Beam steering of external cavity diode laser by an intracavity electro-optic ceramic deflector

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A novel beam-steering external cavity diode laser using an intracavity lead lanthanum zirconate titanate (PLZT) electro-optic ceramic deflector is proposed and demonstrated experimentally. The laser consists of a semiconductor laser with single mode fiber coupled output, polarization controller, PLZT electro-optic ceramic deflector, and output concave mirror. By applying proper driven electrical signals on the PLZT electro-optic deflector, the beam deflection angle achieves 5.8 mrad at 1 000 V. A high-speed beam-steering property with less than 120-ns switching time is also observed. Moreover, a good beam quality with Gaussian spatial profile and a linear polarization state are obtained.

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Fast and precise spatial scanning and directing of an optical beam have important applications in areas such as optical communication, optical storage, optical interconnections, and lidar[1]. Although conventional beam scanning methods using mechanical rotators are commercially available and widely used, their operating speed and directing precision are unsatisfactory. A beam-steering apparatus without moving parts is more attractive because of its higher speed and reliability. Numerous research have focused on the subject with various schemes, such as electro-optic deflectors and acousto-optic deflectors[2,3]. Acousto-optic beam scanning has a relatively high cost, and its response speed and angle resolution limit its development to a certain extent. Electro-optic (EO) devices such as optical phased array (OPA) technology[4,5] and EO prism deflector[6] may provide high-speed and high-precise beam scanning due to a motionless component. However, optical beam quality and limited optical efficiency between the laser and the EO devices are also insurmountable deficiencies. The intracavity beam-steering technology is one very effective solution for overcoming these limitations. Due to the beam-steering devices placed in the laser cavity, the beam quality and optical efficiency will be improved largely which may satisfy the application requirements better. Moreover, a more compact system structure will be realized.

Recently, the intracavity beam-steering architecture based on the conjugate resonator arrangement with a liquid crystal (LC) spatial light modulator embedded in a Nd:YVO_4 laser cavity has been demonstrated[7]. LC technology has good electro-optic performance and low driven voltage, which have been demonstrated maturely[8]. However, its shortcomings, such as long response time, low thermal stability, and small laser-induced damage threshold, are obvious. In the last few decades, transparent EO ceramic (lead lanthanum zirconate titanate (PLZT))[9] has been developed, representing a class of ceramics with good transparency and large EO coefficient. Compared with other electro-optic materials, PLZT EO ceramic has many distinct advantages, such as high electro-optic coefficient (about 10 times that of $LiNbO_3$), availability of larger volume materials, high response speed, broad optical transparency range (about 0.5−10 μm), low cost, and high laser-induced damage threshold. Therefore, PLZT electro-optical ceramic has very extensive applications in the area of photoelectric devices. A PLZT ceramic-based electro-optic beam-steering device was reported with the steering angle of 0.7 mrad[10]. An electro-optic prism deflector based on the PLZT ceramic placed out of cavity was investigated with a 9-mrad deflecting angle[6]. An optical phase-array beam deflector based on the PLZT electro-optic ceramic with the deflection angle of 2.35 mrad has also been demonstrated experimentally[11]. The fast response speed of PLZT materials was measured to be less than 100 ns[9]. Based on the high-speed response property, the PLZT bar was used in an EO switch with less than 31.1-ns switching time[12].

In this letter, we propose and demonstrate experimentally a novel beam-steering external cavity diode laser (ECDL) based on an intracavity EO deflector. The deflector is made of PLZT transparent ceramic with high quadratic EO effect property. By applying proper driven electrical signals on the PLZT EO deflector, the beam deflection angle achieves 5.8 mrad at 1 000 V, and a high-speed beam-steering property with less than 120-ns switching time is observed. A good Gaussian spatial profile and a linear polarization state with the extinction ratio of 230 for the output laser are also realized simultaneously. This laser is expected to have a good future in the areas of free-space communications, lidar, pointing and tracking, and so forth.

The schematic diagram of the proposed intracavity

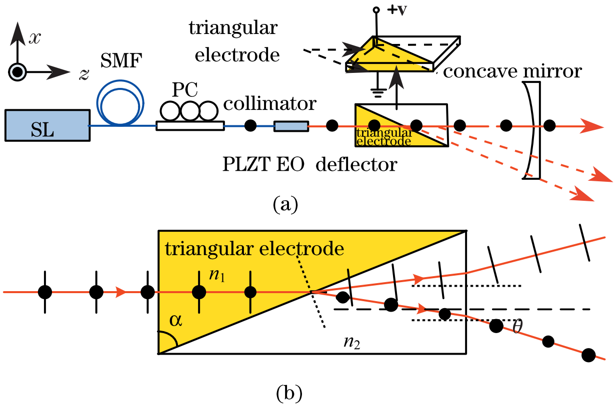

Fig. 1. (a) Schematic diagram of the proposed intracavity beam-steering ECDL; (b) polarization dependence of the PLZT EO deflector.

