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# Electro-optically controlled beam switching via total internal reflection at a domain-engineered interface in $\text{LiNbO}_3$

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## Abstract

We report a novel switching method that occurs due to the electro-optic effect under applied field when a beam incident on an interface between anti-parallel domains in a sample of  $\text{LiNbO}_3$  subtends an angle greater than that required for total internal reflection (TIR). We present data obtained for wavelengths of 0.543 and 1.52  $\mu\text{m}$  and compare this with a theoretical model. This switch has many attractive properties, as TIR is a 100% efficient process leading to the possibility of high contrast ratios; current data shows contrast ratios greater than 100:1 (20 dB). Other properties include relatively simple fabrication procedure, low drive voltages and a wavelength dependence that is less than other electro-optic devices such as Pockels cells. © 2001 Elsevier Science B.V. All rights reserved.

**Keywords:** Total internal reflection; Switching; Electro-optic effect; Lithium niobate; Grazing incidence; Domain engineering

## 1. Introduction

We have developed a novel switching technique [1] that uses the electro-optic effect to induce a change in the refractive index,  $\Delta n$ , of a material that has been domain engineered to produce a boundary between two anti-parallel domain regions. When a beam is incident on the interface between these oppositely oriented domains at a suitably large angle, total internal reflection (TIR) can occur for a sufficiently large difference in refractive indices electrically induced between the two anti-parallel domains.

This method of electro-optically induced TIR is a novel approach for achieving high contrast switching, and presents many advantages when compared to existing techniques that use electro-optic deflection across a boundary [2] rather than reflection at an interface. The values of induced  $\Delta n$  are typically low for electro-optically addressed interfaces between domain-engineered  $\text{LiNbO}_3$ , so prism-type scanning devices have inherently low angular deflection sensitivity. For grazing incidence geometries however, TIR can be extremely sensitive, and for sufficiently large angles of incidence approaching  $90^\circ$ , the voltages required to induce switching can be of order a few volts.

To our knowledge the first reference concerning such TIR switching geometries was reported in connection with bulk Bragg grating structures in

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LiNbO<sub>3</sub> [3], where switching efficiencies of up to 95% were reported. Another paper reporting electro-optic *deflection* across the interface describes our work on large angle ( $\sim 10^\circ$ ) scanning [4], but is different from the results reported in the paper as TIR switching is not explicitly addressed.

## 2. Background

The angle necessary for TIR at an electro-optically addressed interface is given by the usual expression below:

$$\sin \theta_{\text{tir}} = \frac{n - \Delta n}{n + \Delta n} \quad (1)$$

where the equation relating  $\Delta n$ , and electric field,  $E$ , is given by the usual expression below

$$\Delta n = -\frac{1}{2}r_{33}n_e^3E_z \quad (2)$$

where  $r_{33}$  is the largest electro-optic coefficient accessed by extraordinary s-polarised light,  $n_e$  is the wavelength dependent value of extraordinary refractive index, and  $E_z$  is the value of electric field applied across the sample in the  $z$ -direction. While these coefficients which relate to s-polarised light lead to better switching characteristics, switching will also occur when using ordinary p-polarised

light, that accesses the  $r_{13}$  electro-optic coefficient which has a value approximately 1/3 that of  $r_{33}$ , and  $n_e$  is replaced by  $n_o$ , the value of the ordinary refractive index.

The value used for  $r_{33}$  was  $30.8 \times 10^{-12} \text{ mV}^{-1}$  [5] which was the closest published value corresponding to  $0.543 \mu\text{m}$  and the value for  $n_e$  was 2.23 [5] evaluated from the Sellmeier equation for a wavelength of  $0.543 \mu\text{m}$ .

Table 1 below shows values of  $\Delta n$  produced and the angle ( $\theta_{\text{tir}}$ ) necessary for TIR for increasing values of applied voltage for a  $300 \mu\text{m}$  thick sample, where  $\Delta n^*$  is double the value of  $\Delta n$  calculated from Eq. (2) as the change in value of refractive index on each side of the interface is of opposite sign. Fig. 1 shows the minimum angle required for switching to occur as a function of applied voltage.

