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Generation of the second harmonic in ridge waveguides formed in periodically poled lithium niobate

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***Abstract*. Generation of the second harmonic of semiconductor laser radiation in the IR range (980–1140 nm) in ridge waveguides with a large refractive index step, formed in periodically poled nonlinear $LiNbO_3$ crystals, is demonstrated. Ridge waveguides have been prepared by precise cutting using a diamond microsaw. Spectral dependences of the SHG power and intensity distributions in the near field of second harmonic and pump radiations have been measured. The results obtained indicate good prospects of designing tunable laser radiation sources in the visible range due to the SHG in ridge waveguides formed in periodically poled nonlinear crystals under semiconductor laser pumping.**

Keywords: *SHG, periodically poled crystal, ridge waveguide, semiconductor laser.*

1. Introduction

Tunable visible light sources are applied in many promising fields of science and technology, such as biomedicine [1], fluorescent microscopy [2], and spectroscopy [3]. Semiconductor lasers are most preferred for these purposes due to their high efficiency and compactness. Unfortunately, a rather large part of visible range cannot be covered by means of direct generation of semiconductor laser radiation. An alternative approach is frequency doubling using waveguide nonlinear periodically poled crystals. As was shown recently [4, 5], to implement second harmonic frequency tuning in multimode waveguides (induced in nonlinear periodically poled crystals), one must provide quasi-phase-matching conditions for different waveguide modes of the fundamental and second harmonic waves. The tuning spectral range depends directly on the refractive index step between the waveguide core and cladding; increasing this step, one can extend the tuning range. A number of studies have been devoted to the formation of ridge waveguides based on periodically poled lithium niobate (PPLN) for efficient SHG [6–10]. In these studies, a thin PPLN layer was first formed using ion implantation [6] or bringing a PPLN plate into contact with a lithium niobate plate of another orientation or with a lithium tantalate plate, with subsequent thinning of the PPLN plate by means of grinding and polishing [7–10]. Ridge waveguides were cut by a disk microsaw from a planar waveguide. These approaches made it possible to obtain a large refractive index step between the ridge waveguide and environment (air); however, the refractive index step between the waveguide and substrate remained relatively small and did not exceed few hundredths. This problem was solved by forming ridge waveguides with the aid of reactive ion etching [11] and cutting PPLN-waveguides using a disk microsaw [12].

The purpose of this study was to develop a fabrication technology of waveguides with a large refractive index step between the core and cladding in periodically poled crystals for nonlinear conversion of semiconductor laser radiation frequency and to study the SHG in ridge PPLN waveguides fabricated with a disk microsaw.

2. Experimental samples

PPLN plates were prepared by applying an electric field to a system of stripe electrodes with a period of 10 μm, deposited on one of the surfaces of a lithium niobate wafer 76 mm in diameter and 0.5 mm thick. After forming a regular domain structure, the plate was cut into several samples 5 × 5 mm in size. The PPLN plate was attached to the substrate (a single-domain lithium niobate wafer) using a UV glue, which served a lower waveguide boundary with a refractive index $n \approx 1.46$. Thus, the refractive index step in the direction normal to the PPLN plate was ~0.77 for the second harmonic ($n = 2.23$ is the lithium niobate refractive index at $\lambda = 530$ nm) and ~0.69 for the pump radiation ($n = 2.15$ is the lithium niobate refractive index at $\lambda = 1060$ nm).

The glue layer thickness was ~2 μm. The glue was polymerised by exposing it to UV light ($\lambda = 365$ nm) under external pressure. Then the PPLN layer was subjected to one-sided diamond powder grinding and polishing to 5 μm thick. When cutting ridge waveguides by a disk microsaw, an epoxy resin layer with a refractive index $n \approx 1.57$ was deposited onto the PPLN plate in order to avoid cleavages. Figure 1 presents a top view of a PPLN sample with ridge waveguides having a large refractive index step. The images were obtained by optical microscopy in reflected light.

The input and output waveguide end faces were formed by making transverse cuts 500–600 μm deep (Fig. 2). We fabricated waveguides with the following parameters of PPLN

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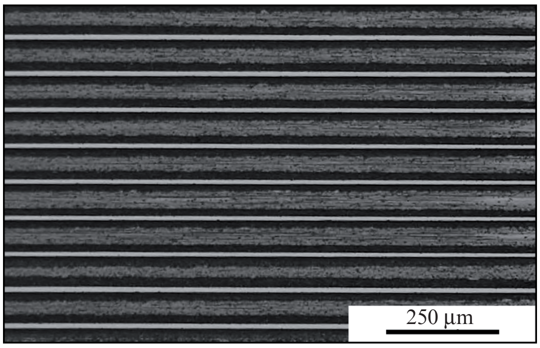

Figure 1. Reflected-light microscopy image of ridge waveguides (top view).