beam-steering ECDL is shown in Fig. 1(a). The active medium is a semiconductor laser (SL) with a working wavelength of 1 550 nm, whose two facets are coated for anti-reflection and high reflection, respectively. A single mode fiber pigtail is coupled for its output. The polarization controller (PC) is used to adjust the polarization direction of the laser while the fiber collimator couples the collimated light into the electrically controllable deflector used to change beam direction. A conventional concave mirror with about 50% reflectivity is used as the output mirror. The key component in our proposed system is the PLZT EO ceramic deflector, which is inserted in the laser cavity to regulate the intracavity wave surface. The deflector is designed and fabricated on a rectangle PLZT ceramic substrate (10×4×1 (mm)) whose top and bottom surfaces are sputtered with a pair of parallel triangular Ti/Pt/Au electrodes. The PLZT ceramic used here is a quadratic EO material; its La/PbZrO3/PbTiO$_3$ proportion is 9/65/35, which is regarded as the largest EO coefficient in the PLZT family. To the 9/65/35 PLZT ceramic, only quadratic terms are considered because unpoled quadratic PLZT ceramics have a symmetric random structure and exhibit little linear EO effect. When an electrical field is applied on the EO deflector (along the y axis), the refractive index of the material under the triangular electrode area will change due to the quadratic EO effect which causes the EO prism effect. The transmission beam then deflects at the interface. Incident lights with different polarization states will show different deflection effects[4]. The y-polarization beam (parallel with the electric field) has a much larger angular deflection than the x-polarization beam with the same applied voltage (Fig. 1(b)). Taking the y-polarization beam as an example, the EO induced index change of the PLZT ceramic is

$$\Delta n_1 = -\frac{1}{2} n_1^3 R_{33} E^2, \qquad (1)$$

where n_1 is the refractive index of the ceramic without the applied field, R_{33} is the EO coefficient, and E is the applied electric field. Thus, the deflection angle variation can be deduced easily from the refractive law in geometrical optics:

$$\theta = -\Delta n_1 \tan \alpha, \qquad (2)$$

where α is the acute angle of the triangular electrode. For our PLZT ceramic sample, $\tan \alpha = 2.5$.

Figure 2 shows the measured results of power-current (P–I) curves for the ECDL. When the PLZT deflector is not inserted into the cavity, the threshold current of the laser is about 20 mA and the slope efficient of the laser energy is 0.046 mW/mA; while the deflector inserted, its threshold current and slope efficient are 28 mA and 0.024 mW/mA, respectively (Fig. 2(a)). The facet Fresnel reflection and transmission loss of PLZT ceramic are believed to be the main factors influencing laser performance. Figure 2(b) shows the variations of P–I curves with different applied voltages. The small difference is induced possibly by the electrically induced loss of ceramic material[4]. In the experiment, we investigate the beam steering of ECDL under the condition of the DC operation in succession. A direct current (DC) driving voltage is applied to the PLZT deflector via its DC ports. With the applied voltage increases, the beam will deflect

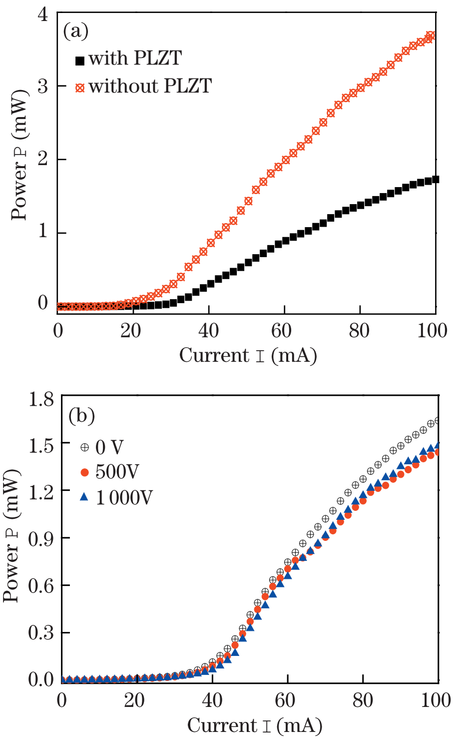

Fig. 2. P—I curves for (a) with and without PLZT deflector; (b) different applied voltages on the PLZT EO deflector.

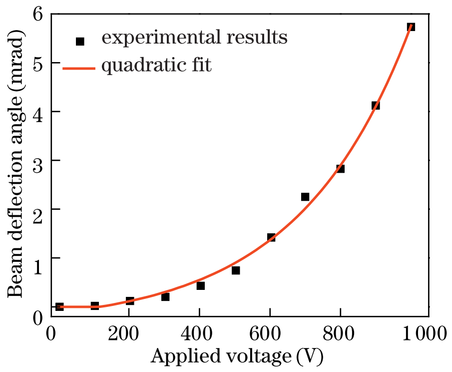

Fig. 3. Variation of laser beam deflection angles with the applied voltage.

due to the EO prism effect. Next, the corresponding output laser from the concave mirror will also deflect in a one-dimensional plane. Figure 3 shows that the beam deflection angle varies with the applied voltage on the deflector when only the y-polarization beam which causes larger angular deflection is selected in the cavity by PC. When the applied voltage is 1 000 V, the deflection angle will achieve 5.8 mrad, which may realize the precise beam scanning. This experimental result just agrees with the theoretical value, which can be calculated from Eqs. (1) and (2). Moreover, a good quadratic curve relation between the deflection angle and the applied voltage is also acquired as a result of the quadratic EO effect of the ceramic material.

