Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optics Communications 233 (2004) 205–209
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Broadband and multiple-channel visible laser generation by use of segmented quasi-phase-matching gratings

Shiming Gao *, Changxi Yang, Xiaosheng Xiao, Guofan Jin

State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing 100084, PR China

Received 24 October 2003; received in revised form 16 January 2004; accepted 20 January 2004

Abstract

We investigate frequency conversion of near-infrared laser sources to generate visible laser outputs with segmented quasi-phase-matching (QPM) gratings through second-harmonic generation process. Analysis shows that segmented gratings have much broader conversion bandwidth and environment temperature tolerance than periodic gratings, which is extremely beneficial for reducing the difficulties of QPM for both laser sources and temperature-controlled devices. By use of a near-infrared broadband laser source, segmented gratings provide potential to realize multichannel visible laser sources that have many applications in, such as, high-density optical storage and high-definition television.

PACS: 42.65.K; 42.79.N; 42.65

Keywords: Frequency conversion; Segmented grating; Second-harmonic generation; Quasi-phase matching

---

1. Introduction

In recent years, quasi-phase-matching (QPM) optical frequency conversion becomes important for generating new laser frequencies with the development of the domain-inversion technologies. Many optical frequency conversion schemes have been demonstrated, for example, second-harmonic generation (SHG) [1–6], difference-frequency generation (DFG) [7], sum-frequency generation (SFG) [8] and third-harmonic generation (THG) [9,10]. Solid-state laser sources in the visible region have many applications, such as biomedicine, medical treatment, optical storage and high-definition television. Using SHG pumped by a near-infrared laser in a QPM structure is a feasible scheme to obtain a visible laser source. In this method, the largest nonlinear coefficient of the crystal is used, which is beneficial for increasing the intensity of the frequency-doubled laser source.

Periodically domain-inverted structures have been widely utilized in $LiTaO_3$ [1,2], $LiNbO_3$ [3,4], KTP [5] and other ferroelectric crystals [6]. As we know, the high transmission region of $LiNbO_3$ is from 0.4 to 5 μm. The absorption and dispersion

---

* Corresponding author. Tel.: +861062795433; fax: +861062784691.
E-mail address: gsm00@mails.tsinghua.edu.cn (S. Gao).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2004.01.034

are lower and the optical damage threshold is higher compared with other crystals. All these properties ensure wide applications of $LiNbO_3$ in laser frequency conversion. Although the periodically QPM structure is easy to be manufactured, the conversion bandwidth is quite narrow, that is, very high quality laser sources are required and the processes are difficult to be operated and controlled. In general, the wavelength bandwidth and temperature tolerance can be enhanced in aperiodic QPM gratings, even multichannel generation is realized [11–13]. In this paper, we concentrate on the investigation of SHG in segmented QPM gratings to broaden the conversion bandwidth and the temperature tolerance, and realize multiple-channel generation.

2. Theoretical analysis

As shown in Fig. 1, the segmented QPM grating is supposed to be fabricated in a Z-cut and X-propagating $LiNbO_3$ crystal and consists of N segments. The device total length is L. The length and the period of each segment are L_i and Λ_i ($i = 1, 2, \ldots, N$). For segment m, the couple equations are expressed as [14,15]

$$\frac{\mathrm{d}A_{1m}}{\mathrm{d}x} = -\mathrm{j}\kappa A_{1m}^{*} A_{2m} \mathrm{e}^{-\mathrm{j}\Delta\Phi_m}, \tag{1}$$

$$\frac{\mathrm{d}A_{2m}}{\mathrm{d}x} = -\mathrm{j}\kappa A_{1m}^{2} \mathrm{e}^{\mathrm{j}\Delta\Phi_m}, \tag{2}$$

where A_1 and A_2 denote the amplitudes of the fundamental signal and the second harmonic respectively. κ is the nonlinear coefficient, and $\Delta\Phi_m$ is the phase mismatch in segment m. They are written as

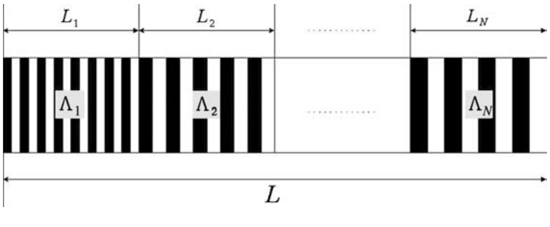

Fig. 1. Schematic description of the segmented QPM grating.

$$\kappa = \frac{\pi d_{\mathrm{eff}}}{n_1 \lambda_1} \sqrt{\frac{2}{\varepsilon_0 c n_2 A_{\mathrm{eff}}}}, \tag{3}$$

$$\Delta\Phi_m = \sum_{i=1}^{m-1} \Delta k_i L_i + \Delta k_m \left(x - \sum_{i=1}^{m-1} L_i \right) \tag{4}$$

and

$$\Delta k_i = k_2 - 2k_1 - 2\pi/\Lambda_i. \tag{5}$$

Here d_{eff} is the effective nonlinear coefficient, A_{eff} is the effective interaction area, λ_1 is the fundamental wavelength, n_1 and n_2 are the refractive indices for the fundamental signal and the second harmonic, and k_1 and k_2 are their wave numbers.