Table 1

Examples of  $\Delta n$  produced and TIR angle implied for  $300 \mu\text{m}$  thick sample as a function of applied voltage

Applied voltage (V)	$E \text{ (V m}^{-1}\text{)}$	$\Delta n^*$	$\theta_{\text{tir}} \text{ (}^\circ\text{)}$
10	$3.33 \times 10^4$	$1.14 \times 10^{-5}$	89.82
100	$3.33 \times 10^5$	$1.14 \times 10^{-4}$	89.42
1000	$3.33 \times 10^6$	$1.14 \times 10^{-3}$	88.16

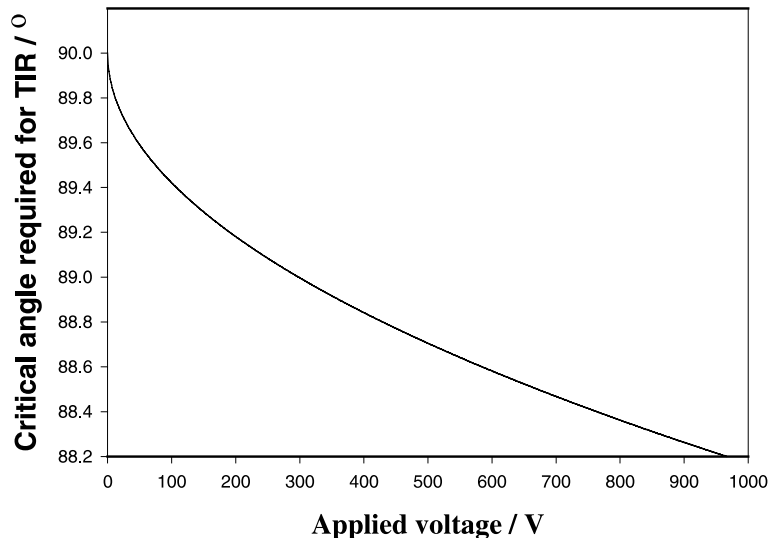


Fig. 1. Critical angle required for TIR as a function of voltage applied across the device of thickness  $300 \mu\text{m}$ .

### 3. Switch experimental details

The schematic of the electro-optically controllable domain-engineered TIR switch can be seen in Fig. 2. The sample was a *z*-cut wafer of congruent LiNbO<sub>3</sub> supplied by Yamaju (Japan), of thickness 300  $\mu\text{m}$ , and dimensions 13.5 mm  $\times$  15 mm in the *x*- and *y*-directions respectively. The two anti-parallel domains were produced by firstly photolithographically patterning the  $-z$  face and then electric field poling the sample. When examined under a polarising optical microscope the interface was seen to be quite smooth, but under high magnification some variation from absolute straightness was observed. This can be seen in Fig. 3, which shows an example of a region of such deviation from linearity. This non-uniformity was observed for all the samples but its extent was

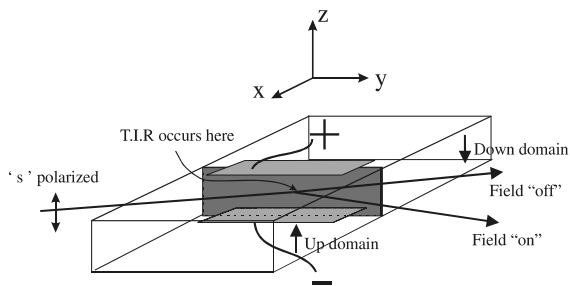


Fig. 2. Schematic diagram for domain-engineered sample.

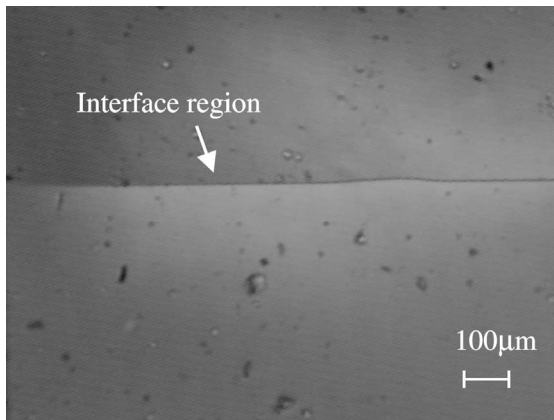


Fig. 3. Domain boundary as viewed using a polarising light microscope.

dependent on the poling parameters used, and also varied between individual samples. The samples were annealed after poling to assist the removal of any residual strain at the interface. Even after annealing for several hours at 200°C however, a small residual refractive index of order  $10^{-5}$  existed at the interface [1]. This residual refractive index can lead to significant Fresnel reflections at grazing angle incidence which will in turn affect the choice of incidence angle used and therefore the contrast ratio achievable.