We then measure the response time of beam steering for the proposed ECDL. The measurement is performed by placing a high-speed photoelectric detector (PD) at the output laser spot when no voltage is applied on the deflector. A fast switching signal with a repetition rate of 10 Hz generated from a nanosecond solid-state high -voltage pulse generator is applied on the PLZT deflector. The experimental results of the driving electrical signal and the optical response signal are shown in Fig. 4. The detected PD signal rises when the voltage falls. The fall time of the driving electrical signal is measured to be 57 ns, which is calculated by obtaining the range between 10% and 90% of the maximum output. The corresponding response time of laser beam deflection signal is measured to be 120 ns, which is decided by the response times of SL and PLZT ceramic material, the accumulation time of laser population inversion, and the cycle transmission time in the early time of laser formation. The method for response time estimation used in this experiment provides acceptable accuracy, but is primarily limited due to the PLZT ceramic capacitance (approximately 0.75 nF here)[13]. The waveform shows some fluctuations, as shown in Fig. 4 , which are believed to be mainly caused by the non-ideal photoelectric detection circuit.

To evaluate the performance of the output laser for ECDL, the spatial profile and polarization characteristic are also measured. Figure 5(a) shows a photograph of the spatial profile using an infrared charge-coupled device (CCD) camera. The size of the laser spot is about 1 mm and is approximately 10 cm away from the output position of the concave mirror. A good Gaussian distribution for the laser intensity, which is clearly superior to the beam quality of the optical phase array technology, is also found[4]. This will have better application in the given environment, such as lidar and laser communication. To understand the polarization characteristic of the output laser, the polarization state is measured by a Glan prism. The corresponding polar plot is shown in Fig. 5(b). An extinction ratio of 230 is obtained, which may be considered as an approximately linear polarization. The fluctuation and asymmetry for the measurement result are believed to be due to the imperfect collimation between the laser beam and the central axis of the Glan prism.

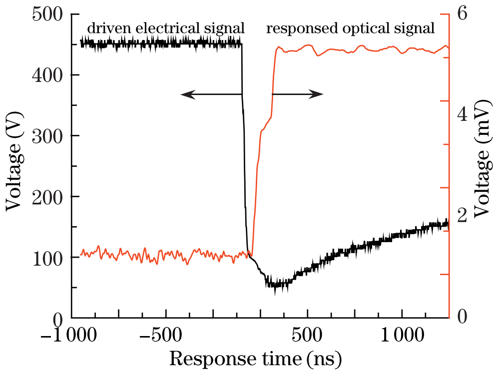

Fig. 4. Measurement of response time for beam steering.

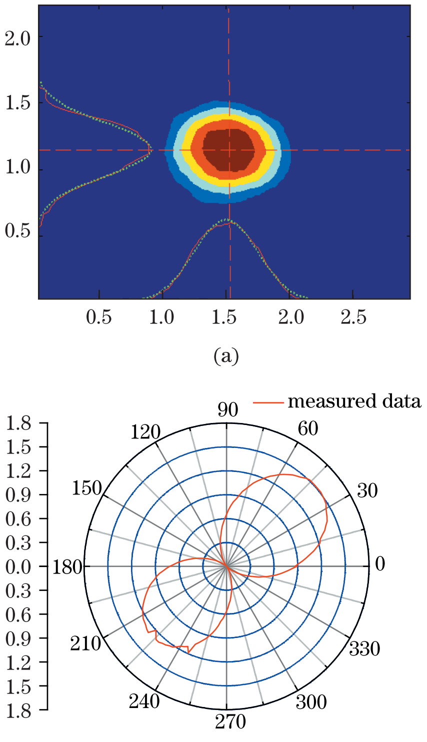

Fig. 5. (a) Photograph of the spatial profile by an infrared up-conversion CCD camera; (b) polar plot for the polarization state of the output beam from ECDL (the dotted line is the Gaussian fitting line).

ECDL performance may be improved further for the proposed scheme. For example, output power can be increased if a SL with higher efficiency is used. Intracavity loss and laser threshold may also be reduced if the PLZT ceramic is coated anti-reflectively. Moreover, to increase output power, an amplifier component can be inserted in the cavity to compose a master oscillator power ampifier (MOPA) configuration, as performed in Ref. [9]. The deflection angle may be enlarged by improving the deflector's design, such as using a larger oblique angle α and cascaded deflectors.

In conclusion, a novel beam-steering ECDL based on an intracavity PLZT EO ceramic deflector is proposed and demonstrated experimentally. A high-speed beam scanning property is observed by applying a fast switching electrical signal on the PLZT deflector. The performances of the output beam are also analyzed with polarization characteristic and spatial profile. The proposed laser can be developed as a practical laser with high output power, precise deflecting angle, and high steering speed, and can be used in the areas of optical communication, optical storage, optical interconnections, and lidar, among other applications.

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