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ELECTROOPTIC WAVEGUIDE MODULATION AND SWITCHING DEVICES

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The electrooptic effect provides a convenient means for controlling the amplitude, phase, frequency and polarisation of a coherent light beam. In practice, it is the linear (Pockels) effect which is used, rather than the quadratic effect discovered in the last century by the Reverend Kerr at Glasgow University! The Pockels effect requires an asymmetric anisotropic material and the most-favoured examples are, in order of preference, single-crystal lithium niobate and lithium tantalate. Even in these materials, the effect is inherently very weak but this weakness is substantially overcome by exploiting the small dimensions possible with light in stripe waveguides and electrodes defined by the readily available high resolution lithography processes. We should also note here that the electrooptic effect in semiconductors such as gallium arsenide and indium phosphide is about a factor of ten weaker than in lithium niobate, but that this is still strong enough to encourage research on devices on such III-V group materials.

Basic equations for the linear electrooptic effect

At this point we shall consider some elementary theory for the electrooptic effect - enabling us to carry out simple calculations which relate typical device dimensions to the voltages required to obtain a useful effect. Firstly, we remember that the velocity of light in a medium of refractive index, n, is slower than the velocity of light in free space according to the equation:

$$v = C/n$$

where c is the velocity of light in free-space and v is the velocity of light in the medium.

Remember also that the wavelength in the medium is likewise reduced in relation to the free-space wavelength. The linear electrooptic effect then produces a change in the refractive index of the medium given by an equation of the form:

$$\Delta n = \underline{a}\, E$$

where Δn is the change in index and $\underline{a}$ is a constant, the size of which depends on the properties of the material according to the relation:

$$\underline{a} = \frac{-n^3 r}{2}$$

This equation is a gross simplification of the equations required to describe the true situation in an actual anisotropic single-crystal medium, with non-uniform electric fields applied to one surface of an inhomogeneous stripe optical waveguide, but it will suffice for the moment. The number r (or, in a real medium, the reduced tensor r_{mn}) is a property of the material - the electro-optic coefficient. As an example, consider the 'large' coefficient $r_{33} = 30.10^{-12}$ m/V available in lithium niobate, together with an applied electric field strength E = 5V/μm, which could be obtained, say, by applying approximately 10 volts across a 2μm gap. The resulting change in refractive index is of magnitude

$$|\Delta n| = \frac{(2.2)^3}{2}.\ 30.10^{-12}(\mathrm{m/V})\ 5.10^6(\mathrm{V/m}) = 8.10^{-4}$$

Even this does not seem large! But what we look for is the total phase change produced over a distance ℓ, at a wavelength of λ. This is given by:

$$\Delta\phi = \Delta n.\ell/\lambda$$

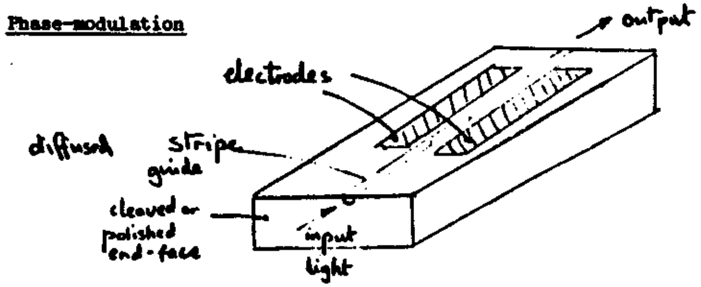
Now, as we shall see, a phase-shift of π may be all that is required, for instanc to take a device from an on-state to an off-state. Taking λ as, say, 0.5μm, we find that we need a length

$$\ell = \pi.\frac{\lambda}{\Delta n} = \frac{\pi.0.5.10^{-6}}{8.10^{-4}}\,\mathrm{m} = 1.96\mathrm{mm}.$$

Such a length can be considered reasonably typical. However, several more millimetres are often needed to manipulate the light beam in the waveguide to the right position for applying modulation or switching. Notice, also, that device length or operating voltages increase with increasing wavelength - because a given phase-change needs a length of a specified number of wavelengths and because waveguide and electrode-gap dimensions tend to increase with wavelength.

Note that the linear electrooptic effect can either reduce or increase the refractive index. Which change actually occurs depends on the direction of the applied electric field and the sign of the electrooptic coefficient - related to the orientation of the single-crystal medium.

