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Femtosecond-Laser-Inscribed BiB_3O_6 Nonlinear Cladding Waveguide for Second-Harmonic Generation

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We report on the fabrication of a nonlinear cladding waveguide in BiB_3O_6 crystal by using femtosecond laser inscription. The waveguide (with a nearly circular cross section of 150 μm diameter) shows good guiding properties in two transverse polarizations. The guided-wave second-harmonic generation (SHG) at 532 nm green light has been realized under CW and pulsed wave pump at 1064 nm, based on the Type I birefringent phase matching configuration. The conversion efficiencies for CW and pulsed green laser SHG are 0.083 and 25%, respectively.

Optical waveguides are desired in photonics owing to the inside high optical intensities with respect to bulk materials. High-performance photonic devices could be constructed and integrated in small circuits by using waveguide structures.[1)] The femtosecond (fs) laser inscription has rapidly become a powerful and unique technique to fabricate waveguides in a wide range of optical materials since 1996.[2–19)] The fs-laser-written waveguides could be classified as directly written structures (Type I waveguides with single line writing), stress-induced waveguides (Type II waveguides with double-line filaments), and cladding waveguides (usually with large area cross sections). Type I waveguides have been widely applied in numerous glasses and $LiNbO_3$ crystal,[9)] and Type II waveguides are fabricated successfully in a few laser crystals (e.g., Nd:YVO_4,[10)] Nd:YAG,[11)] and Nd:GGG[12)]) and $LiNbO_3$.[9)] However, as of yet, the fabrication of such cladding structures was only reported in Nd:YAG crystal[13,14)] and Tm:ZBLAN glass.[15)] Cladding waveguides are confined in the regions with relatively high refractive index surrounded by the fs-laser-induced damage lines or filament tracks. For nonlinear crystals, the cladding structures seem to be much efficient because the large-dimension waveguides may offer good guidance for any polarization direction in the cross-sectional plane, which makes birefringent frequency doubling, under either Type I or Type II phase matching (PM) configuration, efficiently realized. Another advantage of the cladding waveguide is that the large diameter of the waveguide cross-section may match that of the multimode fiber well, and theoretically the mode numbers of the waveguide may be reduced by manipulation of parameters during the fs laser inscription to decrease the refractive index contrast between the tracks and waveguide core.

Bismuth borate (BiB_3O_6 or BiBO) is a very attractive nonlinear crystal with large nonlinear optical coefficients ($d_{\mathrm{eff}} = 3.2\,\mathrm{pm/V}$) and a high damage threshold of ~5 GW/cm^2.[20)] The second-harmonic generation (SHG) from visible till UV light band can be achieved in BiB_3O_6 via birefringent PM.[21)] Chen *et al.* fabricated the first optical waveguide in BiB_3O_6 crystal by using ion implantation,[22)] but the SHG could not be realized due to the poor guiding property of the structure. Recently, Beecher *et al.* have applied Type II fs-laser writing to manufacture a stress-induced waveguide in a BiB_3O_6 crystal,[16)] obtaining SHG in the fabricated structures. In fact, for fs-laser-inscribed nonlinear waveguides, the frequency doubling has been achieved only in birefringent phase-matched $LiNbO_3$ (Type I waveguide)[17)] and BiB_3O_6 (Type II waveguide),[16)] and quasi-phase-matched (QPM) periodically poled $LiNbO_3$ (PPLN)[18)] and $KTiOPO_4$ (PPKTP)[19)] waveguides, and as of yet, there has been no report on SHG from the nonlinear cladding waveguides. In this Letter, we report on the fabrication of BiB_3O_6 cladding waveguides and guided-wave SHG in the fabricated structures.

The optically polished BiB_3O_6 single-crystal wafer was cut with dimensions of $6 \times 10 \times 2\,\mathrm{mm}^3$, and fit the direction of the $1064 \rightarrow 532\,\mathrm{nm}$ birefringent PM SHG ($e + e \rightarrow o$) in the y–z plane ($\theta = 168.7°$, $\varphi = 90°$). The cladding structure was produced by using an amplified Ti:sapphire laser system (Spectra Physics Spitfire, generating linearly polarized 120 fs pulses at 800 nm, with 1 kHz repetition rate and 1 mJ maximum pulse energy). The fs laser beam was focused by a microscope objective (Leica 40×, numerical aperture NA = 0.65), and the pulse energy was set to be 0.42 μJ. The sample was placed in a motorized *XYZ* stage and was scanned along the 6 mm axis at a constant velocity (700 μm/s), producing parallel damage filaments with separations of 4 μm at different depths of the sample. With the programmed model, the cladding structure with nearly circular boundary was fabricated in the BiB_3O_6 crystal. Figure 1 shows the optical transmission microscopy image of the BiB_3O_6 cladding waveguide, which was buried inside the crystal at depth of 200 μm beneath the surface.

