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A Fast, Digital-Indexed Light Deflector

This Communication describes a digital-indexed light deflector. The design of the electro-optic device allows fast ($1\ \mu\text{sec}$) random directing of an intense, coherent laser beam toward any one of a large number of different positions. The present design allows for about 1000 binary addressed positions, and their selection includes some code-converting logic.

Principle of operation

The electro-optic light deflector design is based on crystal optics. The rectangular box shown in Fig. 1 represents the cross section through a transparent, birefringent calcite crystal. A collimated light beam enters this crystal and splits into two components, the ordinary ray and the extraordinary ray. At normal incidence, the ordinary ray propagates straight through the crystal, while the extraordinary ray is diverted. The ray separation angle depends on the birefringence of the crystal and on its orientation. In a properly oriented calcite crystal, this angle is approximately 6° . Both rays leave the crystal in their original direction but are displaced from each other by a distance proportional to the length of the crystal.

The ordinary ray and the extraordinary ray are linearly polarized. Their polarization directions are perpendicular to each other. If, therefore, the incident beam is linearly polarized in one or the other of these directions, it passes the crystal as either the ordinary or the extraordinary ray exclusively.

Figure 2 describes the electro-optic switch which controls the polarization direction of the light beam. The switch consists of a potassium dihydrogen phosphate (KDP) crystal and makes use of the longitudinal electro-optic Pockels effect. This effect and its application have been described extensively by B. H. Billings¹⁻³ and by R. O'B. Carpenter.⁴ The water-clear KDP crystals are

cut perpendicular to their optic axis. At normal incidence, a linearly polarized light beam splits into two components in the directions of the crystallographic x' and y' directions. Both components have the same optical path length in the crystal. Therefore, behind the crystal they recombine into a beam polarized in the original direction. Semi-transparent Nesa electrodes are cemented to the front and back surfaces of the crystals. If immersed in an index-matching fluid, these electrodes yield a transparency of

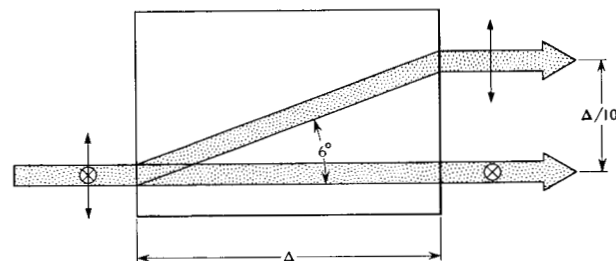
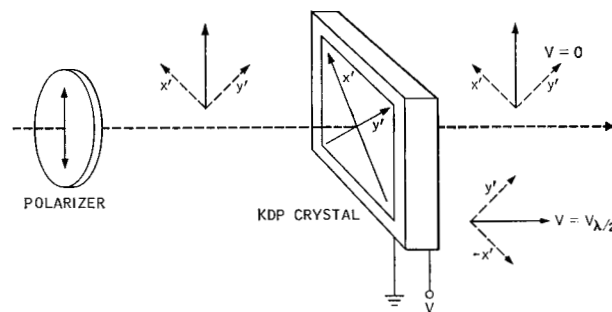


Figure 1 Birefringence in calcite crystals.

Figure 2 Electro-optic switch.



93 per cent. A voltage applied to the electrodes causes in the crystal an electric field which is longitudinal to the direction of the light beam. This field in turn induces an additional birefringence. At the so-called half-wavelength voltage, a path difference of a half wavelength exists between the components. The components behind the crystal now recombine to form a beam with a polarization direction oriented 90° relative to the original direction.

The combination of a birefringent crystal and an electro-optic switch constitutes one stage of the deflector. Several stages are combined as shown in Fig. 3.* In this illustration, *A* denotes electro-optic switches, and *B* denotes birefringent calcite crystals. The incident collimated light beam is linearly polarized in the horizontal direction. Because switch *A*₁ is open, the light passes straight through calcite crystal, *B*₁, as the ordinary ray. Since switch *A*₂ is closed, the plane of polarization behind *A*₂ is vertical, and the light passes through *B*₂ as the extraordinary ray. As switch *A*₃ is open, the polarization direction remains vertical and the beam passes also through *B*₃ as the extraordinary ray.

