A large aperture electro-optic deflector

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An electro-optic laser beam deflector with a clear optical aperture of 8.6 mm has been designed, realized, and tested. The electro-optic material used to implement the device was a MgO:$LiNbO_3$ crystal. The exceptionally large aperture makes the device suitable for applications where fast scanning of high power laser beams is needed. The measured deflection angle was 120 μrad/kV for a total length of electro-optic material of 90 mm. A mode quality analysis of the laser beam revealed that the M^2 of the laser is affected by less than 4% during scan operation when maximum driving voltage is applied. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3144274]

Laser beam deflectors have been of interest for applications in many fields since the invention of the laser in 1960. Already in 1966, Fowler and Schlafer[1] published a complete survey of possible deflection techniques. Nowadays, externally controllable optical deflectors find applications in many branches of applied physics and engineering such as laser printing, writing and readout of optical data storage devices, data processing in optical telecommunications, laser pulse selection for power amplifiers, material processing, laser surgery, and laser based beam diagnostics for particle accelerators to mention a few.

Among all the features that characterize a laser beam deflector, the most relevant are access time, deflection magnitude, optical resolution, beam quality preservation, optical aperture, and maximum laser power handling capability. Due to the enormous number and variety of applications, it is not easy to identify typical requirements for scanning devices in terms of the aforementioned features.

For example, for applications in telecommunications, a high processing speed is often demanded but the intensity of laser beams involved is rarely an issue. For this type of application, therefore, the typical technique used is electro-optics and the focus is more toward the deflection speed and low power consumption and less attention is paid toward the large aperture of the devices.[2–5]

On the other hand, in many other applications such as laser machining and surgery and the novel techniques adopted in accelerator physics for particle beam size measurements,[6] extremely high power laser beams are normally used, therefore devices should be designed with apertures sufficiently large in order to operate below the threshold of optical damage. Electromechanically controllable reflectors (piezoelectric mirrors) are normally chosen in these cases, as coatings can be engineered to withstand very high power and there is no restriction in size. However, such systems have an upper limit on the achievable scan speed (<1 kHz) due to mechanical inertia.

In this paper we propose a design for a deflector, based on electro-optic (EO) modulation, suitable for applications in which high laser power is involved and high operational speed beyond the limits imposed by mechanical movements is required. The operating principle of the device is illustrated in Fig. 1. The deflection of the laser beam is brought about by the generation of a linear gradient of refractive index across the transversal laser beam cross section obtained through the linear EO effect. The active material used for our studies is $LiNbO_3$ (LNB) with a 5 mol. % MgO doping for reducing the unwanted photorefractivity (MgO:LNB), an easily available material with high EO coefficients. In such materials, the EO induced refractive index change is given by[7]

$$\Delta n = \tfrac{1}{2} n_0^3 r_{33} E_z(y), \qquad (1)$$

where r_{33} is the EO coefficient which couples a linearly polarized laser beam to a parallel electrostatic field along the crystallographic c-axis. The arrangement of hyperbolically shaped electrodes as shown in Fig. 1, generates an electric field whose components along the y and z coordinates increase linearly from the center with alternative signs. This is expressed in Eq. (1) by a dependency of E_z on the y variable. Due to the EO coupling between the component E_z and the material optical properties expressed by Eq. (1), the refractive index will be modulated accordingly. The effect of such modulation of the refractive index on a laser beam that propagates through the EO crystal will be that the right side will travel at a different speed than the left one. Thus the laser beam wavefront will deflect in a measure proportional to the refractive index difference and the propagation length. The obtained deflection angle, calculated by taking into account the refraction from the output crystal's surface, is given by

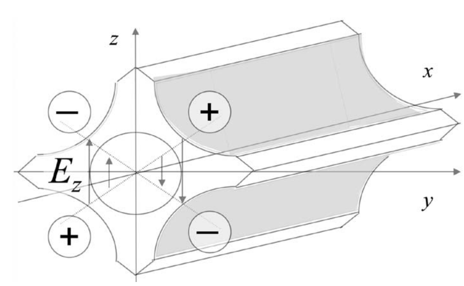

FIG. 1. Schematic of an EO deflector with hyperbolically shaped electrodes.

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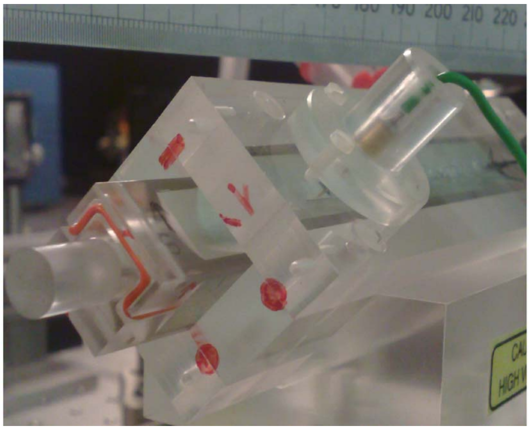

FIG. 2. (Color online) Picture of the deflector. The MgO:LNB crystals are inserted in the center of the holder with hyperbolical electrodes.

