PREPRINT UCRL- 81024

CONF-780804--9

Lawrence Livermore Laboratory

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June 28, 1978

This paper was prepared for the Proceedings of the 13th International Congress on High Speed Photography and Photonics, Tokyo, Japan, August 20-25, 1978

ELECTROOPTIC DEFLECTOR DESIGN CONSIDERATIONS FOR USE IN THE CRYSTAL STREAK CAMERA*

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Figure-of-merit equations for material selection and detailed design equations have been developed to aid in the design of a linear electrooptic deflector element for use in a 10-ps streak camera. The figure of merit indicates that $BaTiO_3$, KTN, and ammonium oxalate (AMO) are suitable materials. Possible deflector designs, including that of a current AMO prototype development program, are discussed. Quadratic (Kerr-effect) operation and materials are discussed along with the possibility for 10.6-μm-wavelength use.

Introduction

Good diagnostics are vital to the success of laser-fusion research. One of the most important diagnostic tools is the ultrafast streak camera. A 10-ps streak camera was designed at Lawrence Livermore Laboratory (LLL) in 1971.[1] This and later versions are now in use at LLL. Available photocathodes permit subnanosecond diagnostics of photon wavelengths from x rays to the infrared limit of the S-1 cathode. Though x-ray and visible (S-20) photocathodes appear to be well understood and can be reliably produced with stable responses, the S-1 cathode has for many years had unstable response near the long-wavelength cutoff,[2] which, unfortunately, is currently a region of much interest (particularly 1.06 μm). At this writing the problem of S-1 cathode stability remains unsolved, though interest in it is growing. Furthermore, there is no photocathode for use at wavelengths longer than those covered by the S-1 (longer than 2 to 3 μm), for example at 10.6 μm for the CO_2 laser. For these reasons, and to design a probably less expensive streak camera, we have investigated direct deflection of a photon beam by use of an electrooptic (EO) deflector.[3,4] Such deflectors were chosen over other methods (such as acoustic and magnetic) for the reasons cited in Ref. 5. In 1976, we reported on a prototype streak camera that was constructed using a commercially available ADP deflector.[5] Results were close to those predicted. Temporal resolution was 1.25 ns per spot for 18 spots at 532-nm wavelength. Since then we have more completely analyzed the principles involved and, using ammonium oxalate, are building a prototype deflector designed to have over 100-spot spatial and 5-ps temporal resolution at wavelengths of 1.06 μm.

Electrooptic-Deflector Design

The equations describing an electrooptic crystal deflector are given in Refs. 5 and 6. Consider an iterated prism deflector, shown in Fig. 1, where n+ and n- refer to the increase and decrease, respectively, in the refractive index, resulting from application of a transverse electric field. The angular deflection $\theta = \theta_o - \theta_i$ (output minus input beam direction) is given by[5,6]

$$\theta = \frac{\ell}{\omega} n_0^3 r E_z \quad , \tag{1}$$

where n_0 is the refractive index with zero electric field, r is the EO coefficient, E_z is the electric field in the z direction, and ℓ and ω are the length and aperture of the deflector. Spatial resolution R, the total number of resolvable spots, is defined here as $R = \theta/\alpha$, where α is the angular resolution. Under the Rayleigh criterion, α is given by $\alpha = 1.22\ \lambda/\omega$, where λ is the wavelength and ω is the deflector usable aperture (Fig. 1). Combining the above equations with Eq. (1) gives

$$R = \frac{n_0^3 r V \ell}{1.22 \lambda z} \quad . \tag{2}$$

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-Eng-48.

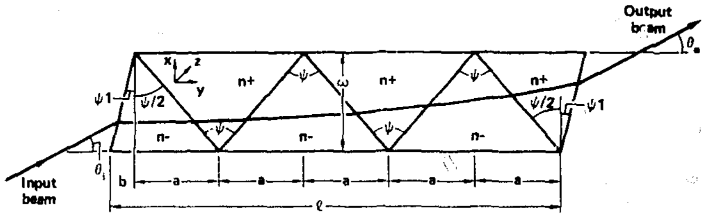

Fig.1. Six-crystal iterated-prism deflector.

Here E_z is replaced by V/z, where z, related to ω by some constant (say z = kω), is the actual crystal thickness in the z direction and V is the applied deflection voltage. Thus, we see by Eq. (2) that spatial resolution is proportional to ℓ/ω.