The displacement between the ordinary and extraordinary rays is proportional to the length of the calcite crystals. In sequential stages, lengths are chosen which increase as 1:2:4:8: . . . Thus, each stage yields a displacement one unit larger than the sum of the displacements of the preceding stages. If there are *n* stages, the number of beam positions is $N = 2^n$; thus 10 stages yield 1000 positions. In the deflector version of Fig. 3, however, the maximum number of positions is much smaller. Generally, economical considerations will limit the aperture of the crystals to 30 mm. At a reasonable beam diameter of about 1 mm, less than 30 positions would be resolvable.

High-resolution deflection is performed in the convergent-beam version of the deflector shown in Fig. 4. A lens is set in front of the deflector to focus the incoming light in a plane behind the deflector. The illustration depicts a case where all three electro-optic switches are closed. The light therefore passes through the first calcite crystal as the extraordinary ray. It passes through the second crystal as the ordinary ray, and through the third crystal again as the extraordinary ray. For reasons of symmetry, the third calcite crystal is turned upside down and yields a deflection in a direction opposite to that of the other calcite crystals.

In the convergent-beam version, the spot size is very small compared to the aperture *a* of the deflector. A large number of different output positions can therefore be resolved at reasonable crystal sizes. As a further advantage, the full aperture at the entrance is used. Thus the light

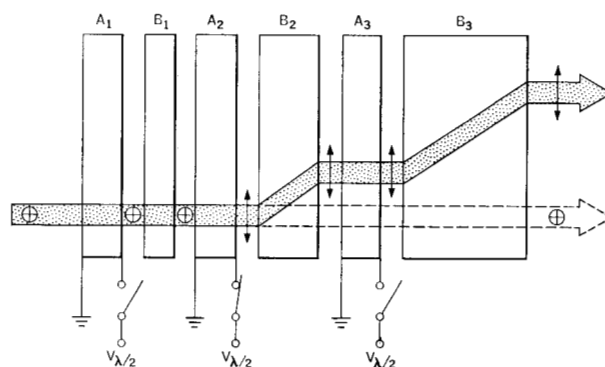
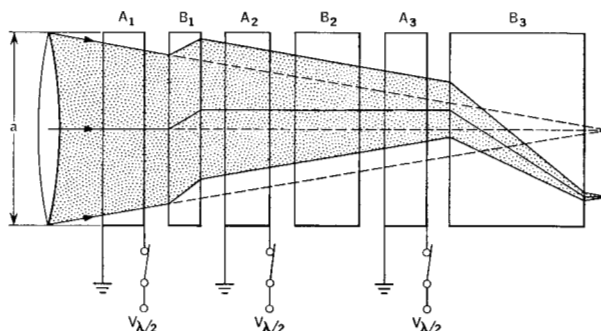


Figure 3 Digital light deflector for collimated beams.

Figure 4 Digital light deflector for convergent beams.



output compared to that in the collimated beam version, is also increased.

In the described deflector the beam is deflected in one dimension. Two-dimensional deflection can be obtained if two one-dimensional deflectors are used in series, each yielding deflection in a direction perpendicular to that of the other.

Resolution

The maximum number of resolvable spots is limited by diffraction occurring at the aperture of the deflector. This is shown (in exaggerated form) in Fig. 5, where *a* denotes the aperture, *l* the length of the deflector, and α the angle of diffraction, measured against the axis of the deflector. At the right side of the illustration, a diffraction pattern is shown as it occurs for each position. In the focal plane, the distance between two minima is $\delta = 2\lambda_M l/a$, where λ_M is the mean wavelength of light in the medium of the deflector. Figure 6 shows the intensity distributions of two adjacent positions. The positions do not overlap if

* A model with three stages was built and tested in the laboratory.

