(12) UK Patent Application (19) GB (11) 2 287 327 (13) A

(43) Date of A Publication 13.09.1995

(21) Application No 9404001.1

(22) Date of Filing 02.03.1994

(71) Applicant(s)
Sharp Kabushiki Kaisha

(Incorporated in Japan)

22-22 Nagaike-cho, Abeno-ku, Osaka, Japan

(72) Inventor(s)
Paul May
Gillian Davis

(74) Agent and/or Address for Service
Marks & Clerk
Alpha Tower, Suffolk Street Queensway,
BIRMINGHAM, B1 1TT, United Kingdom

(51) INT CL^6
G02F 1/055

(52) UK CL (Edition N)
G2F FCE F21D F21X F23E F25M1 F25P1 F25S
U1S S2117 S2122

(56) Documents Cited
GB 2173605 A **GB 1024330 A** **EP 0486769 A2**

(58) Field of Search
UK CL (Edition M) **G2F FCE**
INT CL^5 **G02F 1/03 1/05 1/055**
Online darabase: WPI

(54) **Electro-optic apparatus**

(57) An electro-optic material (2) has first (4) and second (6) regions formed therein. The optic axes of the first and second regions are antiparallel and define a domain inversion pattern. The difference in refractive index between the first and second regions is a function of an electric field applied thereto. The difference in refractive index enables spatial light phase modulators and refractive optical devices having electrical control to be formed.

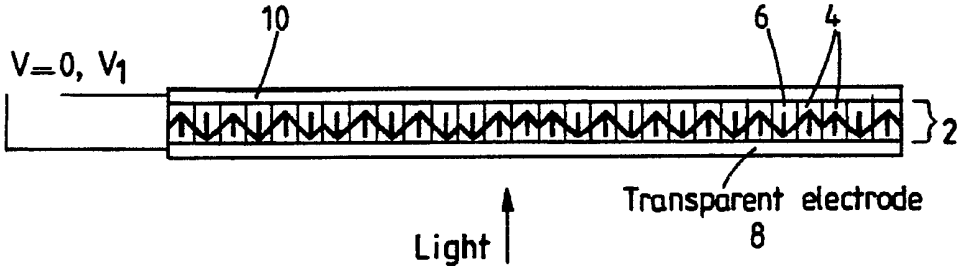


FIG.1.

GB 2 287 327 A

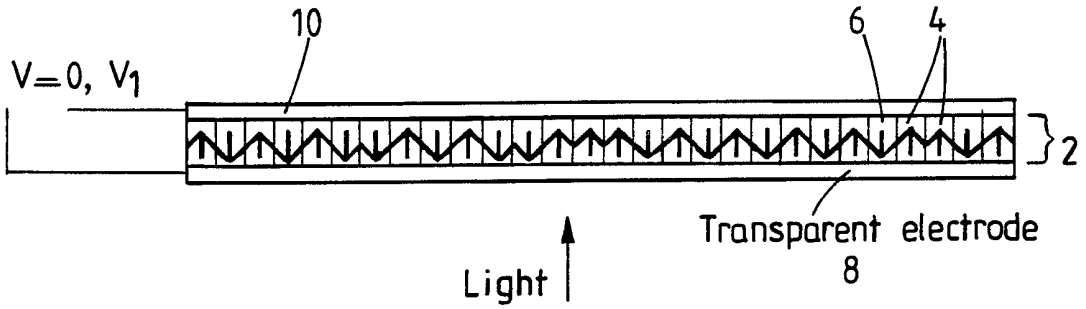


FIG.1.

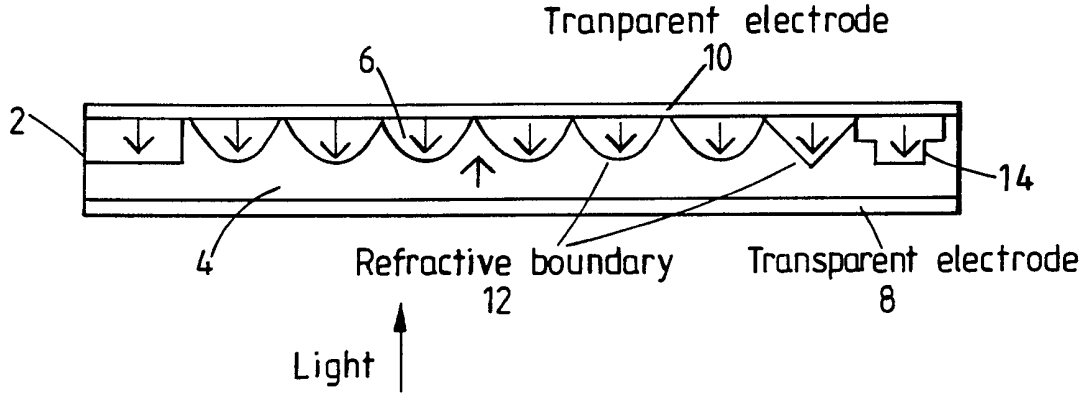


FIG.2.

