# Flexible wavelength conversion via cascaded second order nonlinearity using broadband SHG in MgO-doped PPLN

**Junfeng Zhang, Yuping Chen*, Feng Lu, and Xianfeng Chen****

*The State Key Laboratory on Fiber Optics Local Area Communication Networks and Advanced Optical Communication Systems, Department of Physics, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*

*ypchen@sjtu.edu.cn , **xfchen@sjtu.edu.cn

**Abstract**: In this paper, we experimentally demonstrate flexible wavelength conversion, in which the input signals can be freely converted to output wavelengths through widely and arbitrarily tuning the pump wavelength within a broad second harmonic (SH) bandwidth up to 25 nm. The scheme is based on the cascaded $\chi$ (2) process in a 20-mm periodically poled MgO-doped $LiNbO_3$ (PPMgLN). Also, wavelength broadcasting can be performed by simultaneous use of multiple pumps with wavelengths located in the broad SH bandwidth.



**OCIS codes:** (190.0190) Nonlinear optics; (190.2620) Frequency conversion; (190.4360) Nonlinear optics, devices.

## References and links

1. C. Q. Xu, H. Okayama, and M. Kawahara, "1.5 μm band efficient broadband wavelength conversion by difference frequency generation in a periodically domain-inverted $LiNbO_3$ channel waveguide," Appl. Phys. Lett. **63**, 3559-3561(1993)
2. M. H. Chou, J. Hauden, M. A. Arbore, and M. M. Fejer, "1.5-µm-band wavelength conversion based on difference-frequency generation in $LiNbO_3$ waveguides with integrated coupling structures," Opt. Lett. **23**, 1004-1006 (1998).
3. K. Gallo, G. Assanto, and G. Stegeman, "Efficient wavelength shifting over the erbium amplifier bandwidth via cascaded second order processes in lithium niobate waveguides," Appl. Phys. Lett. **71**, 1020–1022 (1997).
4. M. H. Chou, I. Brener, M. M. Fejer, E. E. Chaban, and S. B. Christman, "1.5-µm-band wavelength conversion based on cascaded second-order nonlinearity in $LiNbO_3$ channel waveguide," IEEE Photon. Technol. Lett. **11**, 653-655 (1999).
5. X. L. Zeng, X. F. Chen, Y. P. Chen, Y. X. Xia, and Y. L. Chen, "Observation of all-optical wavelength conversion based on cascaded effect in periodically poled lithium niobate waveguide," Opt. Laser Technol. **35**, 187-190 (2003).
6. Y. L. Lee, C. Jung, Y. -C. Noh, M. Park, C. Byeon, D. -K. Ko, and J. Lee, "Channel-selective wavelength conversion and tuning in periodically poled Ti:$LiNbO_3$ waveguides," Opt. Express **12**, 2649-2655 (2004).
7. J. Wang, J. Sun, C. Lou, and Q. Sun, "Experimental demonstration of wavelength conversion between ps-pulses based on cascaded sum- and difference frequency generation (SFG+DFG) in $LiNbO_3$ waveguides," Opt. Express **13**, 7405-7414 (2005).
8. Y. H. Min, J. H. Lee, Y. L. Lee, W. Grundköter, V. Quiring, and W. Sohler, "Tunable all-optical wavelength conversion of 5-ps pulses by cascaded sum- and difference frequency generation (cSFG/DFG) in a Ti:PPLN waveguide," OFC '03, Atlanta, GA/USA, March 2003, 767-768.
9. H. Furukawa, A. Nirmalathas, N. Wada, S. Shinada, H. Tsuboya, and T. Miyazaki, "Tunable all-optical wavelength conversion of 160-Gb/s RZ optical signals by cascade SFG-DFG generation in PPLN waveguide," IEEE Photon. Technol. Lett. **19**, 384-386 (2007).
10. M. H. Chou, K. R. Parameswaran, M. M. Fejer, and I. Brener, "Multiple-channel wavelength conversion by use of engineered quasi-phase-matching structures in $LiNbO_3$ waveguides," Opt. Lett. **24,** 1157-1159 (1999).
11. M. Asobe, O. Tadanaga, H. Miyazawa, Y. Nishida, and H. Suzuki, "Multiple quasi-phase-matched $LiNbO_3$ wavelength converter with a continuously phase-modulated domain structure," Opt. Lett. **28**, 558-560 (2003).
12. E. Yamazaki, A. Takada, J. Yamawaku, T. Morioka, O. Tadanaga, and M. Asobe, "Simultaneous and Arbitrary Wavelength Conversion of WDM Signals Using Multiple Wavelength Quasi Phase Matched $LiNbO_3$ waveguide," OFC '04, Los Angels/USA, paper FL6 (2004).