Phase-modulation

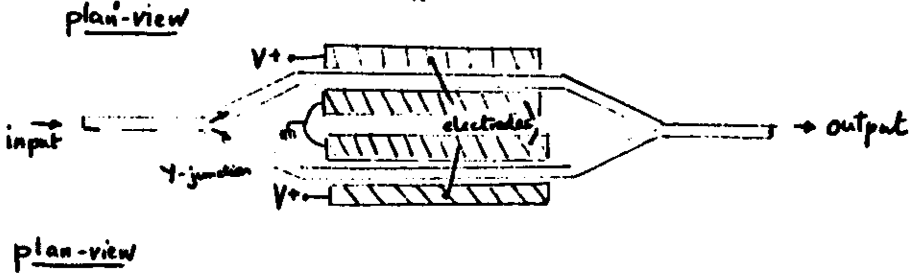


This device acts as a pure phase-modulator provided that a variety of possible effects are avoided - by careful design. In particular, the presence of the electrodes and the application of the electro-optic effect must not induce significant changes in the energy distribution of the waveguide mode - since these imply a substantial amplitude modulation. In fact, as work described in the Ph.D. thesis of B. Bjortorp (Glasgow University, 1983) shows, these effects can be deliberately enhanced to give strong amplitude modulation in a structure which looks, superficially, identical to the phase-modulator structure.

The phase-modulator structure can also be used to produce frequency-shifting - within certain practical limits. This capability is obtained by applying a repeating linear ramp function voltage to the electrodes - with the amplitude adjusted so that a 2π phase shift occurs at the peak applied voltage - followed by an abrupt drop down to zero voltage before the ramp is repeated. Fairly obviously, given sufficient coherence (a demanding requirement) a pure phase modulator could be used to provide phase-shift key (PSK) type digital modulation.

Amplitude Modulation

A popular way to produce amplitude modulation is to use some form of interferometer to convert electro-optic phase-shifts into amplitude changes. One configuration for doing this is the 'Mach-Zehnder' geometry shown below.

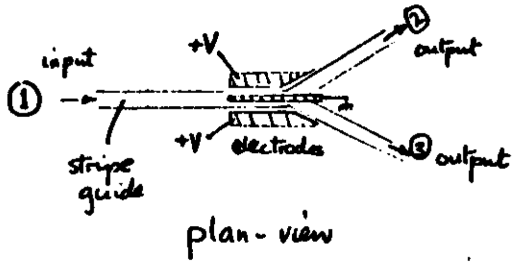


The light in the input waveguide is split into two branches which (for maximum effect) have opposite changes in refractive index induced in them, electrooptically. When light in the two branches is re-combined, the output light level depends on whether the two branch beams are in-or out-of-phase. When they are in-phase (identical optical path lengths in the arms of the interferometer) constructive interference excites the single symmetric output waveguide mode properly. With a relative phase-shift of π radians, the out-of-phase beams interfere destructively - or, in modal terms, launch an antisymmetric, second-order, output mode - which is cut-off and leaks out of the guide.

Another form of interferometer - the Fabry-Perot structure which is a basic feature of most lasers - can also be realised in integrated-optical form - with rather modest finesse (around 10). There is a consequent increase in amplitude modulation sensitivity proportional to the finesse - i.e. one tenth of the on-off voltage difference can be obtained - but with ten times the precision being required to maintain the correct, optically or electrically-biassed, operating point.

Electrooptic Switching

A number of different configurations of electrooptic waveguide switching device have appeared. Firstly, we mention here the Y-junction switch shown schematically below:



In the Y-junction switch, applying the voltage to the two outer electrodes changes the refractive index distribution across the waveguide, so that light in the guide re-distributes its energy to one side or the other and emerges preferentially out of either output port (2) or output port (3).

A fairly similar device is the X-junction switch, as shown below:

This is of more interest as it has two input-ports as well as two output-ports. In the simplest (and somewhat naive) view, applying a voltage between the electrodes locally changes the refractive index to form a total internal reflection 'mirror' - and so light from either of the input waveguides no longer passes straight through the switch but is diverted to the other port. Cross-over angles are typically rather small - in the range 2 to 4 degrees.

A more sophisticated form of cross-over switch results from using the directional coupler principle. In the simplest form, a directional coupler is made with two identical parallel stripe guides spaced sufficiently close together that light input in one guide cumulatively couples across into the other guide. This build-up is continued until there is complete transfer. The applied electro-optic voltage then frustrates the coupling process by inducing a mismatch between the guides. If this mismatch is sufficient then, half-way along the structure, the transfer goes into reverse and all the light is coupled back in the same guide as at the input.

the long-term drifts which occur under steady light level/steady applied voltage leve conditions.

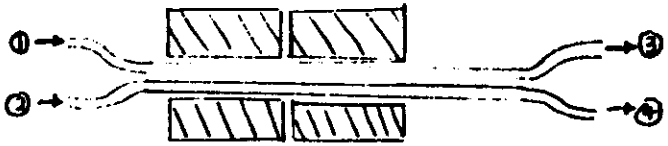
Electrooptic devices: speed of operation

To a reasonably good approximation, planar electrodes on a high-dielectric const medium such as lithium niobate form a pure capacitor, the magnitude of which decrease logarithmically as the electrode gap increases and increases linearly as the electrod length increases. In consequence, while an increase in the electrode length implies smaller switching voltages, it implies proportionately larger capacitance.