In a periodic QPM grating, the grating period at room temperature is determined by

$$\Lambda_0 = \frac{\lambda_1/2/(n_2 - n_1)}{1 + \alpha(T - T_0)}, \tag{6}$$

where T_0 is the room temperature, T is the working temperature, and α is the expansion coefficient. The segmented grating we proposed here is designed near the periodic grating period shown in Eq. (6).

For SHG, the fundamental amplitude is supposed as $A_1(0) = \sqrt{P_1}$, where P_1 is the incident fundamental power at the beginning of the device, and the amplitude of the second harmonic is $A_2(0) = 0$. With these original conditions, the generated second harmonic power at the end of the device that is denoted as $P_2(L)$ can be calculated through numerical iterative method. The conversion efficiency is defined as

$$\eta = 10\lg[P_2(L)/P_1]. \tag{7}$$

The conversion bandwidth is defined as the wavelength region more than half of the maximum efficiency. Similarly, the temperature tolerance is the temperature region where the efficiency is higher than half of the maximum.

3. Results and discussion

We suppose the segmented grating is fabricated at room temperature of 25 °C. The expansion coefficient of $LiNbO_3$ is 16.7×10^{-6}/°C and the effective nonlinear coefficient is calculated as $d_{\mathrm{eff}} =$

$(2/\pi)d_{33}$, where $d_{33} = 27$ pm/V. The fundamental wavelength is 1.0642 μm, and the effective interaction area is 100 μm^2. In order to reduce the optical damage, the working temperature is chosen as 65.5 °C. The corresponding period of the periodic QPM grating should be 6.900 μm. We compare the 2-segment and 3-segment gratings with the periodic grating, where the 2-segment grating periods are 6.900 and 6.893 μm, respectively, and the 3-segment grating periods are 6.900, 6.891 and 6.882 μm. For comparison, we suppose the three gratings are all 15-mm long. In each grating, the segments are equal in length.

With a fundamental power of 1 W, we simulate the conversion efficiencies versus the fundamental wavelength for the three devices in Fig. 2. It is shown that the segmented gratings enhance the conversion bandwidth compared with the periodic grating. The bandwidths are 0.13, 0.51, and 1.14 nm for the periodic, 2-segment, and 3-segment gratings, respectively. The bandwidth of the 2-segment grating is 3.92 times as large as that of the periodic grating, and the 3-segment grating is 8.77 times. When the bandwidth is increased, the conversion efficiency is reduced as a penalty. For example, the efficiencies of the periodic, 2-segmented, and 3-segmented gratings are 32.9%, 11.9%, and 6.5%, respectively. The conversion efficiencies are calculated by adjusting the working temperature when the fundamental wavelength is fixed at 1.0642 μm, as shown in Fig. 3. Similarly, the temperature tolerances of the segmented gratings are broader than that of the periodic grating. They are 1.6, 6.2, and 13.0 °C for the periodic, 2-segment, and 3-segment gratings, respectively. The tolerances of the 2-segment and 3-segment gratings are 3.88 and 8.13 times as large as that of the periodic grating.

For segmented gratings, the QPM conditions are easy to be satisfied in relatively wider laser wavelengths and larger temperature region because of the enhancement of bandwidth and temperature tolerance. The requirement to laser source stability and environment temperature accuracy is greatly reduced. The more segments, the broader the conversion bandwidth and temperature tolerance, however, the lower the conversion efficiency. As shown in Figs. 2 and 3, the efficiencies of the segmented gratings are less than that of the periodic grating. Fortunately, the power of the solid-state lasers in the near-infrared region can reach even several tens of watts. It is possible to increase the