We arranged an end-face coupling system to measure the waveguide losses of the BiB_3O_6 cladding structure. The Fresnel reflection loss was ~0.4 dB in the interface of the waveguide end face and the air. The coupling and propagation losses were ~1 dB and ~0.6 dB/cm, respectively. We also found that the waveguide supported confinement in any polarization direction (i.e., both transverse electric, TE, and transverse magnetic, TM, modes were guided), and the difference in propagation losses between TE and TM modes was only ~8%, showing very good features of the two-dimensional guidance. In addition, by assuming of a refractive step index profile and the measurement of the numerical aperture of the waveguide, one could estimate the refractive index change of the waveguide with the formula:[11)]

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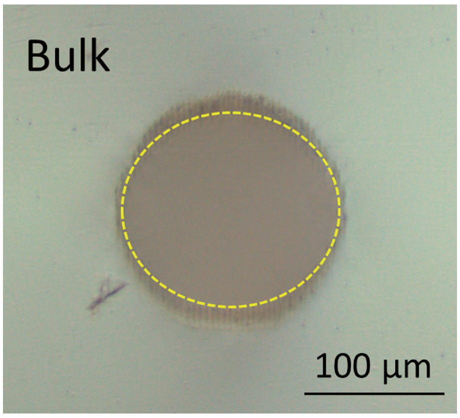

Fig. 1. Optical transmission microscopy image of the BiB_3O_6 cladding waveguide. The dashed line indicates the location of the waveguide boundary.

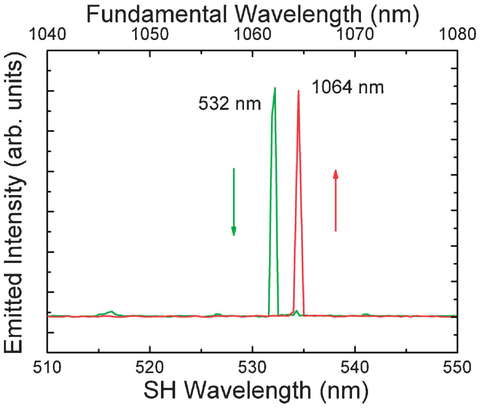

Fig. 2. Typical spectra of fundamental and SH waves from the BiB_3O_6 cladding waveguide.

$$\Delta n = \frac{\sin^2 \Theta_\mathrm{m}}{2n}, \tag{1}$$

where n is the refractive index of the bulk, and Θ_m is the maximum incident angle at which the transmitted power is occurring without any change. According to the measured Θ_m value, we have estimated that there is a refractive index contrast $\Delta n \approx 0.003$ between the damage lines and the waveguide region. This value is comparable to that of the reported fs-laser-written Nd:YAG cladding structure.[13]

The fundamental wave pump beam at 1064 nm (nearly linearly polarized) was either from a CW laser or a pulsed laser (80 µJ pulses with a duration of 11.05 ns at a repetition of 5 kHz). It was coupled into the cladding waveguide by using a convex lens (with focal length of 25 mm). The output laser beams (i.e., fundamental 1064 nm and SH 532 nm) from the waveguide's exit facet was collected by a 20× microscope objective and characterized using a CCD camera (for modal profile imaging), a spectrometer, and a powermeter. The frequency doubling was realized by using a TE-polarized 1064 nm pump, generating SH along TM polarization, i.e., under $\mathrm{TE}^{\omega} + \mathrm{TE}^{\omega} \rightarrow \mathrm{TM}^{2\omega}$, which is in accordance with the bulk Type I PM ($e + e \rightarrow o$). Figure 2 depicts the typical spectra of the fundamental and SH waves from the waveguide under CW pump. It can be seen clearly that the frequency doubling process happens. For pulsed laser pump configuration, we obtained spectroscopic properties similar to the CW case.

Figures 3(a) and 3(b) show the spatial modal profiles of the fundamental and generated SH waves from the BiB_3O_6 cladding waveguide under CW pump, respectively. As one can see, both the fundamental light and SH light are multimode, which is in agreement with the theoretical prediction for a large-area-cross-section waveguide with a moderate refractive index contrast with bulk. In addition, under pulsed laser pump, we obtained multimodal fundamental [Fig. 3(c)] and SH [Fig. 3(d)] profiles, but the mode orders of pulsed lasers are lower than that of the CW laser. This may be partly due to the fact that the beam parameters of the fundamental light from CW and pulsed lasers are different. Moreover, the third-order nonlinear effect (Kerr self-focusing) at high peak power of the pulsed pump may also be a possible reason for the modal profile difference.