If one assumes that an electro-optic device is fed by a coaxial transmission lin of characteristic impedance Z_o terminated close to the device by a load resistor R_L = then the device will operate over a range of frequencies from zero up to a 3dB frequency point given by the inverse of the time constant R_LC, where C is the device capacitance. As an example, with R_L = 50Ω and C = 3pF, we have $R_LC = 1.5.10^{-10}$ seconds, i.e. a 3dB frequency around 7GHz. If this does not seem large enough (!), then the approach to adopt is to use a travelling-wave interaction. For this, the electrodes dimensions are adjusted to match their transmission line impedance to that of the input. The electrodes are then fed at one end and terminated by a matched impedance at the other end. Surprisingly, although the optical phase velocity is abo three times faster than that of the applied microwave signal, the travelling wave approach still gives a useful bandwidth increase - up to about 20GHz.

Applications

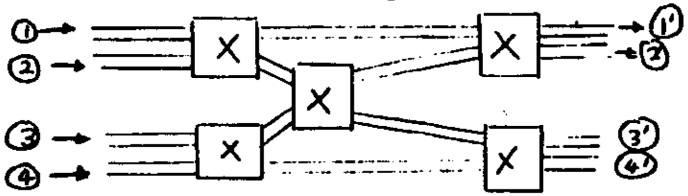
In the context of fibre-optical communications, there is an obvious need for modulation and switching. We have already considered the application of electrooptic devices in switching matrices. Concerning modulation, the simplest need is for a means of turning a light beam on and off to provide a simple on-off-key (OOK) binary modulation system. Guided-wave electrooptic devices can certainly do this at very high speeds (tens of Gigabits per second), but they add an extra complication which for many purposes is unnecessary because satisfactory performance can be obtained by modulating the light source directly. For more advanced applications, the external electrooptic modulator may become essential because it does not also introduce unwante



By using combinations of several sets of electrodes (in the 'stepped Δβ-reversal' configuration') the electro-optic effect can be used both to adjust the effective length of the directional coupler and to switch it.

Electro-optic Switching Matrices

Given the kind of 4-port X-over switch just considered, it is possible to envisage arrays of such switches being used to form multiple input-output matrices. For instance, the arrangement shown schematically below was demonstrated with guided-wave optical switches some years ago.



Performance obtained was fairly modest and required 'hand-tuning' of the applied voltages, but the demonstration certainly stimulated interest in this idea.

Note that by suitable setting of the switches, light in any chosen input (① to ④) waveguide can be directed to any of the output waveguides (①' to ④'). Clearly larger matrices can, in principle, be assembled by using enough switches. A recent paper ('An opto-electronic exchange of the future' presented at ISS '84 Florence, 7-11 May 1984 by R.W. Blackmore et al of the Plessey Company) explores the possibilities of various switching architectures and the relation between performance degradation and the number of switches at practically realisable cross-talk levels. To those with some experience of integrated optic devices, the most crucial practical problems are

shifts in the optical frequency.

Electro-optic waveguide devices can, in fact, provide a number of different functions required both in fibre-optic communications and elsewhere. One function of some potential importance is polarisation rotation - which is needed, for instance, because light arriving from a typical single-mode communications fibre link has random (and varying) polarisation but is required in a specific polarisation for heterodyne detection or for de-multiplexing or switching purposes. It has been shown ('Electro-optic guided-wave device for general polarization transformations', R.C. Alferness (of Bell Labs.) in IEEE Journal of Quantum Electronics, QE-17, June 1981, pp.965-969) that any desired polarisation rotation can be obtained by combining two relative phase-shifter devices with a polarisation converter device. The latter uses an off-diagonal electro-optic coefficient (r_{51} or r_{42} in lithium niobate) together with a periodic electrode structure which matches the birefringent difference between the orthogonally polarized TE and TM modes of a stripe waveguide.

A very different possible application of guided-wave electro-optic devices is an analog-to-digital conversion (and the reverse process of D-toA). A-to-D conversion can be obtained by taking a group of parallel amplitude modulators of the Mach-Zehnder type and exploiting the fact that the transmitted intensity depends periodically on the applied voltage - and that doubling the electrode-length halves the voltage required to go through one period. A parallel group of, say, four devices then have electrode lengths which are successively increased by a factor of two, giving four-bit precision - with the least significant bit emerging from the longest device. Practical considerations of device length clearly make it difficult to go beyond, say, six bits (2mm x 2^{6-1} = 6.4cm), but the main attraction is that operation at Gigabit rates is possible.

We have only been able to hint at the range of possible applications for guided-wave electro-optic devices. The range is steadily expanding - with digital logic functions now included ('An ultrafast all-optical gate', A. Lattes et al (of MIT Lincoln Labs. in IEEE JQE-19, November 1983, pp.1718-1723). Possible applications cover fibre-communications, fibre-fed phased-array radars, optical signal-processing more generally and optical fibre-sensors. A reasonably up-to-date picture can be garnered by obtaining the Conference digest of the Topical Meeting on Guided Wave and Integrated Optics, Orlando, Florida, April 24th-26th, 1984, from the Optical Society of America. Another easy-to-read review article (by I. Bennion) appears in the 1983 Annual Review from the Plessey's Allen Clark Research Centre).