# Bistability at an electro-optic interface

P. W. Smith, W. J. Tomlinson, and P. J. Maloney

*Bell Laboratories, Holmdel, New Jersey 07733*

A. E. Kaplan

*Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

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We report the first known demonstration of a novel bistable optical device that switches an interface between reflecting and transmitting states. Our results are in agreement with a simple graphical analysis.

In this Letter we report the first known demonstration of a new type of bistable optical device—a hybrid nonlinear interface.

A nonlinear interface consists of the interface between two dielectric materials, one of which has an intensity-dependent refractive index. Such an interface has been the subject of much recent work, both theoretical[1] and experimental.[2] It was recently proposed that a hybrid version of a nonlinear interface using electrical feedback to an electro-optic crystal to provide the nonlinearity could be used to provide operation at low laser input powers.[3] This Letter reports the first known experimental demonstration of such a hybrid nonlinear interface and describes some details of the operating characteristics.

Experiments were performed using the setup shown in Fig. 1. A crystal of KD*P was polished to a thickness of 0.5 mm over an area of 1 cm × 5 cm. Metal electrodes were coated on the top and bottom surfaces so that an electric field could be applied in the direction of the $z$ axis of the crystal. This crystal was mounted in a cell containing index-matching oil with a value of refractive index close to that of the KD*P. The entire cell was bonded to a copper block whose temperature could be controlled with a circulating liquid. Because the refractive index of the liquid is a sensitive function of temperature, the index difference between the liquid and the KD*P crystal could be conveniently adjusted by controlling the temperature of the cell. The output beam from a ~1-mW He–Ne laser was incident at a shallow angle onto the polished edge of the KD*P crystal. The angle of incidence could be adjusted by rotating the entire cell assembly on an adjustable mount. The detected reflected light signal was amplified and fed back to the electrodes on the KD*P crystal.

The feedback voltage required to provide hysteresis can be estimated from a graphical analysis of the equations derived in Ref. 3. We find that good hysteresis should be observed for an index change of $\geq 0.1\Delta$, where $\Delta$ is the index difference between the index-matching liquid and the KD*P crystal. For $\Delta = 10^{-3}$ (corresponding to a critical angle of ~2°), we require an index change of $\geq 10^{-4}$. For an applied field along the $z$ axis of the KD*P, and the light incident at 45° to the $x$ and $y$ axes and polarized perpendicular to $z$, the index change produced by a field $E$ is $(n_0^3 r_{63}/2)E$, where, for KD*P, the electro-optic coefficient for these conditions $r_{63}$ is $26 \times 10^{-12}$ m/V. The field required to produce an index change of $\geq 10^{-4}$ is $E \geq 2.4 \times 10^6$ V/m. This corresponds to 1200 V across our 0.5-mm sample, or 2.4 V/$\mu$m.

Figure 2 shows the measured reflectivity as a function of incidence angle for the case in which no electrical feedback was present. The temperature of the matching liquid was adjusted so that the refractive index of the liquid was slightly greater than that of the KD*P, and thus total internal reflection occurred at sufficiently small angles of incidence. For comparison, the theoretical reflectivity versus angle of incidence is plotted for an incident plane wave with a critical angle of 1°. It can be seen that our experimental conditions are different from those used to derive the theoretical curves in Ref. 3, where plane-wave behavior was assumed. To some extent this difference is due to the Gaussian-beam character of our incident beam. The beam used for these experiments had a far-field beam divergence of 0.22° in the index-matching liquid. This accounts for some of but not all the deviation from the plane-wave curve. We believe that the increase in

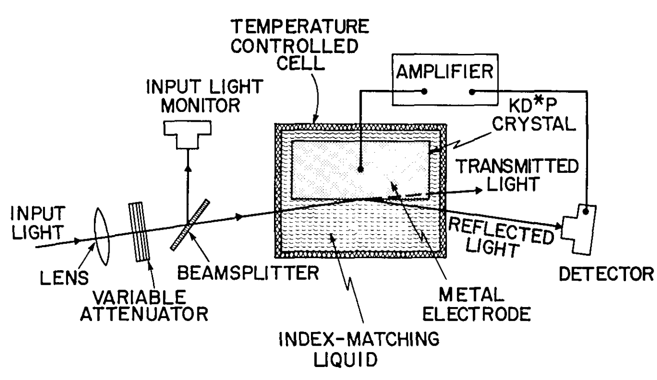


Fig. 1. Schematic of experimental setup (top view).