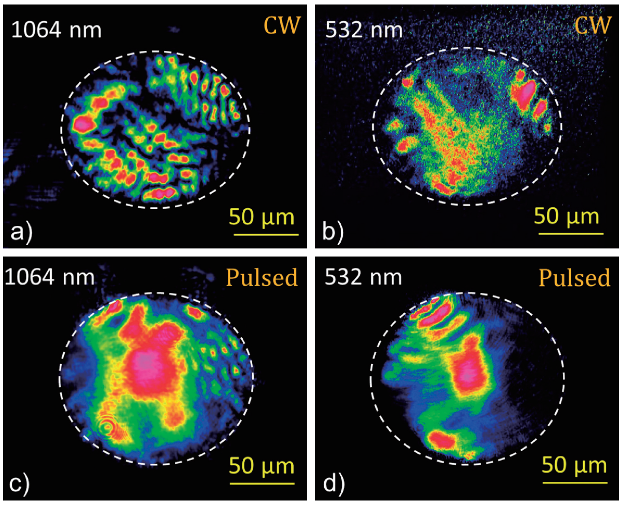

Fig. 3. Modal profiles of the (a) CW fundamental light at 1064 nm, (b) CW SH light at 532 nm, (c) pulsed fundamental light at 1064 nm, and (d) pulsed SH light at 532 nm from the BiB_3O_6 cladding waveguide. The dashed lines indicate the spatial location of the waveguide.

Figure 4(a) shows the power of the output SH wave ($P_\mathrm{CW}{}^{2\omega}$) at 532 nm and SH conversion efficiency as a function of that of the 1064 nm fundamental wave ($P_\mathrm{CW}{}^{\omega}$) from the cladding waveguides. We obtained a maximum green laser output power of 0.092 mW under pump of 110.6 mW infrared light, which corresponds to an SH conversion efficiency of $\eta_\mathrm{CW} = 0.083\%$ (normalized value of 0.75%/W). Compared with the reported value for Type II stress-induced BiB_3O_6 waveguide (~0.015%/W),[16] the conversion efficiency of the cladding waveguide is much higher (approximately 50 times of magnitude). The significant improvement of the SHG efficiency of the cladding waveguide on the stress-induced structures may be partly due to the much lower waveguide losses. For fundamental pulsed laser irradiation [Fig. 4(b)], the maximum SH power (peak value, $P_\mathrm{pulsed}{}^{2\omega}$) reaches 373 W at the pump of 1485 W fundamental light (peak value, $P_\mathrm{pulsed}{}^{\omega}$), resulting in an SH conversion efficiency of 25% (η_pulsed). This value is comparable to those from most nonlinear waveguide systems for SHG.[17,19] The normalized SHG conversion efficiency can therefore be

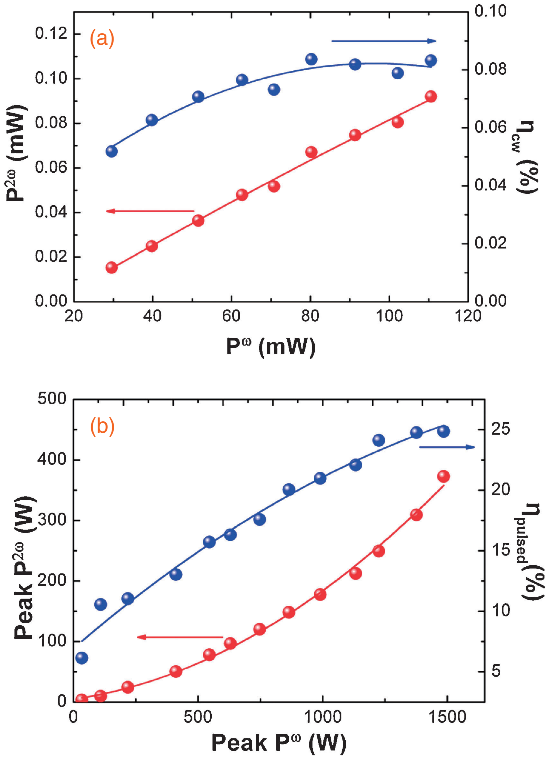

Fig. 4. SHG output power and conversion efficiency versus the fundamental pump power of the cladding waveguides in BiB_3O_6 crystal under (a) CW and (b) pulsed laser pump. The solid lines represent the fit of the experimental data.