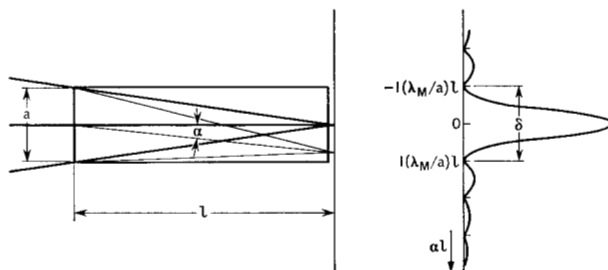


Figure 5 Diffraction at the aperture.

they are separated by δ . For this reason, δ is defined as the smallest possible spot diameter.

In the equation for δ , the length l of a deflector of n stages (respectively $N = 2^n$ positions) can be expressed in terms of the space s needed for the electro-optic switches and the space needed for the deflecting calcite crystals. Thus δ is obtained as a function of the aperture and the number of positions. The smallest possible aperture, a_{MIN} , of the deflector is obtained as the product of the smallest possible spot diameter δ , and the number of resolvable positions N :

$$a_{MIN} = 6.67\lambda(2^n - 1) \left[1 + \sqrt{1 + \frac{3}{10^2} \frac{ns}{\lambda(2^{n/2} - 2^{-n/2})^2}} \right] \quad (1)$$

Here λ is the wavelength of the light in vacuum converted from λ_M by assuming a mean index of refraction of 1.5 in the deflector. Figure 7 shows an evaluation of a_{MIN} plotted for $\lambda = 546.1 \text{ m}\mu$ and $s = 3 \text{ cm}$ versus the number of stages and positions, respectively. The illustration shows that (using an aperture of 2.0 cm) 1000 positions can be resolved. The spot diameter δ in this case would be 20μ .

Brightness

The brightness of the output spot depends mainly on two factors: the brightness of the light source used to illuminate the deflector, and the absorption and reflection losses inside the deflector. The inner surfaces of the parts are cemented together, or immersed in an index-matching fluid, thus eliminating reflection losses. Therefore reflection losses are negligible compared to absorption losses.

Absorption losses occur mainly in the semitransparent electrodes. If reflection losses are again reduced by index matching, the transparency of each electrode amounts to approximately 93 per cent. For a 1000-position deflector (requiring 10 switches with 20 electrodes), the total transparency of all electrodes is $0.93^{20} = 24\%$.

A commercially available He-Ne gas laser of 1.5 mW

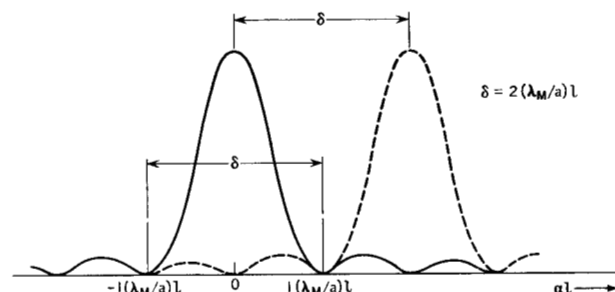
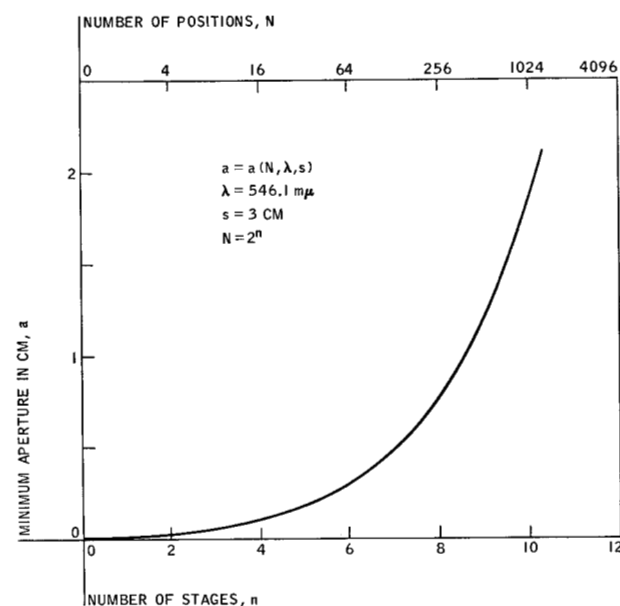


Figure 6 Minimum separation of adjacent positions.