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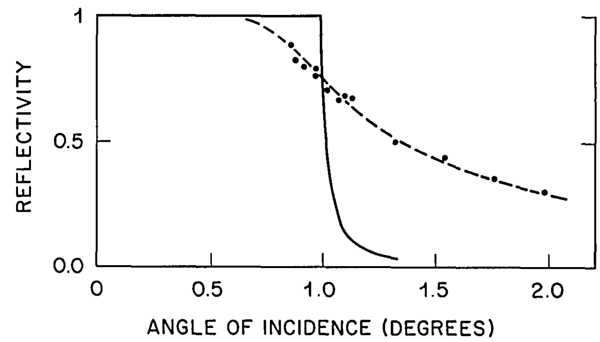


Fig. 2. Measured open-loop reflectivity as a function of angle of incidence for a temperature of 37.4°C. For comparison the computed plane-wave reflectivity (solid line) is shown for a critical angle of 1.0°.

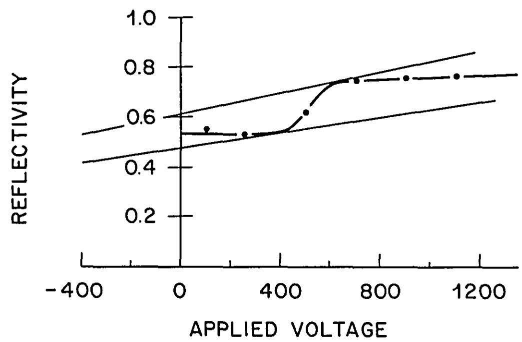


Fig. 3. Measured open-loop reflectivity as function of applied voltage. Two characteristic lines corresponding to the effect of the feedback signal have been drawn from the point on the voltage axis corresponding to the applied bias (−3100 V). The intersection of these lines with the experimental curve should correspond to the critical operating points for upswitching and downswitching.

specular reflectivity observed at the larger angles may be due to an impurity film on the crystal surface.

Because the interface does not behave as an ideal interface with an incident plane wave, the bistable behavior will not be predicted accurately by the formula derived in Ref. 3. A graphical procedure can be used, however, based on the measured interface characteristics. Figure 3 shows the measured (open-loop) reflectivity as a function of applied voltage for a temperature of 38.0°C and an incident angle of 1.0°. The closed-loop characteristics can be found graphically by plotting the linear dependence of applied voltage on the reflected light intensity and finding the points of intersection.[4] (For these experiments a bias voltage of −3100 V was used.) At the input powers corresponding to the lines shown, switching should take place. The output-versus-input characteristic found from this graphical analysis is shown in Fig. 4(a). The experimental hysteresis curve observed when the feedback loop was closed is shown in Fig. 4(b) for the same values of temperature and incidence angle. It can be seen that there is good agreement with the predicted behavior with regard to both the absolute reflectivities and the range of input powers over which hysteris is observed.

It can be shown by using the results of Ref. 3 that the critical angle can be determined by measuring, as a function of angle, the parameter

$$\rho = (P_2 - P_1)/P_1,$$

where $P_2$ is the input power at which upward switching occurs and $P_1$ is the power at which downward switching occurs. $\rho$ should equal zero at the critical angle. Figure 5 shows our measurements of $\rho$ as a function of the angle of incidence for a case corresponding to the conditions under which the data shown in Fig. 2 were obtained. The critical angle from the data of Fig. 5, 0.86°, is in good agreement with that estimated from the curve in Fig. 2.