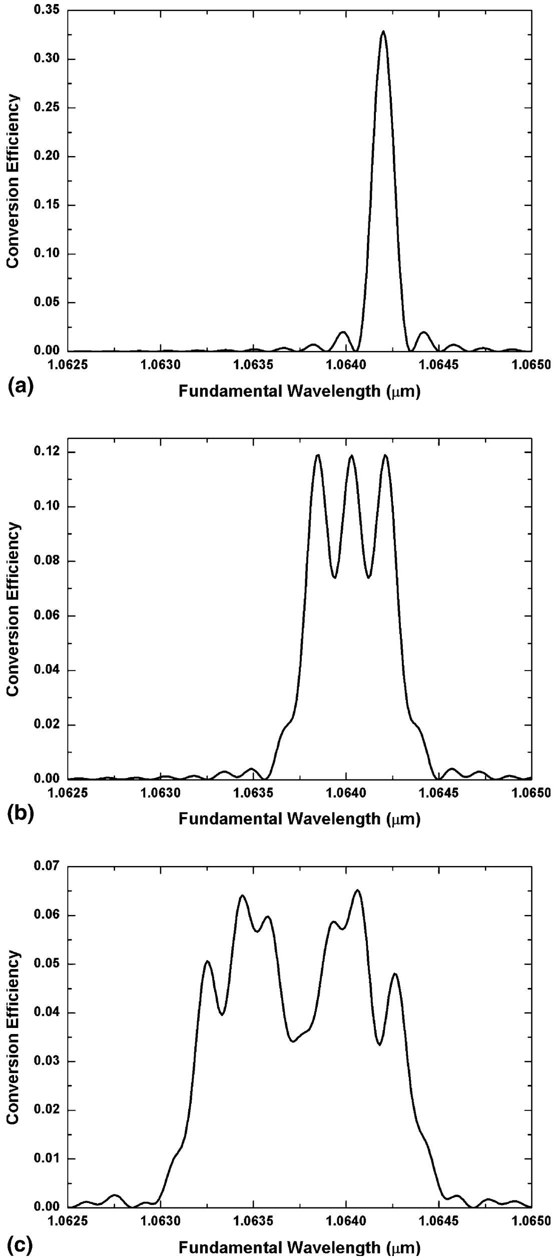

Fig. 2. SHG conversion response versus the fundamental wavelength for: (a) the periodic grating; (b) the 2-segment grating; (c) the 3-segment grating.

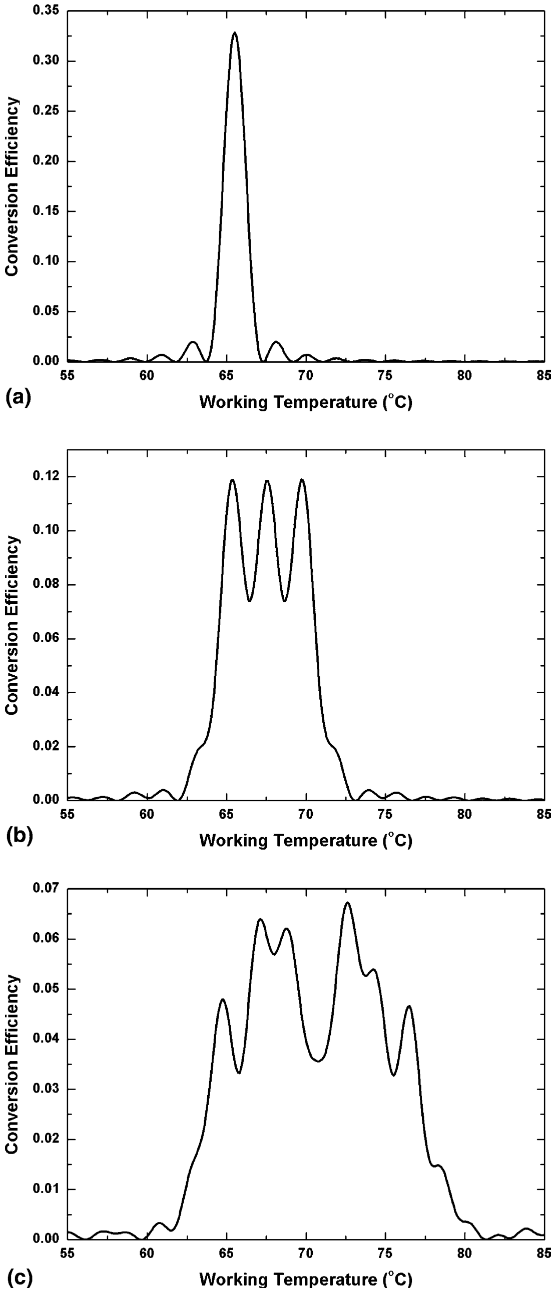

Fig. 3. SHG conversion response versus the working temperature for: (a) the periodic grating; (b) the 2-segment grating; (c) the 3-segment grating.

output power by use of high power fundamental lasers. In addition, the response flatness is affected when the segments are more. The grating should be limited within three segments by taking into consideration all these factors.

