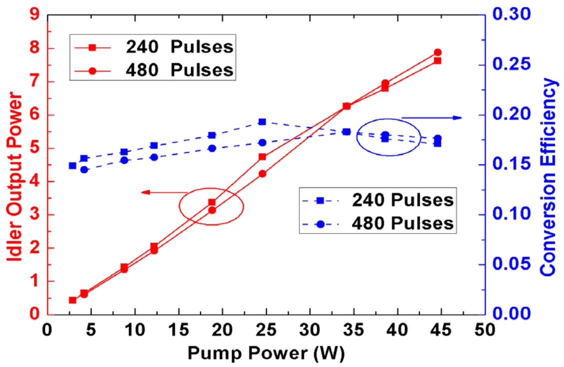

FIGURE 3. Idler output power and pump-to-idler conversion efficiency dependence on the pump power with different number of intra-burst sub-pulses.

The output pulse train from the fiber laser was directed to pump the PPMgLN-based mid-IR OPO system. Figure 3 shows the idler output power and the calculated pump-to-idler conversion efficiency as a function of the pump power with the intra-burst sub-pulses number of 240 and 480. It is clear that the pump peak power was inversely proportional to the number of intra-burst sub-pulses at the same average pump power. To obtain high performance of the OPO system, the output coupler was optimized for each case respectively. As shown in Fig.3, the highest idler output power of 7.9 W was obtained at wavelength of 3.8 μm when the number of intra-burst sub-pulses was set to be 480. The calculated

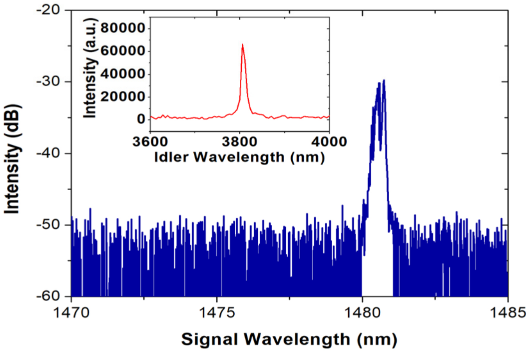

FIGURE 4. **The wavelength of the signal and the idler (inset) of the OPO system.**

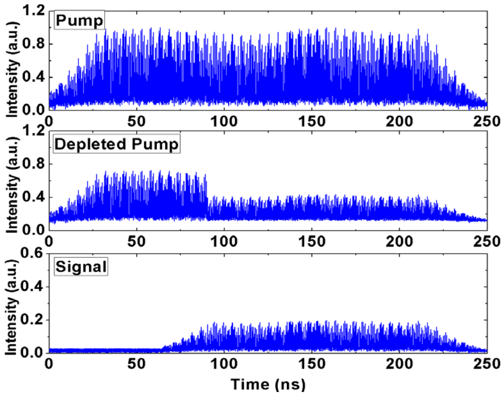

FIGURE 5. **The temporal profiles of the pump, depleted pump and the signal pulses of the OPO system.**

pump-to-idler conversion efficiency was about 17.5%. It was noted that the nonlinear conversion efficiency was almost proportional to the pump power as the pump power increased. However, it was obvious from the curves that there was a roll-off of the conversion efficiency under the pump power above 25 W. We attributed this phenomenon to the extremely high signal wave intensity and idler absorption in the OPO cavity resulted from the high reflectivity (99%) of the output coupler in the signal waveband. Besides, the poor heat dissipation and idler absorption caused temperature fluctuation might be another reason. The spectrum of the signal and idler output were measured via an optical spectrum analyzer (YOKOGAWA AQ6375) and a Fourier transform spectrum analyzer (ARCoptix FTIR-Rocket), respectively, as shown in Figure 4.