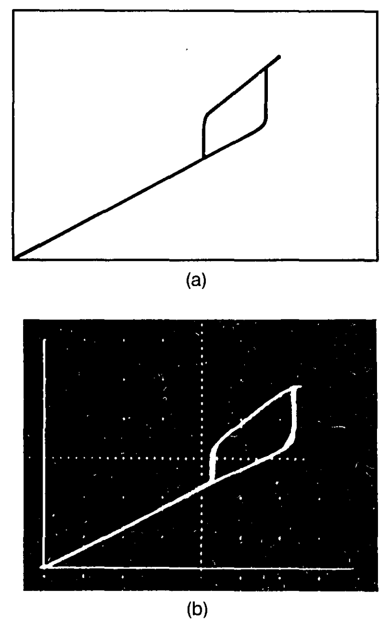


Fig. 4. (a) Characteristic curve (output power versus input power) calculated from the construction in Fig. 3. (b) Experimental closed-loop operating characteristic for the same conditions.

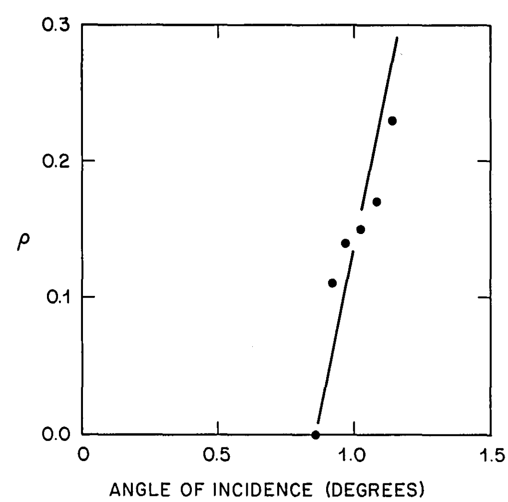


Fig. 5. Experimental measurements of $\rho$ as a function of angle of incidence.

In conclusion, we have reported the first known demonstration of a bistable nonlinear interface using a hybrid system. This device will operate over a broad bandwidth, as no resonator is required. By using a waveguide geometry such as those described in Refs. 5–7 it should be possible to fabricate an efficient integrated device that would operate with low drive voltages.

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## References

1. See, for example, A. E. Kaplan, "Theory of hysteresis reflection and refraction of light by a boundary of a nonlinear medium," Sov. Phys. JETP **45,** 896 (1977); "Theory of plane-wave reflection by the nonlinear interface," in *Optical Bistability*, C. M. Bowden, M. Ciftan, and H. R. Robl, eds. (Plenum, New York, 1981), p. 447.
2. See, for example, P. W. Smith, W. J. Tomlinson, P. J. Maloney, and J.-P. Hermann, "Experimental studies of a nonlinear interface," IEEE J. Quantum Electron. **QE-17,** 340 (1981).
3. A. E. Kaplan, "Bistable reflection of light by an electro-optically driven interface," Appl. Phys. Lett. **38,** 67 (1981).
4. See, for example, P. W. Smith, E. H. Turner, and P. J. Maloney, "Electro-optic nonlinear Fabry–Perot devices," IEEE J. Quantum Electron. **QE-14,** 207 (1978).
5. N. Naitoh, K. Muto, and T. Nakayama, "Mirror-type optical branch and switch," Appl. Opt. **17,** 101 (1978).
6. S. K. Sheem and C. S. Tsai, "Light beam switching and modulation using a built-in dielectric channel in a $LiNbO_3$ planar waveguide," Appl. Opt. 17, 892 (1978).
7. A. Neyer and W. Sohler, "High-speed cutoff modulator using a Ti-diffused $LiNbO_3$ channel waveguide," Appl. Phys. Lett. **35,** 256 (1979).