Temporal Resolution

The temporal resolution τ is defined as $\alpha/\dot{\theta}$, with units of seconds per spot, where $\dot{\theta}$ is the angular rate of change. A deflector having a square cross section, parallel-plate electrode has capacitance C equal to $\varepsilon_0\varepsilon_r\ell$, where ε_0 and ε_r are, respectively, the dielectric constant of free space and the relative dielectric constant of the crystal material. If $\dot{V}$, the time rate of change of the driving or sweep voltage V, is constant, then the driving current is given by $I = C\dot{V}$; hence, $\dot{V} = I/\varepsilon_0\varepsilon_r\ell$. Differentiating Eq. (1) and combining the result with the above and the definition of τ gives

$$\tau = \frac{1.22\lambda z\varepsilon_0\varepsilon_r}{n_0^3 r I} \quad . \tag{3}$$

So from Eq. (3) we see that temporal resolution is proportional to z and thus ω for a square-cross-section deflector.

Vignetting

Deflecting the beam will cause vignetting at the output aperture of a square-cross-section deflector. This problem is best solved by placing a prefocus lens before the deflector to reduce the size of the beam at the exit aperture. This allows the best temporal resolution to be realized and can also make the deflector aperture ω appear larger to an input beam, an advantage because practical considerations require the aperture to be small.

Figure 2 (which is not drawn to scale) shows that positive lens I causes the beam to narrow as it passes through the deflector. The undeflected path within the deflector is shown by the dashed extensions of the rays. The most that ray A can be deflected before the beam is apertured is the distance d/2, as indicated in Fig. 2. Thus the maximum deflection for ray C is also d/2. For ease in analysis, we assume that the entire deflection occurs abruptly at the center of the deflector. It follows that $\tan\theta'/2 = d/2$ and $\tan\phi' = d/2\phi$. Using the small-angle approximation and Snell's law and solving for ϕ, the entrance angle for ray A or B, we get $\phi = \theta/4$. The f number of lens I is easily found:

$$f_I = \frac{1}{2\tan\phi} \approx \frac{1}{2\phi} = \frac{2}{\theta} \tag{4}$$

Although the aperture ω of the deflector will probably be quite small, the system aperture can be increased to D (Fig. 2) by selecting lens I to have focal distance

$$F_I = L + \frac{2\omega}{\theta} = \frac{2D}{\theta} \quad , \tag{5}$$

where L is defined in Fig. 2. The length L is then $2(D - \omega)/\theta$. The focal length of lens II is given by $F_{II} = \omega z/1.22\lambda$, where 2ℓ, (the Rayleigh focal-spot waist size) is the spot size desired on the detector. For example, for a charge-coupled device (CCD) array with a 25-μm element size, one would most likely want the spot size to be 75 μm, covering three elements, so that the detector would not significantly limit the system resolution.

Number of Prisms

The number of prisms, N, needed in the deflector can easily be found by referring to Fig. 1:

$$\ell = \omega[\tan\psi 1 + (N - 1)\tan\psi/2] \quad . \tag{6}$$

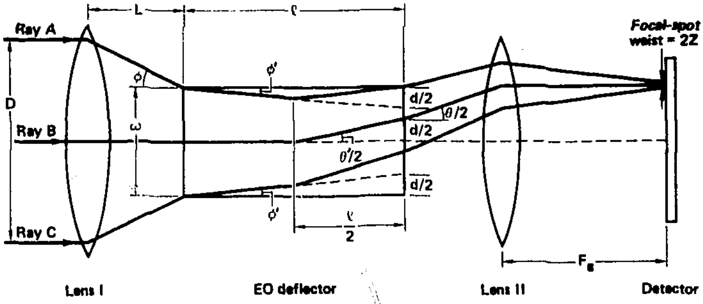

Fig. 2. Schematic of deflector system. Lens I prevents vignetting of beam; lens II focuses beam onto detector.

For $N \geq 10$, $\tan \psi 1 \ll (N - 1) \tan \psi/2$, and we find that

$$N \approx 1 + \frac{\ell}{\omega \tan \psi/2} \quad . \qquad (7)$$

Because, for this type of deflector, the deflection occurs only when the beam passes an interface at an angle different from normal, cutting the crystal entrance and exit surface at an angle $\psi 1$ from the normal, as shown in Fig. 1, provides two more interfaces and increases the deflection by some factor related to N. This factor increases with $\psi 1$, but so does deflection nonlinearity with applied voltage. Calculations indicate that if $\psi 1 \approx 0.5 \sin^{-1} 1/n_0$, there is little effect on linearity (~2%).