#91465 - $15.00 USD Received 7 Jan 2008; revised 28 Mar 2008; accepted 28 Mar 2008; published 1 May 2008

13. Y. W. Lee, F. C. Fan, Y. C. Huang, B. Y. Gu, B. Z. Dong, and M. H. Chou, "Nonlinear multiwavelength conversion based on an aperiodic optical superlattice in lithium niobate," Opt. Lett. **27**, 2191-2193 (2002).
14. B. Zhou, C.-Q. Xu, B. Chen, Y. Nihei. A. Harada, X. F. Yang, and C. Lu, "Efficient 1.5-µm-band MgO-doped $LiNbO_3$ quasi-phase-matched wavelength converters," Jpn. J. Appl. Phys. **40**, 796-798, (2001).
15. C. -Q. Xu and B. Chen, "Cascaded wavelength conversions based on sum-frequency generation and difference-frequency generation," Opt. Lett. **29**, 292-294 (2004).
16. N . E. Yu, J. H. Ro, M. Cha, S. Kurimura, and T. Taira, "Broadband quasi-phase-matched second-harmonic generation in MgO-doped periodically poled $LiNbO_3$ at the communications band," Opt. Lett. **27**, 1046-1048 (2002).
17. J. Zhang, Y. Chen, F. Lu, W. Lu, W. Dang, X. Chen, and Y. Xia, "Effect of MgO doping of periodically poled lithium niobate on second-harmonic generation of femtosecond laser pulses," Appl. Opt. **46,** 7792-7796 (2007).
18. Y. Chen, R. Wu, X. Zeng, Y. Xia and X. Chen, "Type-I Qaphase-matched blue secong harmonic generation with different polarization in periodically poled $LiNbO_3$," Opt. Laser Technol. **38**, 19-22 (2006).
19. D. E. Zelmon, D. L. Small, and D. Jundt, "Infrared corrected Sellmeier coefficients for congruently grown lithium niobate and 5 mol.% magnesium oxide –doped lithium niobate," J. Opt. Soc. Am. B **14**, 3319-3322 (1997).
20. D. Gurkan, M. C. Hauer, A. B. Sahin, Z. Pan, S. Lee, A. E. Willner, K. R. Parameswaran and M. M. Fejer, "Demonstration of multi-wavelength all-optical header recognition using a PPLN and optical correlators," in Proc. 27th Eur. Conf. Opt. Commun., Amsterdam The Netherlands: Sep. 30-Oct. 4 2001,Vol. 3, pp. 312-313.
21. C. Langrock, S. Kumar, J. E. McGeehan, A. E. Willner, and M. M. Fejer, "All-Optical Signal Processing Using $\chi^{(2)}$ Nonlinearities in Guided-Wave Devices," J. Lightwave Technol. **24**, 2579-2592 (2006).

## 1. Introduction

All optical wavelength conversion is essential for all-optical signal processing, especially for dense wavelength division multiplexed (DWDM) optical networks. Future DWDM optical networks require wavelength conversion to route and switch the information carried by different wavelengths/channels, which can help optical networks to overcome wavelength channel contentions, and fulfill higher flexibility and efficiency in traffic management and dynamic reconfiguration. Among various wavelength conversion approaches, the wavelength converter based on quasi-phase-matching (QPM) nonlinear materials is of great attraction, for this kind of wavelength converter has the advantages of high speed, low noise and complete transparency to the signal format owing to its pure optical nonlinear processes. Moreover, broadcasting wavelength conversion based on QPM technique may play a significant role in future DWDM networks such as video distribution and teleconferencing.

