Fabrication of magneto-optical microstructure by femtosecond laser pulses

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We investigate femtosecond laser direct writing (FLDW) in the fabrication of magneto-optical (MO) microstructures. The experimental results show that FDLW can introduce positive refractive index change in the MO materials. With the increase of the writing intensity of femtosecond laser pulses, refractive index change increases, whereas Verdet constant of the damaged area decreases nonlinearly. With suitable writing intensity, we obtain a single-mode waveguide in which Verdet constant is 80% of the bulk MO glass.

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Femtosecond laser direct writing (FLDW) is a powerful tool for fabricating optical microstructures[1], which is localized at the focus of incident pulse for the ultrahigh peak power and ultrashort pulse duration of the femtosecond pulse. With the help of nonlinear optical effects, such as multiphoton absorption, the spatial size of the optical microstructures written by the femtosecond pulses can be less than tens nanometers[2].

FLDW can be used to write optical microstructures in nearly all kinds of materials. In transparent medias, such as glass and polymer, the microstructures fabricated by FLDW can be not only one-dimensional (e.g., waveguide)[3] or two-dimensional (2D, e.g. grating)[4], but also three-dimensional (3D, such as photonic crystal)[5]. In metals[6], ceramics[7], and other opaque materials[8,9], FLDW can write 2D microstructures onto the surface of such materials. The microstructures can be fabricated, not only by scanning point by point, but also by the interference between femtosecond pulses and the substrate[10].

In FLDW, femtosecond pulses introduce the change of refractive index and/or absorption coefficient into the substrates, thereby fabricating optical microstructures. Many works have been carried out to optimize the characters of FLDW, such as improving the spatial resolution of the microstructures[11] and increasing writing speed[12]. However, femtosecond pulses may also change the optical nonlinear effect of the substrate, such as the electro-optical effect in lithium niobate crystal[13]. In this letter, we studied the influence of femtosecond pulses on the nonlinearity in the magneto-optical (MO) glass. Our results showed that, in MO glass, the Verdet constant and the refractive index changed nonlinearly with the writing intensity of femtosecond laser. With FLDW, a single-mode waveguide with Verdet constant higher than 80% of the bulk glass was fabricated successfully.

In our experiments, the MO glass is TG_{20} (Tb_2O_3-SiO_2-Al_2O_3-B_2O_3) from Shanghai Daheng Company with a refractive index of n_d=1.69 and Abbe's number of 53.14. The size of the sample is 7.2×11.7×14.4 (mm). All of the six glass surfaces are polished for the convenience of writing and real-time monitoring.

The experimental setup is schematically shown in Fig. 1. Linearly polarized femtosecond pulses from an amplified Ti:Sapphire laser are focused onto the MO glass by a 20× microscopy objective lens (LMPLanFL, Olympus Company), which is labeled as objective lens (OB) in Fig. 1. The central wavelength of the femtosecond pulses is 800 nm. The pulse duration is approximately 120 fs. The repetition rate of the pulses is 1 kHz. Before using the objective lens, a computer-controlled shutter is used to adjust the exposure time, and neutron filters (NDs) are used to adjust the writing intensity inside the glass. Our sample (S) is fixed on a 3D linear stage. With the movement of linear stage, the focus of the laser pulses scans through the glass. As a result, a strip of optical damage can be written onto the MO glass. The scanning speed is 0.1 mm/s without special emphasis. In our experiments, an online monitoring system composed by a halogen lamp (HL), another OB, and a CCD camera is used to observe the writing process real-time.

As the first step of our experiment, we check the dependence of the laser-induced refractive index change versus the average intensity of the writing beam I. A typical top-view of the written region in the TG_{20} glass is shown in Fig. 2(a), where I = 0.69 mW. Clearly, FLDW can introduce optical damage onto the MO glass.

In order to check the sign of the refractive index change

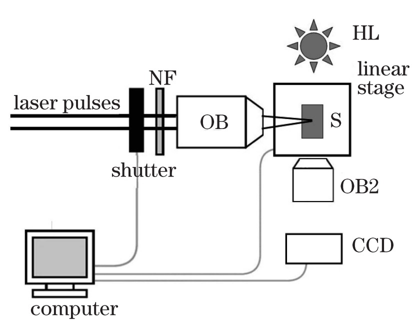

Fig. 1. Diagram of experimental setup.

in the MO glass, we focus a green laser beam ($\lambda = 532$ nm) onto the damaged strip by a 10× objective lens. The result (Fig. 2(b)) shows that the strip can guide the incident beam, which means the refractive index change is positive.

In order to obtain the single-mode waveguide, we check the beam guiding results versus the average writing intensity. Figures 3(a)–(c) show the results when $I = 0.12$, 0.23, and 0.36 mW, respectively. When $I = 0.12$ mW, the waveguide is in single mode. When writing intensity is higher than 0.12 mW, higher-order modes propagate inside the waveguide. This phenomenon means that high writing intensity causes a large refractive index change in the written region. We cannot measure the refractive index change directly. From the beam-guiding effect, we can estimate that the refractive index change in the written region can reach 10^{-3}.