Design values of aperture size, deflector length, and deflection angle can easily be found from the crystal properties and design-requirement parameters by solving Eq. (3) for z and Eq. (2) for ℓ:

$$z = \frac{n_0^3 r \; I\tau}{\varepsilon_0 \varepsilon_r \; 1.22\lambda} \quad , \qquad (8)$$

$$\omega = \frac{1.22\lambda R z}{n_0^3 r \; V} = \frac{R I \tau}{\varepsilon_0 \varepsilon_r V} \quad . \qquad (9)$$

Combining Eqs. (1) and (9) gives $\theta = 1.22\lambda R/\omega$.

Resolution Figures of Merit

The spatial resolution figure of merit MR can be found by rearranging Eq. (2) such that all of the crystal material properties are on one side and the circuit or external parameters are on the other:

$$MR = n_0^3 r = \frac{1.22\lambda R z}{\omega V} \quad . \qquad (10)$$

Similarly, from Eq. (3), the temporal resolution figure of merit $M\tau$ is found:

$$M\tau = \frac{n_0^3 r}{\varepsilon_r} = \frac{1.22\lambda z \; \varepsilon_0}{I\tau} \quad . \qquad (11)$$

Design Example

For lowest temporal resolution, Eq. (3) indicates that the crystal cross section should be minimized. Handling considerations limit z to about 0.6 mm and more practically to about 1 or 2 mm. Equation (2) indicates that spatial resolution is maximized when ℓ/z is maximized. This figure can be made as large as desired and is limited only by the fabrication effort of the builder. We have selected 60 as a reasonable upper limit. The larger the apex angle ψ, the fewer the number of prisms required, but handling problems grow with the two extremely sharp edges at the other two corners of the prisms. For this reason, we have chosen ψ to be about 2 rad, making the maximum N about 40 prisms. Using these guidelines for crystal size, and assuming 4000 V at 120 A for deflection drive, for a design-goal resolution of 200 spots at 1.06-µm wavelength and 10 ps per spot, we can calculate from Eqs. (10) and (11) the figure-of-merit minimums required for selection of a material. The results are $MR_{min} = 1.08 \times 10^{-9}$ and $M\tau_{min} = 9.5 \times 10^{-12}$.

Table 1 lists a few popular electrooptic materials and their pertinent

Table 1. Summary of some possible materials for linear deflector use. (Values for r, ϵ_r, and n_0 are from Refs. 6-12.)

Material	EO coefficient (r), 10^{-12}m/V	Relative dielectric constant; ϵ_r or ϵ_1, ϵ_3	n_0	Figure of merit MR, 10^{-9}m/V >1.08	Figure of merit MT, 10^{-12}m/V >9.5	Comment
ADP	24.5	56, 15	1.5	0.083	1.5	
KDP	10.3	44, 21	1.5	0.035	0.79	
KD*P	26.4	58, 50	1.5	0.089	1.5	
$LiNbO_3$	30.8 (r_{33})	80, 30	2.2	0.328	4.1	
$LiTaO_3$	30.3 (r_{33})	42.8	2.14	0.297	6.9	
$BaTiO_3$ const. strain (clamped)	840 (r_{42})	1970, 11	2.4	11.6	5.9	Very difficult to make stable, good-quality pieces
AMO	327 (r_{52})	17	1.5	1.1	65	
KTN	14000 (r_{42})	Very high, ~5500	2.3	170	31	Cannot now be reliably made.
HIO_3	?	20, 11	2	?	?	Very little known

properties. Only $BaTiO_3$, ammonium oxalate (AMO), and KTN appear to be usable. Materials $BaTiO_3$ and KTN are very difficult to manufacture in stable form and with good optical quality at the present time. However a 1-mm-aperture $BaTiO_3$ deflector (ω = 1 mm, z = 1.2 mm) that is 6.6 mm long and uses six prisms (or at least five) will produce 200 spots and have 19.4-ps temporal resolution. Using KTN, a 2-mm aperture, 2-mm-long deflector would produce 527 spots and have a 6-ps temporal resolution.