At the highest pump power of 45.3 W, the pulse shapes of the pump, the depleted pump and the signal (at 1479 nm) were measured and plotted in Figure 5. The fluctuation of the signal pulses was also been observed. The number of the intra-burst sub-pulses was set to be 240. The burst pulse width of the pump was about 220 ns. It is clear that the sub-pulses of the pump pulse burst were not depleted at the beginning since the lack of signal and idler intensity. The buildup of the signal and idler waves occurred in the first 80 sub-pulses. For the remaining 160 sub-pulses, the pump wave was continually converted into the signal and idler waves. The buildup time was reduced as the pump peak power enhanced and thus the conversion efficiency increased correspondingly. During the parametric conversion process, no back-conversion effect was observed when the pump peak power increased. It has been theoretically pointed out [9] and experimentally confirmed [10], [13], [15], [16] that by using a steep leading edge pulse or rectangular pulse to pump the OPO, the pump energy during the OPO buildup time can be minimized and the back-conversion be eliminated. As known, for a rectangular pulse pumped OPO, the following behavior could occur during the parametric conversion process. If the pump peak power exceeds the threshold, the conversion efficiency will increase with the pump peak power because of the reduced buildup time. But when the pump peak power reaches a certain level, the back-conversion effect will start to emerge, and thus the conversion efficiency will reduce accordingly. Hence, in order to obtain a relative high conversion efficiency, the pump peak power should be kept at a moderate level while the conventional rectangular pump pulse is used. Clearly, the pump pulse shape obtained here was favorable to the OPO operation because it offered similar advantage of the conventional rectangular pump pulse. As mentioned before, the maximum conversion efficiency of 19.6% was not obtained with the highest pump power, and the conversion efficiency was reduced when the pump power exceeded 25 W as shown in Fig. 3. We believed that this phenomenon was attributed to some other limitations, such as thermal effect resulted cavity loss increase in the optical parametric oscillator. To demonstrate the advantages of the quasi-synchronously pumping schemed OPO, a conventional long pulse pumped OPO which was operated with a similar pump peak power and the same PPMgLN crystal was also employed for comparison. Under the maximum pump power of 26 W, the output power of about 3.1 W and the pump-to-idler conversion efficiency of about 12.7% were obtained for the conventional long pulse pumped OPO system. Clearly, a great improvement of 40% in pump-to-idler conversion efficiency was achieved by using the quasi-synchronously pumping scheme.

IV. CONCLUSION

In conclusion, we have carried out investigations of a high conversion efficiency, mid-infrared pulses generated via quasi-synchronously pumped optical parametric oscillator. High power laser emission at 3.8 μm was generated with an average output power up to 7.9 W under the pump power of 45.3 W. By applying the quasi-synchronously pumping scheme, the buildup time of the signal laser pulse could be minimized and no back-conversion effect was observed while the pump peak power was increased. Maximum pump-to-idler conversion efficiency of 19.6% was achieved when the number of intra-burst sub-pulses was set to be 240. Considering the high level of system compactness and high energy output, we believe this high conversion efficiency mid-infrared OPO system will find great practical applications in many fields.

REFERENCES

[1] K. P. Petrov, L. Goldberg, R. F. Curl, F. K. Tittel, and W. K. Burns, "Detection of CO in air by diode-pumped 46-μm difference-frequency generation in quasi-phase-matched LiNbO$_3$," *Opt. Lett.*, vol. 21, no. 1, pp. 86–88, Jan. 1996.

[2] U. Willer, M. Saraji, A. Khorsandi, P. Geiser, and W. Schade, "Near- and mid-infrared laser monitoring of industrial processes, environment and security applications," *Opt. Lasers Eng.*, vol. 44, no. 7, pp. 699–710, Jul. 2006.

[3] H. H. P. T. Bekman, J. C. van den Heuvel, F. J. M. van Putten, and H. M. A. Schleijpen, "Development of a mid-infrared laser for study of infrared countermeasures techniques," *Proc. SPIE* , vol. 5615, pp. 27–38, Dec. 2004.

[4] R. L. Sutherland, *Handbook of Nonlinear Optics*. New York, NY, USA: Marcel Dekker, 1996.

[5] R. Lifshitz, A. Arie, and A. Bahabad, "Photonic quasicrystals for nonlinear optical frequency conversion," *Phys. Rev. Lett.*, vol. 95, no. 13, Sep. 2005, Art. no. 133901.

[6] D. Lin, S.-U. Alam, Y. Shen, T. Chen, B. Wu, and D. J. Richardson, "Large aperture PPMgLN based high-power optical parametric oscillator at 38 μm pumped by a nanosecond linearly polarized fiber MOPA," *Opt. Express*, vol. 20, no. 14, p. 15008, Jul. 2012.