In FLDW, the scanning speed of the focused femtosecond pulses is another key parameter. Figure 4 shows the dependence of beam guiding on the scanning speed. Here, the writing intensity is maintained at 0.12 mW. The scanning speeds are 0.01 and 0.05 mm/s, respectively. Compared with the result of the scanning speed of 0.1 mm/s (shown in Fig. 3(a)), when the scanning speed is low, the waveguide will be in multi mode. With decrease of the scanning speed, the total exposure energy at each point of the waveguide increases, similar to the case when we maintain high scanning speed and high writing intensity. Therefore, lower scanning speed will introduce higher refractive index change in the glass and produce a multimode waveguide. With a writing intensity of 0.12 mW, the best scanning speed for the fabrication of a single-mode waveguide is 0.1 mm/s.

Generally, the MO effect is the change of optical parameters of a light beam induced by external magnetic field. Normally, MO effect refers to the change in the intensity or the polarization state, including Faraday effect, MO Kerr effect, and Cotton-Mouton effect[14]. For example, when Faraday effect occurs, the linear polarization direction of the incident beam rotates (called magnetic rotation or Faraday rotation), or the elliptical polarization changes accordingly with the rotation of the

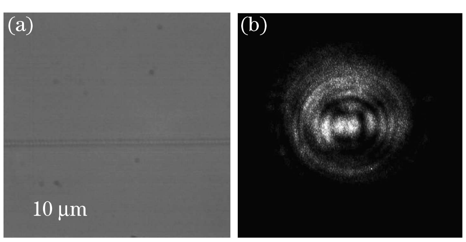

Fig. 2. (a) Top-view of the waveguide and (b) photo of the guided beam at the exit of the waveguide. ($I = 0.69$ mW).

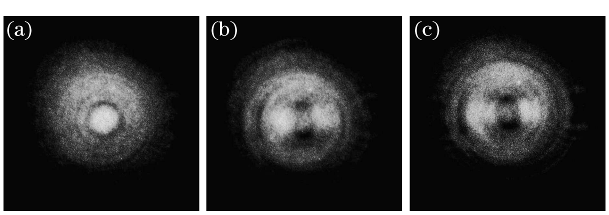

Fig. 3. Beam guiding experimental results for different writing intensities I of (a) 0.12, (b) 0.23, and (c) 0.36 mW.

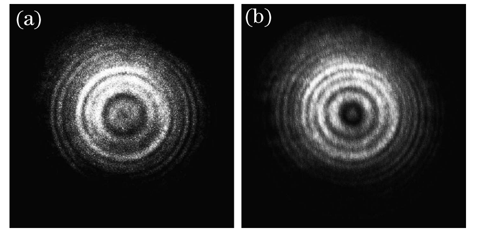

Fig. 4. Photos of guided beam when the scanning speeds are (a) 0.01 and (b) 0.05 mm/s. ($I = 0.12$ mW).

principle axis (called magnetic circular dichroism or Faraday ellipticity).

In this work, we are only concerned with Faraday rotation in the TG_{20} glass. The MO glass with the waveguide inside is inserted into an electromagnetic coil to check its MO effect. The waveguide is parallel to the magnetic field. A linear polarized (TE mode) green beam ($\lambda = 532$ nm) is coupled onto the waveguide. At the exit port of the waveguide, the beams of TE and TM waveguide modes are separated due to polarization, and the intensities of the two beams, I_{TE} and I_{TM}, are measured.

In bulk MO materials under uniform magnetic field, the rotation angle of the linear direction θ_{F} can be described by

$$\theta_{\mathrm{F}} = V_{\mathrm{B}} \int_0^L B(x)\mathrm{d}x, \tag{1}$$

where V_{B} is the Verdet constant of the bulk materials, L presents the sample length, and $B(x)$ is the varying magnetic flux density along the waveguide. In Eq. (1), the nonuniform distribution of B has been considered. Therefore, the TE-TM mode conversion ratio in the bulk glass R_{B} is

$$R_{\mathrm{B}} = \frac{I_{\mathrm{TM}}}{I_0} = \sin^2\theta_{\mathrm{F}} = \sin^2\left[V_{\mathrm{B}} \int_0^L B(x)\mathrm{d}x\right], \tag{2}$$

where I_0 is I_{TE} when $B = 0$.

In MO waveguide, the TE-TM waveguide mode conversion ratio R_{W} has different forms from the bulk materials[15]:

$$R_{\mathrm{W}} = \frac{\theta_{\mathrm{F}}^2}{\theta_{\mathrm{F}}^2 + (\Delta\beta L/2)^2}\sin^2[\sqrt{\theta_{\mathrm{F}}^2 + (\Delta\beta L/2)^2}]. \tag{3}$$

In circular waveguide with diameter of several micrometers, the phase mismatch between the TE and TM modes, $\Delta\beta$, is negligible. Therefore, we have

$$R_{\mathrm{W}} = \sin^2\theta_{\mathrm{F}} = \sin^2\left[V_{\mathrm{W}} \int_0^L B(x)\mathrm{d}x\right], \tag{4}$$

where V_{W} is the Verdet constant of the waveguide. It has the same form as R_{B} in bulk materials.