Wavelength conversion through QPM-difference-frequency generation (DFG) has been realized in periodically poled lithium niobate (PPLN) waveguides [1,2]. DFG-based converter shows high conversion efficiency, but is complicated in mode matching of signal light (1.5-µm-band) and pump light (0.77-µm-band). To mitigate the mode matching complication, wavelength conversion based on cascaded $\chi$ (2) process involving cascaded second-harmonic generation (SHG) and DFG (cSHG/DFG) or cascaded sum- and difference frequency generation (cSFG/DFG) was proposed and demonstrated [3-9]. In these schemes, the pump band is narrow and therefore signals can only be switched to limited wavelengths, resulting in poor flexibility of the converter. By imposing intentionally designed structure to QPM device, multiple pumps in a large wavelength tuning range can be realized, which improves the flexibility of the converter [10-13]. However, the pump wavelength channels are discrete and cannot be adjusted once the designed QPM structures are formed.

Besides, the operation temperature of the above PPLN-based wavelength converter should be set high enough (90 ºC or higher) to eliminate photorefractive damage (PRD) effect induced by strong pump power, causing much inconvenience for practical application [6,10,11]. In order to enable the device to work at lower temperature, MgO-doped PPLN (PPMgLN) with large PRD resistance was proposed to fabricate wavelength converter [14,15].

To pursue highly flexible wavelength conversion with lower operation temperature, a broad and continuous pump band in PPMgLN is needed to ensure that the input signals can be freely converted to the desired output channels. It is noticed that broadband type I QPM SHG in PPLN has been proposed and realized [16-18]. However, to the best of our knowledge,

#91465 - $15.00 USD Received 7 Jan 2008; revised 28 Mar 2008; accepted 28 Mar 2008; published 1 May 2008

highly flexible wavelength conversion by arbitrarily tuning pump wavelengths using this type QPM broad second-harmonic (SH) bandwidth has not yet been reported.

In this paper, for the first time, flexible wavelength conversion via cSHG/DFG process is experimentally demonstrated by arbitrarily tuning the pump wavelength within the broad and continuous SH bandwidth. The pump SH bandwidth is large up to 25 nm and obtained by the type-I QPM SHG at 38 ºC in a 20-mm-long bulk PPMgLN. Also, potential wavelength broadcasting with transparent bit-rate is also proposed by simultaneously employing multiple pumps within the broad SH bandwidth, which is very attractive for the future all-optical networks.

## 2. SHG characteristics

A Z-cut 5-mol. % MgO-doped PPMgLN for the wavelength converter was fabricated by the electrical poling method. The QPM grating period is 20.4µm, which enables the device to perform 1.5-µm-band wavelength conversion. Using type I interaction, a broadband SHG can be realized in this device, because QPM and group velocity matching (GVM) conditions are simultaneously satisfied at proper wavelength and temperature [16-18]. The dimension of this device is 20mm×10mm×0.5mm. By carefully tuning the pump wavelength and temperature, we obtain broadband SHG as plotted in Fig. 1. The circles are experimental results with pump wavelength tuning from 1540 nm to 1572 nm. The solid line is the theoretical curve of a broad SH bandwidth calculated by Sellmeier equations of 5-mol. % MgO-doped PPMgLN with a grating period of 20.4µm [19]. The peak normalized SH efficiency is 0.1%/W with incident pump power of 300 mW when the pump wavelength is 1562 nm at 38 ºC. The full width at half maximum (FWHM) of SH efficiency, namely SH bandwidth, is about 25nm for the 20-mm-long PPMgLN. This broad SH bandwidth can be used for arbitrarily tuning pump wavelengths to yield free output wavelengths, as well as for simultaneously employing multiple pumps to perform wavelength broadcasting.