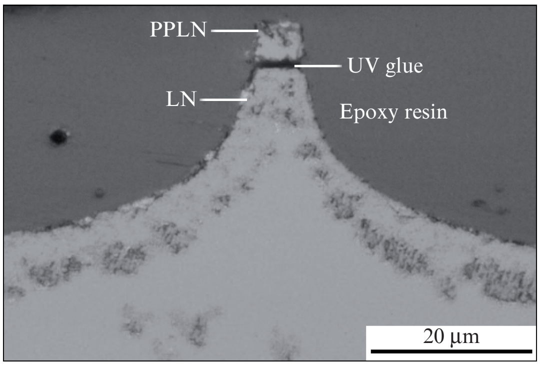

Figure 2. Reflected-light microscopy image of a waveguide in epoxy resin (view from the end face; LN stands for lithium niobate).

layer: thickness up to 5 μm, width up to 8 μm, length 5 mm, and domain structure period 10 μm.

3. Experimental

We studied the SHG for semiconductor laser radiation in PPLN ridge waveguides. A Littrow external cavity semiconductor laser [13] was used. The radiation wavelength was tuned in a wide spectral range: from 980 to 1140 nm. The laser was equipped with a fibre output, which significantly simplified radiation input into the ridge waveguide formed in PPLN. The radiation input efficiency was ~50%. The poling was tuned using an achromatic half-wave plate. An optical scheme of the experimental setup is presented in Fig. 3.

We measured the spectrum of SHG power P_{SH} in ridge PPLN waveguides. The pump power P_p in the entire spectral

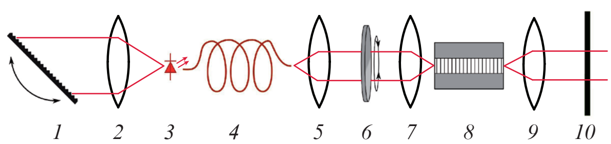

Figure 3. Optical scheme of the experimental setup: (*1*) diffraction grating (1200 lines mm^{-1}); (*2*, *5*, *7*) aspherical lenses (30$^\times$, Newfocus); (*3*) laser diode; (*4*) Panda 980 optical fiber; (*6*) achromatic half-wave plate (Thorlabs); (*8*) PPLN with a ridge waveguide; (*9*) microlens (8$^\times$, LOMO); (*10*) SZS 22 colour filter.

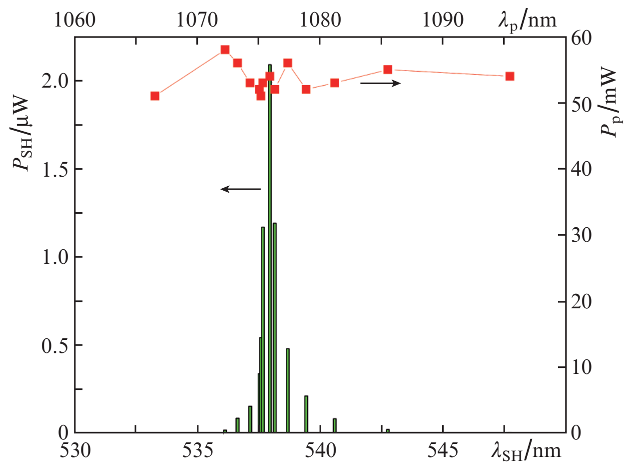

Figure 4. Spectral dependences of the second-harmonic power in PPLN ridge waveguides (elongated rectangles) and pump power (squares, upper wavelength scale).

range under study was 50–60 mW. The wavelength dependence of SHG power is presented in Fig. 4. The tuning spectral width was ~10 nm, with a power peak at a wavelength of 537.45 nm.

The dependence of the second-harmonic power on pump power was measured using a Newport 841-PE power meter with an 818-UV measuring head. When measuring the second-harmonic power, we applied an SZS 22 colour filter, which completely cut off the pump radiation. The dependence of second-harmonic power at $\lambda = 537.95$ nm on pump power is presented in Fig. 5 on a double logarithmic scale. A linear approximation shows that the second-harmonic power is proportional to pump power with an exponent of 1.88 ± 0.03.

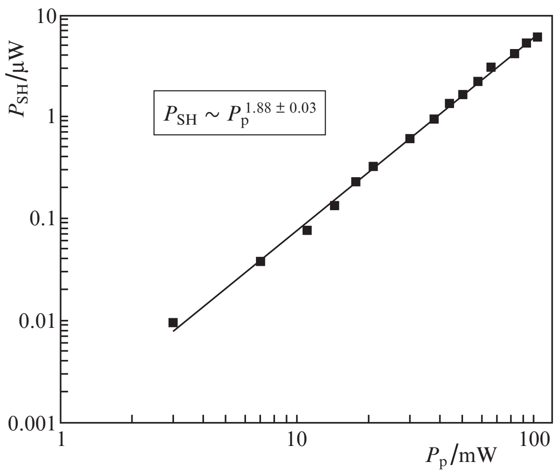

Figure 5. Dependence of the second-harmonic power at $\lambda = 537.95$ nm on pump power and its approximation by a power-law dependence with an exponent of 1.88 ± 0.03.