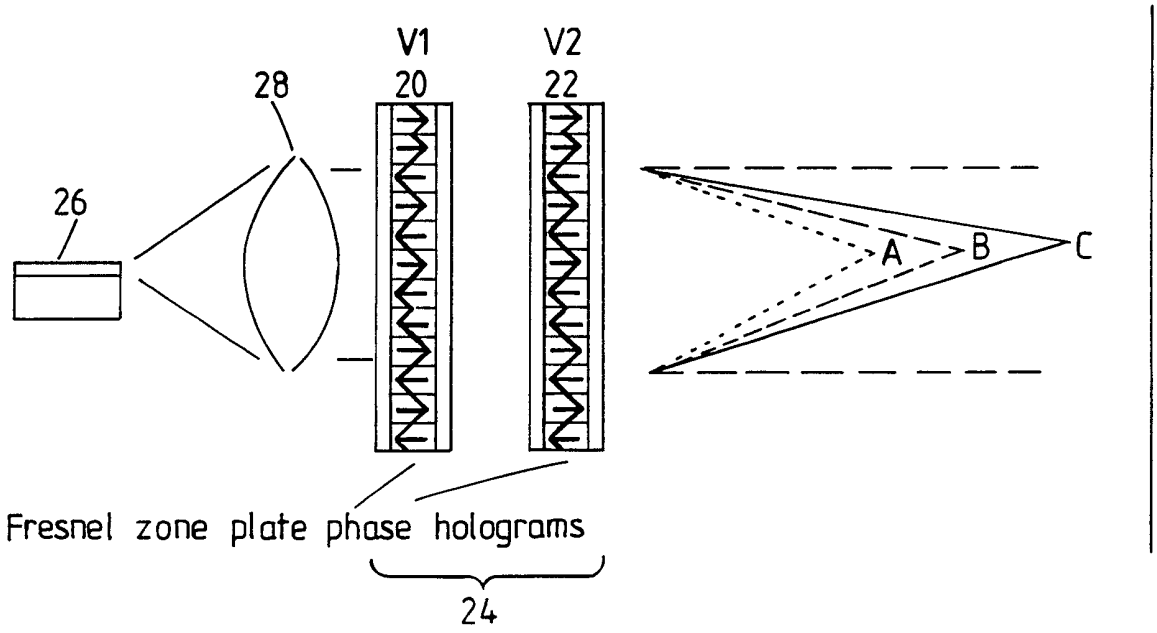


FIG.3.

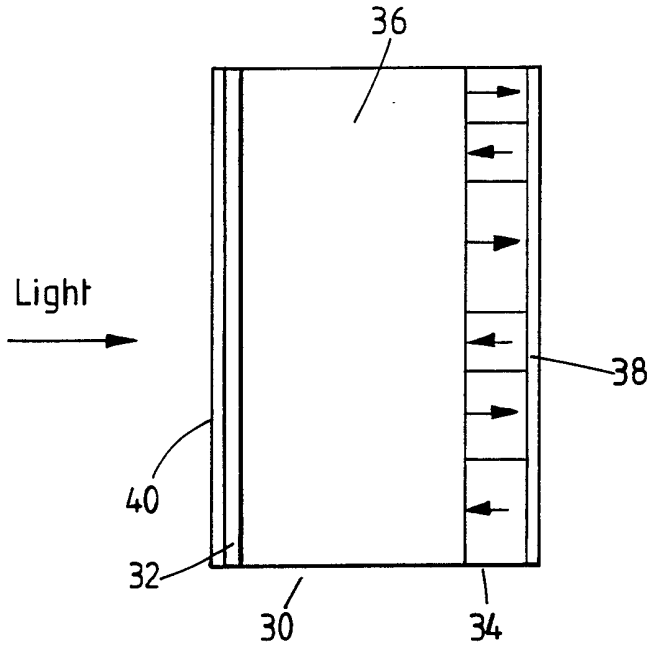


FIG.4.

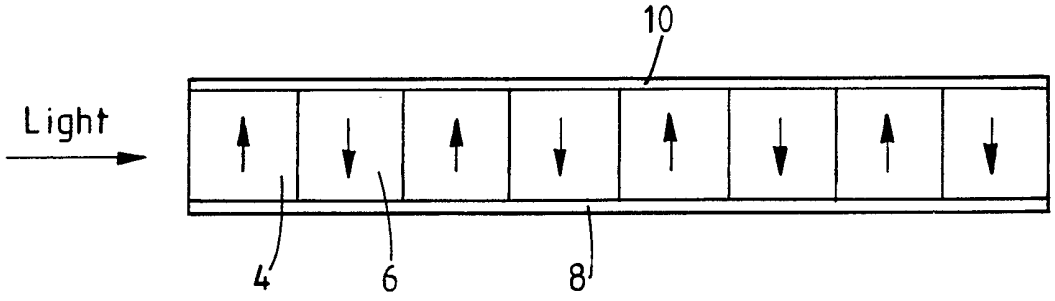


FIG.5.