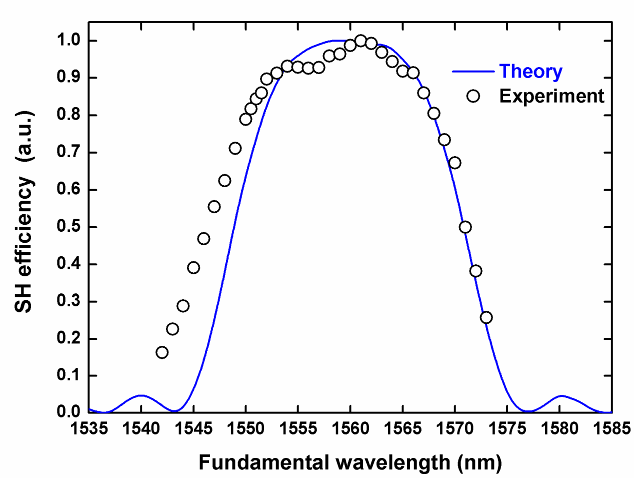


Fig. 1. SHG wavelength tuning curve for PPMgLN with a 20.4 µm grating period. The circles and solid line indicate the experimental and theoretical results, respectively. At 38 ºC, the peak normalized SH efficiency is 0.1%/W at 1562 nm. The measured SH bandwidth is about 25 nm.

We also measured the temperature tolerance of the device as shown in Fig. 2, which is important to SHG process. The pump wavelength is fixed at 1562 nm when the temperature is tuned. The circles are experimental data and the solid line is the best fitting to them. From Fig. 2, we can find that the optimal temperature is 38 ºC, at which the SH efficiency reaches its maximum value. The measured 3dB temperature bandwidth is 0.9 ºC.

#91465 - $15.00 USD Received 7 Jan 2008; revised 28 Mar 2008; accepted 28 Mar 2008; published 1 May 2008

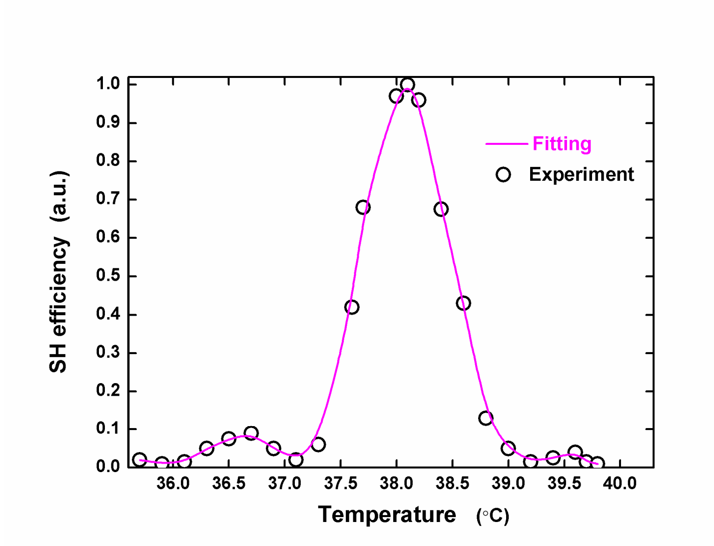


Fig. 2. SHG temperature tuning curve. The pump wavelength is fixed at 1562 nm. The circles are experimental results and the solid line is the best fit of the experimental data. The optimal SHG temperature is 38 ºC. The measured temperature bandwidth is 0.9 ºC

## 3. Experimental results and discussion

Figure 3 shows the schematic diagram of the experimental setup for flexible wavelength conversion. Two tunable lasers act as the pump and signal source, respectively. Both the pump and signal light are mixed by a 90:10 coupler and then boosted by an erbium-doped fiber amplifier (EDFA). Loose focusing is employed in the experiment with a 10 cm focus lens to obtain output beam size of 150 µm in PPMgLN sample. The temperature of PPMgLN is controlled by a temperature controller with an accuracy of 0.1 ºC. The output light from the converter is observed by an optical spectrum analyzer (OSA). Since we use type I SHG, two polarization controllers (PC) are implemented to ensure that the pump and signal lights are both ordinary lights for Z-cut PPMgLN. No output SH light was observed when the pump and signal were extraordinary lights.