As was shown in [4, 5], wavelength conversion in waveguides based on periodically poled nonlinear crystals can be implemented when the conditions for quasi-phase-matching between different waveguide modes of the second harmonic and pumping are satisfied. Because of the refractive index dispersion in nonlinear crystals, which generally impedes phase matching, the phase matching between a lower IR mode and a higher visible light mode in a multimode periodically poled waveguide reduces the differences between the effective refractive indices and provides a blue shift of generated radiation with respect to the poling period. Similarly, a large difference between the effective refractive indices for the higher IR modes and lower visible light mode leads to a red shift.

We measured the near-field intensity distributions on the output waveguide face for second-harmonic and pump radiations with different wavelengths (Fig. 6). One can clearly see that the SHG wavelength conversion is provided due to the significant change in the waveguide mode intensity distribution. Our study revealed also a significant 'leakage' of radiation through the lower waveguide boundary, a sign that the UV glue layer was insufficiently thick. As can be seen in Fig. 6, a small number of fundamental (pump) waveguide modes is maintained in the entire conversion range; apparently, this circumstance significantly narrows the SHG wavelength conversion range for the samples under study.

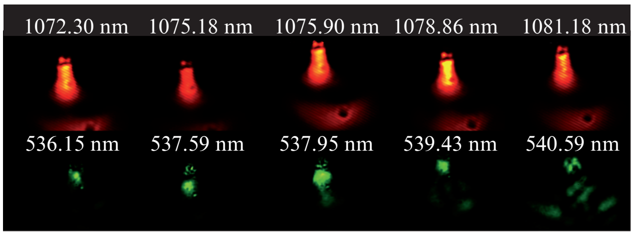

Figure 6. Intensity distributions in the near field of second-harmonic and pump radiations with different wavelengths.

4. Conclusions

We fabricated experimental samples of ridge waveguides in PPLN with a large refractive index step between the waveguide core and claddings (about 0.77 for the second harmonic and about 0.69 for the pump radiation) and performed experiments on SHG in these waveguides. It was shown that the phase matching between a lower pump mode and a higher second-harmonic mode reduces the difference between the effective refractive indices and provides a blue shift of generated radiation with respect to the poling period in multimode periodically poled waveguides with a large refractive index step between the core and claddings. Similarly, a large difference between the effective refractive indices of higher IR modes and lower visible light mode leads to a red shift. The novel fabrication technology of ridge waveguides can be widely applied to design visible-light laser sources on their basis, which can be tuned in a wide spectral range.

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References

1. Telford W.G. *Methods Cell. Biol.*, **102**, 375 (2011).
2. Claxton N.S., Fellers T.J., Davidson M.W. http://olympusfluoview.com/theory/LSCMIntro.pdf.
3. Sumpf B., Maiwald M., Sowoidnich K., Kronfeldt H.-D. *Proc. SPIE*, **8718**, 87180D (2013).
4. Fedorova K.A., Sokolovskii G.S., Battle P.R., Livshits D.A., Rafailov E.U. *Opt. Lett.*, **40**, 835 (2015).
5. Fedorova K.A., Sokolovskii G.S., Battle P.R., Livshits D.A., Rafailov E.U. *Laser Phys. Lett.*, **9**, 790 (2012).
6. Ai L., Wang L., Tan Y., Akhmadaliev S., Zhou S., Chen F. *IEEE J. Lightwave Technol.*, **35**, 2476 (2017).
7. Nishida Y., Miyazawa H., Asobe M., Tadanaga O., Suzuki H. *Electron. Lett.*, **39**, 609 (2003).
8. Nishikawa T., Ozawa A., Nishida Y., Asobe M., Hong F.-L., Hänsch T.W. *Opt. Express*, **17**, 17793 (2009).
9. Kretzschmar N., Eismann U., Sievers F., Chevy F., Salomon C. *Opt. Express*, **25**, 14843 (2017).
10. Fedorova K.A., Sokolovskii G.S., Khomylev M., Livshits D.A., Rafailov E.U. *Opt. Lett.*, **39**, 6672 (2014).
11. Courjal N., Devaux F., Gerthoffer A., Guyot C., Henrot F., Ndao A., Bernal M.-P. *Opt. Express*, **23**, 13983 (2015).
12. Chauvet M., Henrot F., Bassignot F., Devaux F., Gauthier-Manuel L., Pêcheur V., Maillotte H., Dahmani B. *J. Opt.*, **18**, 085503 (2016).
13. Vinokurov D.A., Deryagin A.G., Dyudelev V.V., Kuchinskii V.I., Lyutetskii A.V., Pikhtin N.A., Sokolovskii G.S., Stankevich A.L., Tarasov I.S. *Techn. Phys. Lett.*, **34**, 187 (2008).