Experimental data was obtained using polarised He–Ne lasers at wavelengths of 0.543 and 1.52  $\mu\text{m}$ . In each case the beam was initially passed through a spatial filter consisting of two microscope objectives (10 $\times$ ) and a pinhole before being focussed into the LiNbO<sub>3</sub> sample. Focussing was achieved using a lens of focal length 160 mm, which produced a spot size of the order of 25  $\mu\text{m}$  for 0.543  $\mu\text{m}$  light, and 64  $\mu\text{m}$  for 1.52  $\mu\text{m}$  light. The electrodes were fabricated on both  $-z$  and  $+z$  faces and were of dimensions  $\sim 12 \text{ mm} \times 2 \text{ mm}$  and were positioned across the domain-interface region. The input and output faces were parallel polished and insulating supports were used to mount the device.

### 4. Modelling of switching behaviour

We have developed a two-dimensional theoretical model for the TIR switch, which can be used to predict the switching characteristics expected for any combinations of incident angle ( $\theta_{\text{inc}}$ ), wavelength ( $\lambda$ ), spot size ( $\omega_0$ ), sample thickness ( $d$ ) and wavelength dependent refractive index ( $n_e$ ), as determined by the normal Sellmeier equations for LiNbO<sub>3</sub> [6].

Firstly, the model has been used to characterise the beam incident on the interface for any value of angle,  $\theta_{\text{inc}}$ . In Fig. 4(a) we show a schematic for the interaction of the incident beam at the interface region. For the purposes of this model the beam incident along the interface is divided into a number of slices. The lower part of the diagram shows the corresponding intensity profile; it was found that a high level of accuracy could be achieved by using a minimum of 50 slices. Fig. 4(b)

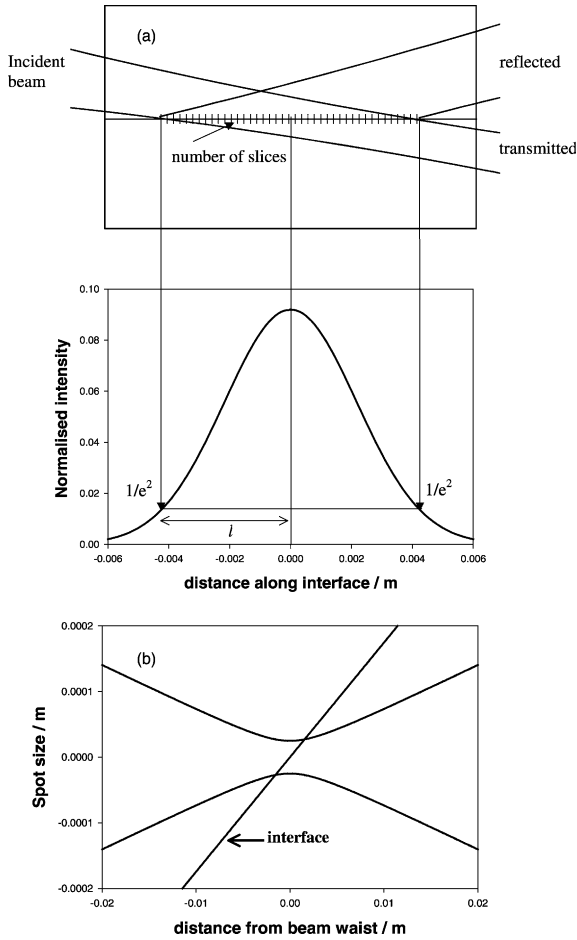


Fig. 4. (a) Schematic for interaction of incident beam with interface with the intensity profile of beam projected along the domain boundary for  $1.52 \mu\text{m}$  light with a spot size of  $64 \mu\text{m}$  incident at an angle of  $89^\circ$  where the intensity has been normalised such that total power under curve is equal to total power in beam. (b) Beam profile observed at the domain boundary for  $0.543 \mu\text{m}$  light with a spot size of  $25 \mu\text{m}$  incident at an angle of  $89^\circ$ .