It appears that AMO can be easily grown with good optical quality by evaporating a water solution.[8] Currently, we are sponsoring a prototype project that aims to grow enough to produce a deflector. The aperture will be 2 mm for ease of fabrication, and the length will be 60 mm. The deflector will use about a 2-rad Ψ and 20 prisms. For a 6000-V drive, 153-spot spatial and 2.9-ps temporal resolutions are expected. The transit time through this deflector will be 300 ps, so a strip-line or possibly a traveling-wave deflection electrode structure will have to be used to prevent distortion resulting from transit-time dispersion within the deflector.

Quadratic Operation and Longer Wavelengths

Some crystals displaying no linear electrooptic effect and some, such as KTN, that change from linear to quadratic when operated above the Curie temperature can be used for deflectors by taking advantage of the quadratic electrooptic effect. Retardation Γ, the angular phase difference created by an electric field, is given by

$$\Gamma_L = \frac{\pi n_0^3 r\, E_z \ell}{\lambda} \qquad (12)$$

for the linear case[13] and by

$$\Gamma_Q = \frac{\pi \epsilon_0^2 (\epsilon_r - 1)^2\, n_0^3\, (g_{11} - g_{12})\, E_z^2 \ell}{\lambda} \qquad (13)$$

for the quadratic case. Here $(g_{11} - g_{12})$ is a common quadratic electrooptic coefficient. To find an effective figure of merit for the quadratic case, we can assume $\Gamma_L = \Gamma_Q$ and solve for $n_0^3 r$. This gives

$$MR_{eff} = n_0^3 r_{eff} = \epsilon_0^2 (\epsilon_r - 1)^2\, n_0^3 \times (g_{11} - g_{12}) E_z \;, \qquad (14)$$

and the temporal figure of merit is

$$MT_{eff} = MR/\epsilon_r \approx \epsilon_0^2 \epsilon_r n_0^3 (g_{11} - g_{12}) E_z \;. \qquad (15)$$

The units for the above are usually mks. For polar liquids that have a quadratic or Kerr effect, the Kerr constants are used, and these are generally given in electrostatic units (esu). The phase retardation in this case is given by[15] $\Gamma_Q = 2\pi\ell KE_z^2$, where K is the Kerr constant. Again solving this equation and Eq. (12) for an effective figure of merit and using mks units (K in esu divided by 9 × 10^6 gives K in mks units) gives $MR_{eff} = 2\lambda E_z K$ and $M\tau_{eff} = 2\lambda E_z K/\varepsilon r$.

Calculations indicate that a simple decaying-exponential voltage waveform used as a sweep will make the deflection of a quadratic material linear to within about 20% over a reasonably large part of the deflection. A deflector using liquids could be built with a container having a quadrupole electrode configuration like the one used on the Coherent Associates Model 12 deflector.*

Unfortunately, common quadratic electrooptic materials produce rather low figures of merit for our design goals for a deflector. As an example, for $BaTiO_3$, $(g_{11} - g_{12}) = 0.13$ at 632.8 nm[14], producing an MR_{eff} of 2.18×10^{-9} and an $M\tau_{eff}$ of 1.108×10^{-12}, both of which are lower than for the linear case at 1.06 µm. For the polar liquid nitrobenzene, K is 326×10^{-9} esu at 589 nm,[15] yielding an MR_{eff} of 0.017×10^{-9} and an $M\tau_{eff}$ of 0.474×10^{-12}. The required figures of merit are even larger at greater wavelengths, making these materials not very useful at 10.6 µm, for example.

Similarly other materials (quadratic and linear) that transmit at 10.6 µm, such as CdTe, ZnTe, InAs, and Te, appear to have figures of merit too low to be useful, at least for our requirements (though accurate and reliable EO coefficients have been difficult to find in the literature). As an example, GaAs at 10.6 µm[16] yields $MR = 59.6 \times 10^{-12}$ and $M\tau = 5.18 \times 10^{-12}$, adequate for only about an 11-spot deflector with a temporal resolution of about 180 ps. Hopefully, some new materials will be found from which to make a deflector that is more practical at longer wavelengths.

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*Coherent Associates Model 12 E-O Beam Deflector; Coherent Associates, 42 Shelter Rock Road, Danbury, Conn. 06810. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Acknowledgments

I wish to thank John Emmett for his encouragement and Lamar Coleman for his support in this study. Also, thanks to Bert Johnson and Dave Attwood for their technical help.

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