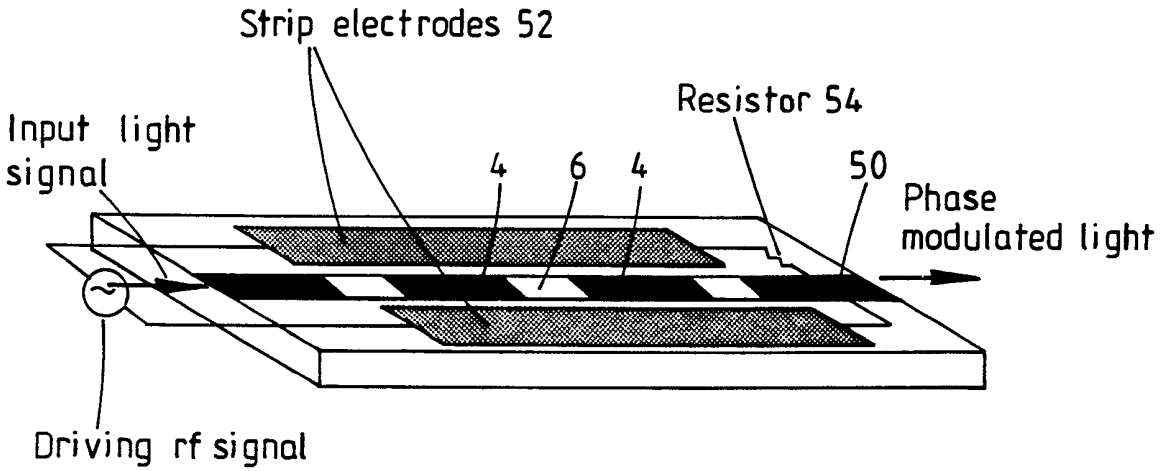

Strip electrodes 52
Resistor 54
Input light signal
4
6
4
50
Phase modulated light
Driving rf signal

FIG.6.

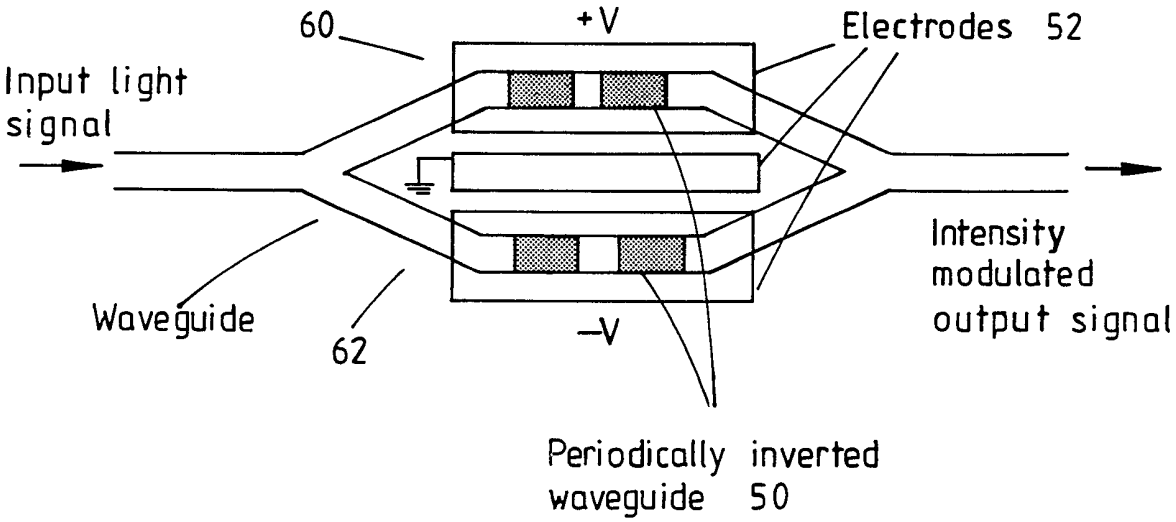

60
+V
Electrodes 52
Input light signal
Intensity modulated output signal
Waveguide
62
–V
Periodically inverted waveguide 50

FIG.7.

OPTICAL APPARATUS

The present invention relates to an optical apparatus. Such an apparatus is suited for use as a spatial light phase modulator or as an electrically controllable refractive or reflective optic device.

Such devices are suited, amongst other things, for use in optical computing, data storage and beam steering applications.