depicts the modelling results showing the extent to which the  $1/e^2$  beam contour spreads at the interface due to the grazing angle of incidence and yields the values for where the  $1/e^2$  beam profile crosses the interface. Making the assumption that the beam profile at the interface is Gaussian, the intensity profile,  $I$ , of the beam across the interface can be given for any angle of  $\theta_{\text{inc}}$  using the expression

$$I = \frac{P_{\text{total}}}{l} \sqrt{\frac{2}{\pi}} \exp\left(\frac{-2z^2}{l^2}\right) \quad (3)$$

where  $P_{\text{total}}$  is the total input power of the incident beam,  $l$  is the  $1/e^2$  width of the Gaussian intensity profile projected along the interface and  $z$  is the distance along the device where  $z = 0$  corresponds to the position of the beam waist. The power in each slice is given by the expression

$$P_{\text{slice}} = \frac{P_{\text{total}}}{2} \left( \text{erf}\left(\sqrt{\frac{2x_2}{l}}\right) - \text{erf}\left(\sqrt{\frac{2x_1}{l}}\right) \right) \quad (4)$$

where erf is the error function and  $x_1$  and  $x_2$  are two points that define the slice width.

There is a variation in the angle of incidence across the beam width, and this is shown in Fig. 5. Each slice therefore has a different effective angle of incidence, and knowing this the reflectivities of each slice can be calculated by modifying the standard Fresnel equation as applicable to Fig. 6 [7] to be in terms of  $\theta_{\text{inc}}$  only, which becomes

$$R_s = \left( \frac{[\cos(\sin^{-1}[n_{\text{it}} \sin \theta_{\text{inc}} - \cos \theta_{\text{inc}} n_{\text{it}}])]}{[\cos(\sin^{-1}[n_{\text{it}} \sin \theta_{\text{inc}} + \cos \theta_{\text{inc}} n_{\text{it}}])]} \right)^2 \quad (5)$$

where  $n_{\text{it}} = n_{\text{inc}}/n_{\text{t}}$ .

The power reflected for each slice is then calculated by multiplying the reflectivity for each slice by the power in each slice. The sum of the power of the slices that have reflectivities that fall within the parameters necessary for TIR is then calculated. This procedure is evaluated for 1000 points between 0 and 1000 V. The percentage of the total power is then plotted against voltage, and this allows a comparison to be made with the experimental data collected.

## 5. Experimental results

Fig. 6 also shows the geometry of interaction for the beam with the interface for all the results that follow. The  $2\theta_{\text{ext}}$  angle is determined before measuring any power reflectivities and  $\theta_{\text{inc}}$  is given by the expression below

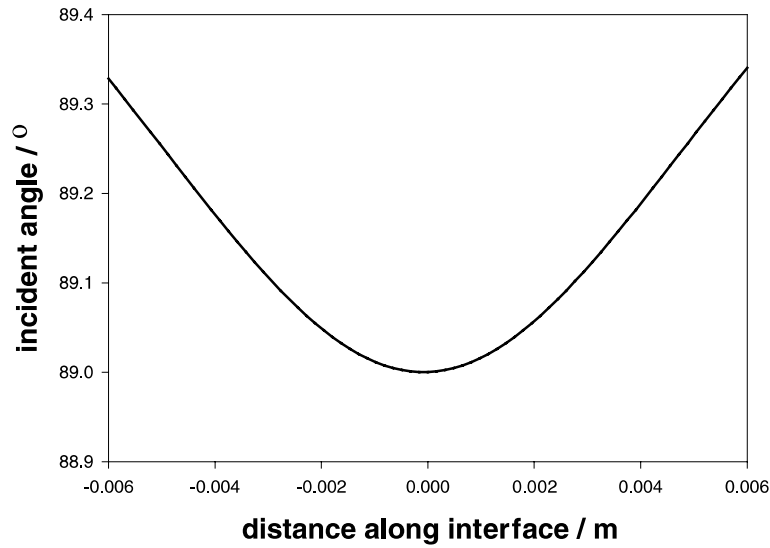


Fig. 5. Variation of incident beam angle across domain boundary for 1.52  $\mu\text{m}$  light with a spot size of 64  $\mu\text{m}$  incident at an angle of 89°.