Here, we study $V_{\mathrm{W}}/V_{\mathrm{B}}$ (i.e., the normalized Verdet constant of the waveguides), because we cannot measure $B(x)$ accurately. In a good approximation, $B(x)$ is proportional to the current A applied on the coil (i.e., $B(x) = CA$, where C is a constant decided by the parameters of the coil). Equations (2) and (3) can be rewritten as the formulae of current A:

$$R_{\mathrm{B}} = \sin^2\left[V_{\mathrm{B}} \int_0^L B(x)\mathrm{d}x\right] = \sin^2\left[AV_{\mathrm{B}} \int_0^L C\mathrm{d}x\right], \tag{5}$$

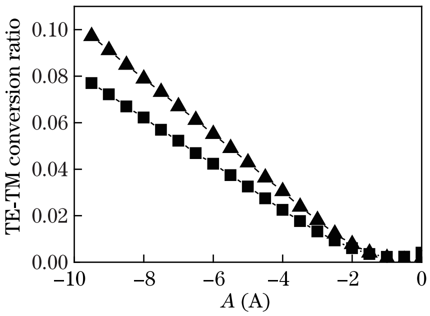

Fig. 5. TE-TM conversion ratio versus the current A. The squares and the triangles represent the case for the waveguides shown in Fig. 3(a) and the bulk glass, respectively.

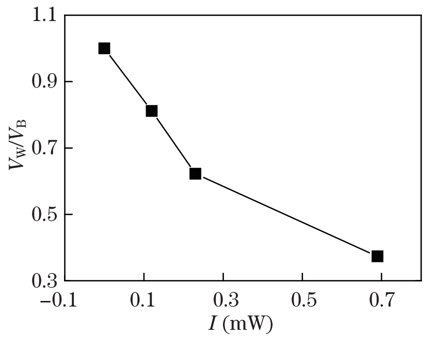

Fig. 6. Dependence of normalized Verdet constant V_W/V_B on the writing intensity I.

$$R_W = \sin^2\left[AV_W\int_0^L C\mathrm{d}x\right]. \quad (6)$$

Fitting the variation of TE-TM conversion ratio versus the current A, we can obtain V_W/V_B, as shown in Fig. 5. Gives the R_W of the waveguide shown in Fig. 3(a) and R_B versus A. We find that V_W/V_B is 0.811.

We check the dependence of V_W/V_B on writing intensity as shown in Fig. 6. The scanning speed is 0.1 mm/s. We can see that the normalized Verdet constant of the waveguide deceases nonlinearly with the increase of the writing intensity. When $I = 0.12$ mW (i.e., the case of the single-mode waveguide), V_W/V_B is 0.811. This result means that most MO activity is kept in the single-mode waveguide written by FLDW. When the intensity increases to 0.69 mW, V_W/V_B decreases to 0.373. In the waveguide fabricated by the writing intensity of 0.69 mW, the waveguide loss is not only higher, but the external modulation of polarization state becomes more difficult in comparison to the case of the single-mode waveguide.

In TG_{20} glass, the MO effect results from the response of the Tb^{3+} ions to the external magnetic field. Using electron paramagnetic resonance measurements, Shih *et al.*[16] confirmed that, when the writing intensity was small, most Tb ions at the optically damaged region of TG_{20} glass kept valence as 3+. This case is similar to our case of I=0.12 mW. In our experiment, we check the MO effect of the waveguide fabricated by hih intensity, say 0.69 mW, which is not considered by Shih *et al.* Our results indicate that, with higher writing intensity, a greater portion of the Tb^{3+} ions will be ionized into Tb^{4+}, and, therefore, Verdet constant decreases nonlinearly with the increase of the writing intensity. This phenomenon may be caused by multiphoton absorption process that is dominant at high writing intensity.

The scanning speed has smaller influence on the Verdet constant compared with writing intensity. When scanning speed is 0.01 mm/s and writing intensity is 0.12 mW, the Verdet constant is 0.771, which is close to the value when scanning speed is 0.1 mm/s (i.e., 0.811).

In conclusion, we check the dependence of properties of the waveguide fabricated by FLDW in MO TG_{20} glass. The results show that, with the increase of writing intensity, the positive refractive index change increases, whereas Verdet constant decreases nonlinearly. Under suitable writing intensity and scanning speed, writing active MO microstructures is possible. We successfully fabricate a single-mode waveguide while maintaining more than 80% Verdet constant. In this letter, we use the damaged part of the substrate to guide the incident beam. Completely destroying the MO activity of the substrate with high writing intensity is possible. With the spatial modulation of optical activity, more unique MO integrated devices can be fabricated by FLDW.

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