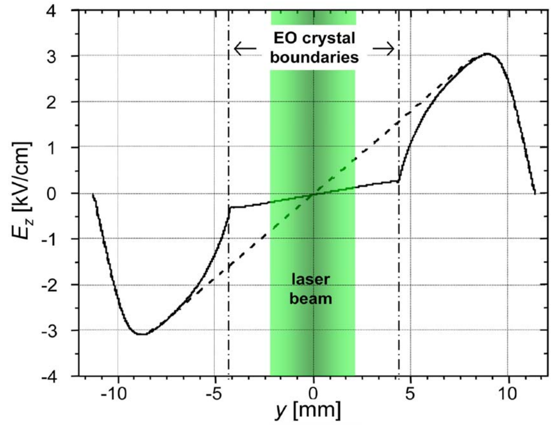

FIG. 3. (Color online) Plot of the variation of the z component of the electrostatic field along the transverse coordinate y for a homogeneous medium (dashed line) and for a hybrid structure (solid line).

$$\Delta\theta = L\frac{\partial}{\partial y}\Delta n, \tag{2}$$

where Δn is, according to Eq. (1), a linear function of the transverse coordinate y.

The standard design, in which the electrodes are shaped directly on the EO crystal, presents restrictions for the device optical aperture. In fact, to obtain a device with large clear aperture, it would require growing optically homogeneous and defect-free crystals of extremely large dimensions (16×16 mm^2 for a clear aperture of 8.6 mm), with obvious technical growth issues. In order to overcome this problem, we propose a hybrid solution in which the electrodes are shaped on a holder made of a common polymer. A picture of the device is shown in Fig. 2. Two cylindrically shaped MgO:LNB crystals with diameter 8.6 mm and length 45 mm were inserted in the center of the holder, for a total active length of 90 mm. The obvious advantage of this configuration is that the clear aperture coincides with the diameter of the EO crystal cylinder. In agreement to the 99% criterion for Gaussian beams,[8] the maximum beam diameter ($2w@1/e^2$) that can be propagated with less than 1% loss and limited diffraction effects is 5.5 mm; moreover, since there is no complex shaping of the crystal, the device is also a cost effective solution for use in harsh conditions where frequent replacement of EO material might be needed. On the other hand, the presence of a discontinuity of dielectric relative constant ε_r at the interface between the two media, i.e., the crystal and the polymer, needs to be taken into account when calculating the distribution of the electrostatic field. The electric field distribution in such heterogeneous system has been calculated using BELA (basic electrostatic analysis), a software package for the finite element analysis of two-dimensional problems in electrostatics. The calculation was done for a voltage of ± 5 kV applied on the electrodes and it took into account the nonisotropy of the LNB dielectric constant. The effect of the interface is reported in Fig. 3. The variation of E_z along the y coordinate is linear from left to right in the case of a homogeneous structure (dashed line in Fig. 3), whereas in the hybrid case (solid line in Fig. 3) there is a discontinuity about the boundaries (drawn on the picture as vertical dashed lines). From the plot it is possible to see that the divergence from the linear trend disappears within less than 1 mm inside the crystal, therefore a laser beam spot of 5.5 mm diameter lies all within the linear region. The other effect is a drop in the amplitude of the field by a factor of 5, consistent with the sudden increase of dielectric constant. This decrement significantly affects the performance of the device but could be reduced by choosing different materials for the holder and the EO core with better dielectric matching.

The experimental setup used to test the device is sketched in Fig. 4. The laser used for these tests was a frequency doubled mode-locked Nd:YVO_4 laser emitting 10 ps pulses at 532 nm with a repetition rate of 130 kHz. The laser beam propagating through the deflector was collimated to a spot size $2w=5.4$ mm, close to the limit for an aperture of 8.6 mm. Images of the laser were recorded by a charge-coupled device (CCD) camera placed after a plano-convex lens with a focal length $f=1$ m. A National Instruments™ PC card, controlled by a custom developed software written in LABVIEW™, was employed to generate two functions synchronized to the laser: the input for a 60 dB linear amplifier with 50 kHz bandwidth, used to drive the EO device, and a subharmonic signal for triggering the CCD camera.

Figure 5(a) reported a series of images, sampled every 2 kV of the laser profile during scan operation. The high voltage function consisted of a series of stepped ramps alternating between -5 and $+5$ kV with a step of 1 kV. Each step contained three laser pulses and was 23 μs long, therefore a full scan of 11 such steps lasted 253 μs. The plot in Fig.

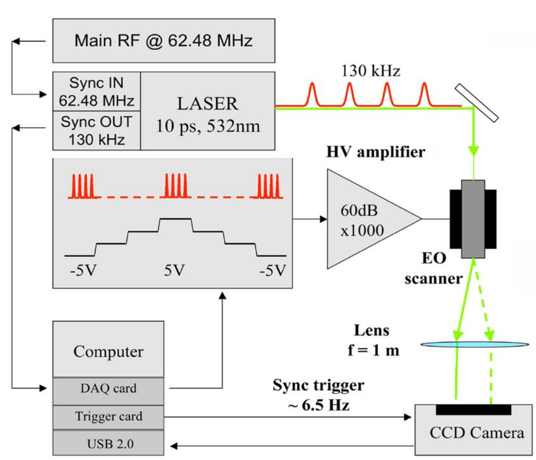

FIG. 4. (Color online) Experimental setup.