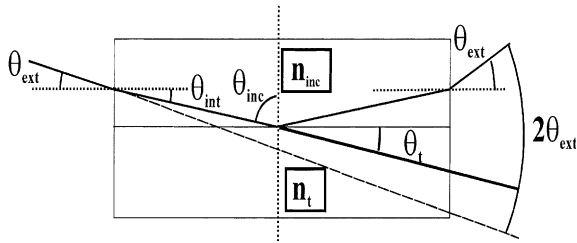


Fig. 6. Schematic for Fresnel reflection and geometry of interaction at interface.

$$\theta_{\text{inc}} = 90 - \theta_{\text{int}} = 90 - \left( \sin^{-1} \left( \frac{\theta_{\text{ext}}}{n_c} \right) \right) \quad (6)$$

Initially results were taken using the 0.543  $\mu\text{m}$  laser to characterise the presence and the strength of any residual refractive index at the interface. Powers in the reflected beam were measured at various angles with no voltage applied. The data was then superimposed onto standard Fresnel reflectivity curves and visually best fitted to obtain values for  $\Delta n$  in the interface region. The values of residual refractive index for both polarisations on each side of the interface can be seen in Table 2.

Switching data was recorded using this wavelength for both s- and p-polarised light, and these results are shown in Fig. 7. As expected when

Table 2

Best-fitted residual refractive index on either side of the domain boundary

	'+' side	'-' side
s-polarisation	1.000046	0.999890
p-polarisation	1.000020	0.999985

considering the values of the respective electro-optic coefficients accessed by each polarisation orientation, the switching of s-polarised light occurs much before that of the p-polarised light. The contrast ratio achieved was observed to be greater than 100:1 (20 dB).

Switching data was also recorded at the longer He–Ne laser wavelength of 1.52  $\mu\text{m}$  where good switching characteristics were again observed. Detailed comparison is now possible between the theoretical curves generated by the model, and experimental data points. As seen in Fig. 8 good agreement can be obtained for the early stages of switching at low applied voltages. The lack of fit as TIR is approached can be accounted for, for example by introducing a small random angle varying between 0° and 0.2° across the interface in the numerical model to closer match the actual randomness observed for the interface. The model is

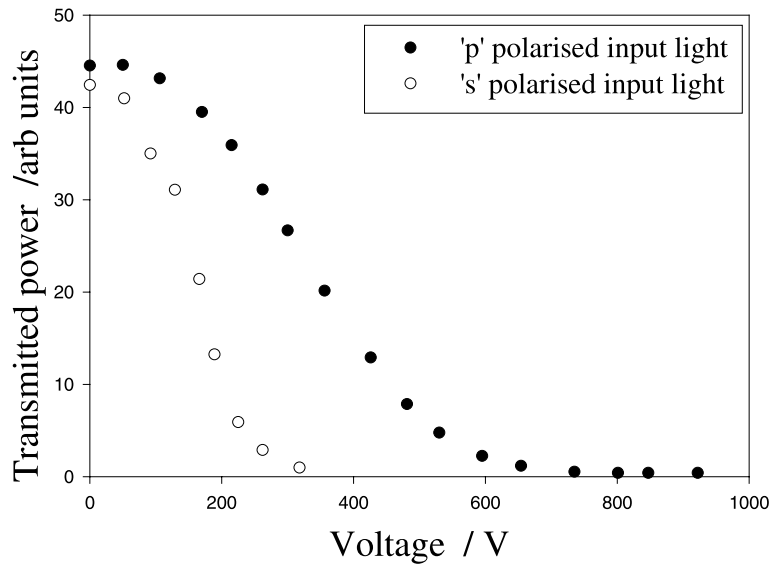


Fig. 7. Comparison of switching for s- and p-polarisations for light of  $0.543 \mu\text{m}$  incident at an angle of  $88.5^\circ$ .