calculated to be $\sim 4.6 \times 10^{-2}\% \cdot W^{-1} \cdot cm^{-2}$ in the cladding waveguide, which is significantly higher than that of the bulk ($\sim 6.6 \times 10^{-6}\% \cdot W^{-1} \cdot cm^{-2}$).[23]

In summary, we have successfully fabricated a cladding waveguide in a BiB_3O_6 nonlinear crystal by using fs laser inscription. The SHG based on birefringent Type I phase matching from 1064 to 532 nm has been realized under both CW and pulsed laser configuration. The CW SHG conversion efficiency of the cladding waveguide has been found to be 50 times higher than that of the stress-induced waveguides. The pulsed SHG of green light reaches a conversion efficiency as high as 25%. The excellent SHG performance indicates potential applications of the fs-laser-written BiB_3O_6 cladding waveguides as efficient integrated frequency converters. In addition, since the diameter of the cladding waveguide fits the optical multimode fibers, one can expect easy connection and integration of the fiber-waveguide photonic system by using the cladding structures.

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1) C. Grivas: Prog. Quantum Electron. **35** (2011) 159.
2) K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao: Opt. Lett. **21** (1996) 1729.
3) R. R. Gattass and E. Mazur: Nat. Photonics **2** (2008) 219.
4) M. Ams, G. D. Marshall, P. Dekker, J. A. Piper, and M. J. Withford: Laser Photonics Rev. **3** (2009) 535.
5) G. A. Torchia, A. Rodenas, A. Benayas, E. Cantelar, L. Roso, and D. Jaque: Appl. Phys. Lett. **92** (2008) 111103.
6) V. Apostolopoulos, L. Laversenne, T. Colomb, C. Depeursinge, R. P. Salathe, M. Pollnau, R. Osellame, G. Cerullo, and P. Laporta: Appl. Phys. Lett. **85** (2004) 1122.
7) A. Rodenas and A. K. Kar: Opt. Express **19** (2011) 17820.
8) T. Calmano, J. Siebenmorgen, F. Reichert, M. Fechner, A. Paschke, N. Hansen, K. Petermann, and G. Huber: Opt. Lett. **36** (2011) 4620.
9) J. Burghoff, S. Nolte, and A. Tunnermann: Appl. Phys. A **89** (2007) 127.
10) Y. Tan, F. Chen, J. R. Vázquez de Aldana, G. A. Torchia, A. Benayas, and D. Jaque: Appl. Phys. Lett. **97** (2010) 031119.
11) T. Calmano, J. Siebenmorgen, O. Hellmig, K. Petermann, and G. Huber: Appl. Phys. B **100** (2010) 131.
12) C. Zhang, N. N. Dong, J. Yang, F. Chen, J. R. Vázquez de Aldana, and Q. M. Lu: Opt. Express **19** (2011) 12503.
13) A. G. Okhrimchuk, A. Shestakov, I. Khrushchev, and J. Mitchell: Opt. Lett. **30** (2005) 2248.
14) A. Okhrimchuk, V. Mezentsev, A. Shestakov, and I. Bennion: Opt. Express **20** (2012) 3832.
15) D. G. Lancaster, S. Gross, H. Ebendorff, K. Kuan, M. Ams, and M. Withford: Opt. Lett. **36** (2011) 1587.
16) S. J. Beecher, R. R. Thomson, D. T. Reid, N. D. Psaila, M. Ebrahim-Zadeh, and A. K. Kar: Opt. Lett. **36** (2011) 4548.
17) J. Burghoff, C. Grebing, S. Nolte, and A. Tünnermann: Appl. Phys. Lett. **89** (2006) 081108.
18) R. Osellame, M. Lobino, N. Chiodo, M. Marangoni, G. Cerullo, R. Ramponi, H. T. Bookey, R. R. Thomson, N. D. Psaila, and A. K. Kar: Appl. Phys. Lett. **90** (2007) 241107.
19) S. Zhang, J. Yao, W. Liu, Z. Huang, J. Wang, Y. Li, C. Tu, and F. Lu: Opt. Express **16** (2008) 14180.
20) D. N. Nikogosyan: *Nonlinear Optical Crystals: A Complete Survey* (Springer, New York, 2005).
21) M. Ghotbi and M. Ebrahim-Zadeh: Opt. Express **12** (2004) 6002.
22) F. Chen, H. Hu, K. M. Wang, B. Teng, J. Y. Wang, Q. M. Lu, and D. Y. Shen: Opt. Lett. **26** (2001) 1993.
23) Z. Wang, B. Teng, K. Fu, X. Xu, R. Song, C. Du, H. Jiang, J. Wang, Y. Liu, and Z. Shao: Opt. Commun. **202** (2002) 217.