It is possible to realize multichannel frequency conversion with segmented gratings. As shown in Fig. 4, the conversion efficiencies versus the fundamental wavelength are plotted for the 2-segment and 3-segment gratings, where the periods of the 2-segment grating are 6.900 and 6.870 μm, and the periods of the 3-segment grating are 6.900, 6.870 and 6.840 μm, respectively. The two gratings have the same length of 15 mm. For each grating, the segments are equally long. In Fig. 4, the number of conversion channels is the same as the segment number of the grating. If a broadband laser source in the near-infrared region is used as the incident fundamental signal, multiple channel visible lasers can be generated simultaneously. Adjusting the segmented grating periods can change the gener-

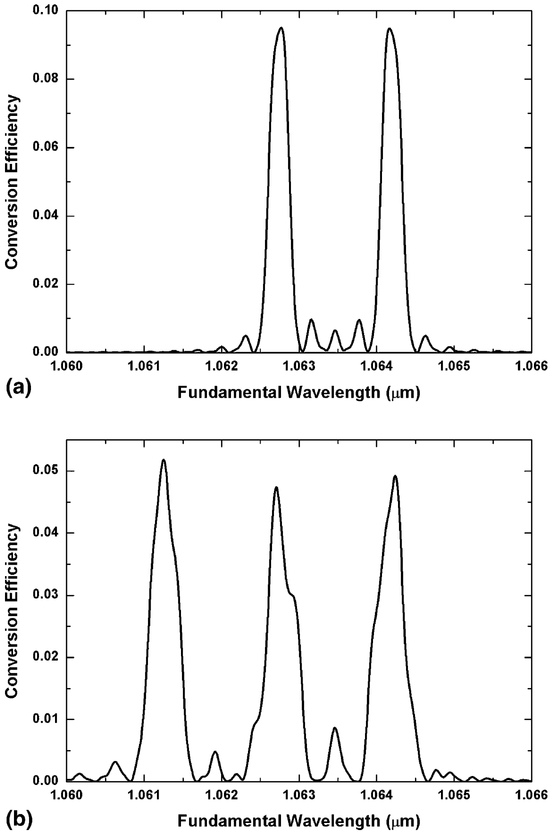

Fig. 4. Multichannel frequency conversion by use of: (a) the 2-segment grating; (b) the 3-segment grating.

ated wavelengths. Since the conversion efficiency is reduced with the channel number increasing, the segment number should be chosen by taking into consideration the requirement of the channel number and efficiency synthetically in practical applications.

4. Conclusion

We have investigated frequency conversion from the near-infrared region to the visible region by SHG in segmented QPM gratings. The segmented gratings show much broader conversion bandwidth and temperature tolerance. They are about four and eight times as large as those of the periodic grating for the 2-segment and 3-segment gratings. Segmented gratings make it possible to realize multiple-channel laser sources in the visible region with near-infrared broadband laser sources.

Acknowledgements

This work is supported in part by the Trans-Century Training Programme Foundation for the Talents by the Ministry of Education of China.

References

[1] K. Mizuuchi, K. Yamamoto, Appl. Phys. Lett. 60 (1992) 1283.
[2] J.P. Meyn, M.M. Fejer, Opt. Lett. 22 (1997) 1214.
[3] K.R. Parameswaran, J.R. Kurz, R.V. Roussev, M.M. Fejer, Opt. Lett. 27 (2002) 43.
[4] P. Ni, B. Ma, X. Wang, B. Cheng, D. Zhang, Appl. Phys. Lett. 82 (2003) 4230.
[5] U.L. Andersen, P. Buchhave, Opt. Express 10 (2002) 887.
[6] H.Y. Chen, J.S. Sue, Y.H. Lin, S. Chao, Opt. Lett. 28 (2003) 917.
[7] M. Fujimura, A. Shiratsuki, T. Suhara, H. Nishihara, Jpn. J. Appl. Phys. 37 (1998) L659.
[8] D. Taverner, P. Britton, P.G.R. Smith, D.J. Richardson, G.W. Ross, D.C. Hanna, Opt. Lett. 23 (1998) 162.
[9] K. Koch, G.T. Moore, J. Opt. Soc. Am. B 16 (1999) 448.
[10] S.N. Zhu, Y.Y. Zhu, N.B. Ming, Science 278 (1997) 843.
[11] S.N. Zhu, Y.Y. Zhu, Y.Q. Qin, H.F. Wang, C.Z. Ge, N.B. Ming, Phys. Rev. Lett. 78 (1997) 2752.
[12] H. Liu, S.N. Zhu, Y.Y. Zhu, N.B. Ming, X.C. Lin, W.J. Ling, A.Y. Yao, Z.Y. Xu, Appl. Phys. Lett. 81 (2002) 3326.
[13] J. Liao, J.L. He, H. Liu, H.T. Wang, S.N. Zhu, Y.Y. Zhu, N.B. Ming, Appl. Phys. Lett. 82 (2003) 3159.
[14] T. Suhara, H. Nishihara, IEEE J. Quantum Electron. 26 (1990) 1265.
[15] L.E. Myers, R.C. Eckardt, M.M. Fejer, R.L. Byer, W.R. Bosenberg, J.W. Pierce, J. Opt. Soc. Am. B 12 (1995) 2102.