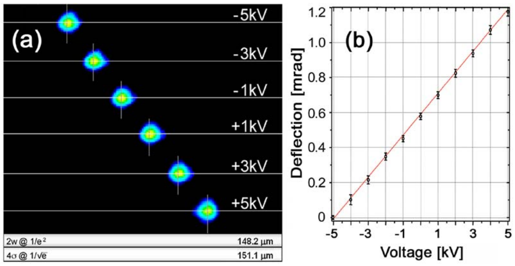

FIG. 5. (Color online) (a) Series of images of the laser pulses taken by the CCD camera during scan. (b) Plot of the angular deflection vs applied voltage. The angular values were calculated as a ratio between the beam displacement at the focal plane and the focal length of the lens (1 m).

5(b) shows the normalized angular beam deflection against the applied voltage during such a scan. The obtained deflection for our 90 mm long EO device is 1.2 mrad, corresponding to a deflection power of 1.33 mrad kV^{-1} m^{-1}. The measured deflection was in agreement with the theoretical value obtained by combining Eqs. (2) and (1) with $E_z(y)$ calculated from the BELA simulation (plot in Fig. 3). The deflection strength of an optical deflector is often quantified by calculating the number of resolvable spots contained within the deflection range. Two Gaussian functions can be considered resolved when their overlap has a minimum; this happens when they are separated by a distance larger than 1.2 times w. From this consideration we can calculate the number of resolvable spots of our device as a ratio between the maximum displacement at the focus ($\Delta\theta \cdot f$) and 1.2 times the focused beam waist w_0. The obtained value for $w_0=74$ μm and $\Delta\theta \cdot f=1.2$ mm is therefore approximately 13 spots, which is comparable to the values reported in literature for other types of EO deflectors.[3,4]

Concerning the performance of the deflector in terms of beam quality preservation, from the images reported in Fig. 5(a) it is already possible to see that the laser beam maintains its Gaussian shape and its circularity. A measurement of the laser quality factor M^2 after propagation through the crystals is reported in Fig. 6. Data were taken with an applied voltage of 5 kV for a set of CCD longitudinal positions using a CW second harmonic Nd:YVO_4 laser operating at 532 nm, with $M^2=1.05$. The laser was collimated to 5.4 mm waist and focused by a planoconvex lens with focal length of 2 m. As we can see, the propagation through EO deflector affects the beam quality by less than 4%; indeed the M^2 increases to 1.09 in the horizontal and to 1.07 in the vertical axis.

In conclusion, we realized an EO deflector and demonstrated its operation using a pulsed laser with a repetition rate of 130 kHz. The duration of a scan was 253 μs and it was limited by the high voltage amplifier bandwidth. The clear aperture of the device was 8.6 mm and could accept a laser beam with an input size of 5.4 mm with limited effects on the beam quality. In fact, the beam quality factor M^2 was increased by less than 4% during scan operation. This extremely large aperture makes the EO deflector suitable for applications where high power lasers are involved. The obtained deflection strength in terms of the number of resolvable spots was 13, and might be improved by up to a factor of 5 by choosing materials with better dielectric matching.

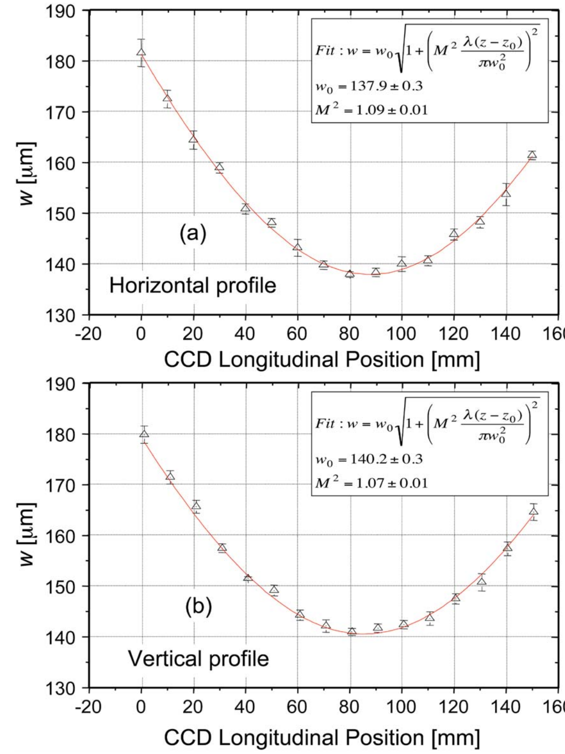

FIG. 6. (Color online) Plots of the longitudinal variation of the horizontal (a) and vertical (b) laser spot size for the M^2 analysis. Every point is an average of 64 values taken from single-pulse images synchronized to an applied voltage of +5 kV.

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