Figure 7 Minimum aperture of deflector versus number of positions.



output, and $632.8 \text{ m}\mu$ wavelength, will be considered as a light source. In single-mode operation, this laser has a brightness of $3 \times 10^5 \text{ W/cm}^2 \text{ sterad}$ or $1.5 \times 10^{11} \text{ ft-L}$. Taking into account the light losses in the deflector, the brightness of the output spots is about $7.5 \times 10^4 \text{ W/cm}^2 \text{ sterad}$ or $4 \times 10^{10} \text{ ft-L}$.

Contrast

The contrast ratio gives the level of brightness of a switched output relative to the brightness in the unswitched positions. The latter results from light whose polarization is not oriented exactly as the ordinary or the extraordinary ray.

Errors in polarization are introduced by deviations of the switching voltage from the half-wavelength voltage.

The amount of light going to an undesired position is proportional to $\sin^2(\pi/2)(\Delta V/V_{\lambda/2})$, where ΔV is the deviation of the voltage from the half-wavelength voltage, $V_{\lambda/2}$. A contrast ratio of 100 to 1 can be maintained as long as the fluctuations of the signal do not exceed 6%.

Another source of polarization error is due to the angular-field birefringence of the KDP crystals. Only those rays that are parallel to the optic axis of the crystal maintain their polarization direction if the switch is open and experience a rotation of 90° if the switch is closed. Obliquely incident beams experience additional birefringence in the KDP crystal. Calculations indicate that the background brightness ratio due to this effect is less than 1/100 if the thickness of KDP crystals is less than 3 mm, and the angle of convergence of the beam does not exceed 2° .

If a better contrast ratio is desired, the amplitude of the switching signal must be maintained to closer tolerances, and the angular-field birefringence must be compensated as described, for example, by B. H. Billings.³

Maximum deflection rate

The maximum deflection rate is determined by the power consumption of the deflector. The power needed for each deflection is mainly reactive. On the average, one-half of the KDP crystals have to be charged to the half-wavelength voltage. During this process the small fraction of this energy given by the loss factor of KDP is dissipated in the deflector. The following calculation determines the deflection rate at which the dissipated power amounts to 5 W. This deflection rate may be defined as the maximum rate.

If, according to Eq. (1), the area of the KDP crystals is expressed in terms of the number of possible output positions, one gets for the energy W necessary for each deflection

$$W = C(N)N^2 \log_2 N \frac{1}{d} \epsilon V_{\lambda/2}^2, \quad (2)$$

where $C(N)$ comprises constants and varies only slightly with N . At $\lambda = 546.1 \text{ m}\mu$ wavelength, $s = 3 \text{ cm}$ space provided for each KDP crystal, and $N = 1000$ positions, $C(1000)$ is $0.8 \times 10^{-19} \text{ amp-cm-sec/v}$. The letter d denotes the thickness of the KDP crystals. At $N = 1000$

positions, $d = 0.2 \text{ cm}$, $\epsilon = 21$, and $V_{\lambda/2} = 7.7 \text{ kv}$, one gets $W = 5 \times 10^{-3} \text{ joules}$.

The loss factor, $\tan \delta_{\text{KDP}}$, of KDP material was reported by von Hippel.⁵ Above 10^4 cps it is $< 5 \times 10^{-4}$. Using this value, one finds the deflection rate at which 5 W are dissipated to be 2×10^6 deflections per second.

Summary

The device described in this paper is capable of positioning a light beam to any one out of, say, 1000 linearly arranged positions. The light beam is controlled by electric signals applied to electro-optic switches. The deflection is performed in either one or two dimensions. The positions are digitally indexed, thus allowing a high-speed-random access to each position. The locations of the positions are determined by the geometric design; therefore they are independent of the amplitude of the control signal and do not follow its fluctuations. The deflected light beam can originate from any source, and the light absorption in the deflector is reasonably small. Thus, when using a laser source, the outcoming beam can be very bright. The contrast ratio of the brightness in switched and unswitched positions is about 100 to 1. The maximum deflection rate depends on the allowable power dissipation in the electro-optic switches.

A deflection rate of 2×10^6 deflections per second seems feasible.

Acknowledgment

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