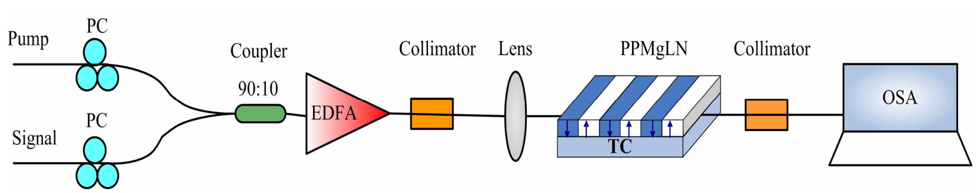


Fig. 3. Schematic diagram of the experimental setup; PC: polarization controller, EDFA: erbium-doped fiber amplifier, PPMgLN: periodically poled MgO-doped lithium niobate, TC: temperature controller, OSA: optical spectrum analyzer.

The mechanism for wavelength conversion based on cSHG/DFG process comprises of two steps. First, the pump light with frequency $\omega_p$ is doubled to SH frequency $2\omega_p$ by SHG process. Then, the frequency of signal light $\omega_s$ is converted to the frequency of converted light $\omega_c$ ($\omega_c=2\omega_p-\omega_s$) by DFG process. The measured wavelength conversion diagram with pump tuning is shown in Fig. 4.

#91465 - $15.00 USD Received 7 Jan 2008; revised 28 Mar 2008; accepted 28 Mar 2008; published 1 May 2008

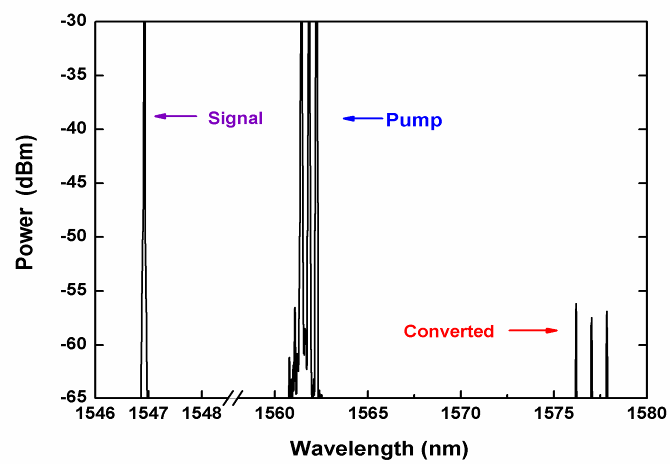


Fig. 4. Measured wavelength conversion with pump tuning. The signal wavelength is fixed at 1546.92 nm. The pump wavelength is selected to be 1561.42, 1561.83, 1562.23 nm in the broad SH bandwidth, and the correspondingly converted lights are at the wavelengths of 1576.20, 1577.03 and 1577.86 nm, respectively. Three individual optical spectrums are combined to form this plot.

In the experiment, the signal wavelength is fixed at 1546.92 nm. The pump wavelength is tuned to 1561.42, 1561.83, 1562.23 nm, and the correspondingly converted lights are at the wavelengths of 1576.20, 1577.03 and 1577.86 nm, respectively. The three pump wavelengths are selected according to International Telecommunication Union (ITU) grid with 50GHz spacing to obtain three converted lights with 100 GHz spacing. Figure 4 is the combination of the three individual optical spectrums. In Fig. 4, one fixed input signal is freely converted to three different output channels pumped by three different wavelengths within the broad SH pump bandwidth. In our experiment, from the OSA spectrum, we observed that the peak intensities of signal and pumps were about 6 and 14 dBm, which has exceeded the maximum of the vertical axis of Fig. 4. This scheme provides more flexibility for wavelength conversion than the approaches using narrow band pump [5]. However, we noticed that the experiment exhibits low conversion efficiencies (-62.3, -63.2 and -62.9 dB respectively), which mainly results from the use of the nonlinear coefficient d31 in SHG and the lack of guiding structure in bulk PPMgLN. Currently, we are not able to measure the DFG signal bandwidth. In our experiment, due to the low conversion efficiency, the signal should be amplified by a high power EDFA, which only covers C-band window. This problem will also be mitigated by fabricating waveguide structure on bulk device and the related work is in progress. We can further enhance the conversion efficiency by increasing the device length and pump power [4]. The expected conversion efficiency can be around -30dB in PPMgLN waveguide.