[7] G. K. Samanta, A. Aadhi, and M. Ebrahim-Zadeh, "Continuous-wave, two-crystal, singly-resonant optical parametric oscillator: Theory and experiment," *Opt. Express*, vol. 21, no. 8, pp. 9520–9540, Apr. 2013.

[8] S. Sharabi, G. Porat, and A. Arie, "Improved idler beam quality via simultaneous parametric oscillation and signal-to-idler conversion," *Opt. Lett.*, vol. 39, no. 7, pp. 2152–2155, Apr. 2014.

[9] Z. Sacks, O. Gayer, E. Tal, and A. Arie, "Improving the efficiency of an optical parametric oscillator by tailoring the pump pulse shape," *Opt. Express*, vol. 18, no. 12, pp. 12669–12674, Jun. 2010.

[10] Y. Shen, S.-U. Alam, K. Kang Chen, D. Lin, S. Cai, B. Wu, P. Jiang, A. Malinowski, and D. J. Richardson, "PPMgLN-based high-power optical parametric oscillator pumped by Yb^{3+}-doped fiber amplifier incorporates active pulse shaping," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 2, pp. 385–392, Mar./Apr. 2009.

[11] T. Chen, P. Jiang, D. Yang, C. Hu, B. Wu, and Y. Shen, "High-power PPMgLN-based optical parametric oscillator pumped by a linearly polarized, semi-fiber-coupled acousto-optic Q-switched fiber master oscillator power amplifier," *Appl. Opt.*, vol. 52, no. 25, p. 6316, Sep. 2013.

[12] T. Chen, K. Wei, P. Jiang, B. Wu, and Y. Shen, "High-power multichannel PPMgLN-based optical parametric oscillator pumped by a master oscillation power amplification-structured Q-switched fiber laser," *Appl. Opt.*, vol. 51, no. 28, pp. 6881–6885, Oct. 2012.

[13] L. Wang, Q. Liu, E. Ji, H. Chen, and M. Gong, "40 μm, high repetition rate periodically poled magnesium-oxide-doped lithium niobate mid-infrared optical parametric oscillator pumped by steep leading edge pulsed fiber laser," *Appl. Opt.*, vol. 53, no. 29, pp. 6729–6734, Oct. 2014.

[14] G. Aoust, A. Godard, M. Raybaut, J.-B. Dherbecourt, G. Canat, and M. Lefebvre, "Pump duration optimization for optical parametric oscillators," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 31, no. 12, pp. 3113–3117, Dec. 2014.

[15] Q. Liu, L. Wang, H. Chen, P. Yan, and M. Gong, "High repetition rate, 4 μm mid-infrared generation with periodically poled magnesium-oxide-doped lithium niobate based optical parametric oscillator pumped by fiber laser," *Appl. Phys. Express*, vol. 6, no. 5, pp. 2704–2708, May 2013.

[16] P. Jiang, T. Chen, B. Wu, D. Yang, C. Hu, P. Wu, and Y. Shen, "Compact high power mid-infrared optical parametric oscillator pumped by a gain-switched fiber laser with 'figure-of-h' pulse shape," *Opt. Express*, vol. 23, no. 3, pp. 2633–2638, Feb. 2015.

[17] S. Zhu, "Quasi-phase-matched third-harmonic generation in a quasi-periodic optical superlattice," *Science*, vol. 278, no. 5339, pp. 843–846, Oct. 1997.

[18] T. Chen, B. Wu, W. Liu, P. Jiang, J. Kong, and Y. Shen, "Efficient parametric conversion from 106 to 38 μm by an aperiodically poled cascaded lithium niobate," *Opt. Lett.*, vol. 36, no. 6, pp. 921–923, Mar. 2011.

[19] T. Chen, P. Jiang, B. Wu, R. Shu, C. Hu, and Y. Shen, "Temperature insensitive, high-power cascaded optical parametric oscillator based on an aperiodically poled lithium niobate crystal," *Opt. Express*, vol. 22, no. 22, pp. 26900–26907, Nov. 2014.

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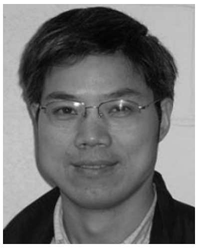

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