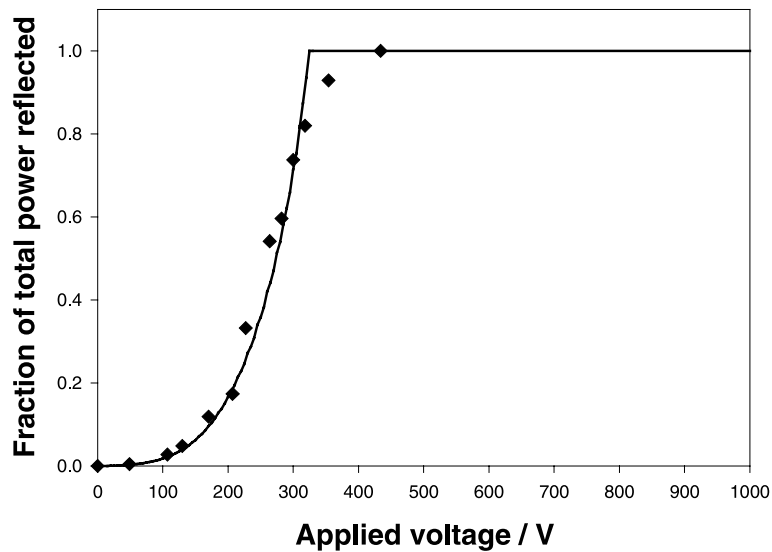


Fig. 8. Comparison of model and switching data for s-polarised light at  $1.52 \mu\text{m}$  incident at an angle of  $89.1^\circ$  (points are experimental measurements, solid line is theoretical fit).

now seen to round off slightly at the top, and under suitable model parameters a closer match can be obtained to the experimental results. The contrast ratio in this case for  $1.52 \mu\text{m}$  light is much greater than 100:1 but the measurement of exact values are currently limited by the resolution of the apparatus used for measurement.

As previously mentioned the switch is much less wavelength dependent than other electro-optic switches such as a Pockels cell, and a comparison of voltages required for TIR for the switch and the half wave voltage,  $V_\pi$ , for a Pockels cell confirms this. The half wave voltage for a Pockels cell can be calculated using the expression below

$$V_{\pi} = \frac{\lambda}{2n_e^3 r_{33}} \quad (7)$$

where  $\lambda$  is the wavelength of interaction. For the TIR switch, substituting for  $E_z = V/d$  where  $V$  is the voltage applied across the interface and  $d$  is the switch thickness and rearranging Eq. (2) the voltage required for TIR switching can be given by the expression

$$V = \frac{2\Delta n d}{r_{33} n_e^3} = \frac{\Delta n^* d}{r_{33} n_e^3} \quad (8)$$

It is clear from Eq. (7) that the value of  $V_{\pi}$  is directly proportional to  $\lambda$ , in contrast to our TIR switch however, in which  $\lambda$  does not appear. As  $r_{33}$  and  $n_e$  and their intrinsic wavelength dispersion are common to both Eqs. (7) and (8) this leads to the approximation that the TIR switch operation is effectively wavelength independent. For longer wavelength operation, there are clearly geometrical factors such as Gaussian beam focussing constraints, interface lengths required and so on, but the argument concerning effective wavelength independence is valid.

## 6. Further work

Alternative manufacturing techniques will also be investigated; these include direct bonding of two  $z$ -cut samples of LiNbO<sub>3</sub> to form a switch consisting of two oppositely oriented domains. An advantage of this bonding technique is that no residual strain should remain as observed for the poled domain switch, and the straightness of the interface between the two domains should improve dramatically thereby. Another method of switch manufacture we are keen to investigate involves the poling technique as previously described but using *stoichiometric* lithium tantalate (LiTaO<sub>3</sub>) and LiNbO<sub>3</sub>. This interest has arisen because manufacturers [8] report that these crystals require a lower coercive field for poling, and have higher electro-optic coefficients than the congruent materials; the coefficients for these new materials are shown in Table 3. Additionally the quality of poled interfaces has been observed to be superior to those from congruent LiNbO<sub>3</sub> [9].

Table 3

Electro-optic coefficients and coercive fields required for domain switching for *stoichiometric* lithium tantalate and lithium niobate

Properties	Stoichiometric LiNbO <sub>3</sub>	Stoichiometric LiTaO <sub>3</sub>
$E$ -field for domain switch (coercive field) (kV/mm)	<4	<1.7
$r_{33}$ electro-optic coefficients (pm/V)	38.3	35.5

## 7. Conclusions

We have presented a novel electro-optic switching technique that shows good contrast ratios of greater than 100:1 (20 dB), by optimising the manufacturing method the contrast ratio could increase significantly and fulfil the potential associated with TIR (TIR is a 100% efficient process). The switch has been shown to function well at wavelengths of 0.543  $\mu\text{m}$  and the useful telecoms wavelength of 1.52  $\mu\text{m}$ . It has also been shown that the switching behaviour fits well to curves as predicted by a theoretical model.

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