To demonstrate the merit of the wide and continuous SHG pump wavelength bandwidth, we perform a highly flexible wavelength conversion by using 9 pumps separately. The experimental results are illustrated in Fig. 5, in which limited wavelength conversion using narrow band pump is compared with our results. In Fig. 5(a), the input signals (1545.32, 1548.51 and 1551.72 nm) can only be converted to another fixed corresponding wavelengths (1582.85, 1579.52 and 1576.20 nm) by a single pump (1563.86 nm) for the narrow pump band. While in Fig. 5(b), each of the three input signals with 400 GHz spacing (1545.32, 1548.51 and 1551.72 nm) is converted to one output of the three channels with 100 GHz spacing (1574.54, 1575.37 and 1576.20 nm) by a selected pump. Hence, a highly flexible wavelength conversion, in which each of the 3 inputs can be switched to each of the 3 outputs arbitrarily, is demonstrated by employing 9 pumps separately. In this flexible wavelength

#91465 - $15.00 USD Received 7 Jan 2008; revised 28 Mar 2008; accepted 28 Mar 2008; published 1 May 2008

conversion shown in Fig. 5, the 9 pumps are of 1559.79, 1560.20, 1560.61, 1561.42, 1561.83, 1562.23, 1563.05, 1563.45 and 1563.86 nm, which are all located at the broad SH pump bandwidth respectively.

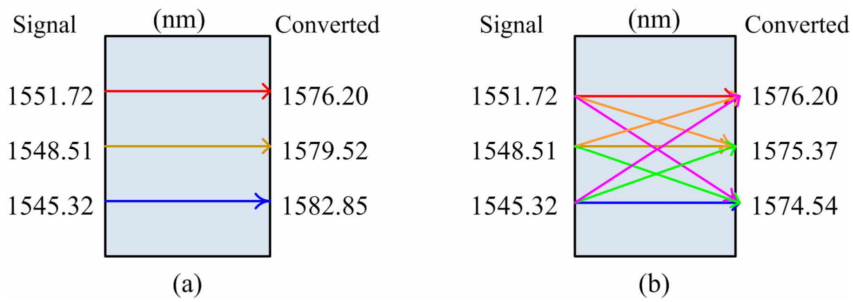


Fig. 5. Limited wavelength conversion by narrow band pump versus flexible wavelength conversion by broadband pump. (a) Input signals are converted to fixed channels by a single pump (1563.86 nm). (b) Flexible wavelength conversion using 9 pumps separately

Furthermore, by simultaneously using M pumps within the broad SH bandwidth of 25 nm, our wavelength conversion scheme can perform N×M wavelength broadcasting, in which each of N input signal lights can be converted by M pumps to M output wavelengths. However, due to the total pump tolerance, each of the M pumps will be lower than the single pump, resulting in efficiency dropping for wavelength broadcasting. In addition, multiple pumps can be used to enable simultaneous multi-channel all-optical header recognition, and to perform a multi-pole multi-throw switch, in which several inputs are directed to a set of outputs [20,21].

## 4. Conclusion

In conclusion, we have experimentally demonstrated flexible wavelength conversion based on cSHG/DFG process in a 20-mm long bulk PPMgLN, which employs a broadband SHG with a 25 nm pump wavelength bandwidth. In our scheme of wavelength conversion, there is another advantage of large temperature tolerance of 0.9 ºC. Also by simultaneously using multiple pumps, the device can perform N×M wavelength broadcasting potentially by employing PPMgLN waveguide. The low conversion efficiency can also be enhanced if adopting the waveguide structure in our experiment. Based on the flexible wavelength conversion scheme proposed in this paper, future works will focus on improving the performance of wavelength conversion, especially exploring its various applications to accommodate the rapidly increasing demands on the high speed and large capacity optical communications.


## Acknowledgments

This research is supported by the National Natural Science Foundation of China (60407006), the National High Technology Research and Development Program (863) of China (No.2007AA01Z273), the National High Technology Research and Development Program (973) of China (No. 2006CB806000) , and the Shanghai Leading Academic Discipline Project (No. B201).