According to a first aspect of the present invention, there is provided an optical apparatus comprising an electro-optic material having at least one first region having a crystal axis along a first direction, at least one second region having a crystal axis along a second direction, and means for applying an electric field across the at least one first region and the at least one second region.

It is thus possible to vary refractive indices of the first and second regions with respect to one another. Variations in the refractive indices allow the relative travel times of light propagation through the first and second regions to be varied, thereby allowing controllable phase shifts to be introduced. Additionally, optical elements, such as lenses, utilising refractive optics can be fabricated since such devices require a refractive index change across a boundary. The refractive index change is electrically controllable and hence the properties of such devices are electrically controllable. Furthermore, periodic structures having alternating regions of different refractive indices can be used to form reflection gratings, transmission gratings and Bragg reflectors. The refractive indices of the first and second regions may be controlled to

switch such devices on and off and to control their operating characteristics. Thus the provision of electro-optic material having spatially varying electro-optic domains can be used in a variety of optical applications.

Furthermore, the properties of the device rely only on the pattern of the first and second regions and not on having to form complex electrode patterns. Thus the need to provide patterned electrodes is avoided.

Preferably the first direction makes an angle of 180 degrees with respect to the second direction. Thus the directions are parallel but opposite and may be described as being anti-parallel. The term "anti-parallel" will be used herein to describe lines or directions which are parallel and opposite. The term "parallel" will be used herein to describe lines which make angles of zero and 180 degrees with respect to one another. Thus anti-parallel is to be construed as a special case of parallel. The regions thus form inverted and non-inverted domains.

Preferably the electro-optic material is planar (i.e. a sheet of material, though not necessarily restricted to lying in a geometrical plane).

Advantageously the means for applying the electric field is arranged to apply a field which is parallel to the first direction. For example, electrodes may be formed on either side of a sheet of electro-optic material, thereby allowing relatively large voltage gradients to be applied to the material. The optic axes of the first and second regions may be perpendicular to the plane of the sheet and anti-parallel with each other. In use, light may be arranged to propagate perpendicularly to the sheet of electro-optic material such that the first and second regions are optically in parallel. It is thus possible to form an electrically

controllable spatial phase modulator. Such a spatial phase modulator may be used, for example, to form a phase grating or a phase plate.

In an alternative arrangement, the first and second regions may be optically in series. For example, a planar device comprising a planar first region may have a plurality of second regions formed therein such that the second regions do not extend completely through the first region. Thus light propagating perpendicular to the plane of the device will pass through an interface between the first and second regions. Suitable profiling of the interface can be used to form lenses, lenticles, prisms and other elements relying on refraction. Complex elements, such as Fresnel lenses, may be formed by cooperation of the individual interfaces. Since the focal length of a lens depends, amongst other things, on the change of refractive index across an interface between two materials, it is thus possible to form lenses whose focal lengths are electrically controllable. The first and second regions are interchangeable.

As a further alternative, the first and second regions may be arranged in series in an alternating periodic fashion. The regions are thus controllable to act as a grating and may, for example, form a distributed Bragg reflector and hence may be controlled to reflect light preferentially at a first wavelength, the strength of reflection being a function of the voltage applied across the first and second regions.

Preferably the first and second regions have substantially equal refractive indices in the absence of an applied electric field. Thus the optical device, be it a spatial phase modulator, a phase plate, a beam steering device, a lens or array of lenses or a grating, will not be optically active when no potential difference exists across the electro-optic material.

Advantageously the electro-optic material may be provided as one wall on a liquid crystal cell. Thus a liquid crystal cell, such as a ferroelectric liquid crystal (FLC) cell, would have the liquid crystal aligning in a spatially varying pattern in accordance with the pattern of first and second regions formed in the electro-optic device.

The present invention will further be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a spatial light phase modulator constituting a first embodiment of the present invention;

Figure 2 is a schematic diagram of an electrically controllable lens array constituting a second embodiment of the present invention;

Figure 3 is a schematic diagram of a beam steering device constituting a third embodiment of the present invention;

Figure 4 is a schematic diagram of a spatial light phase modulator constituting a fourth embodiment of the present invention; and

Figure 5 is a schematic diagram of a grating constituting a further embodiment of the present invention.

Figure 1 shows a spatial light phase modulator comprising a layer of electro-optic material, indicated generally as 2, having a plurality of first and second regions 4 and 6, respectively, formed therein. Substantially transparent first and second electrodes 8 and 10 are formed on opposite sides of the layer 2. The electrodes 8 and 10 are planar sheets and may be formed of indium-tin oxide.

The first regions 4 have optic axes pointing from the first electrode 8 towards the second electrode 10, whereas the second regions 6 have optic axes pointing from the second electrode 10 towards the first electrode 8. Thus the regions cooperate to define a domain inversion pattern , i.e. a pattern formed by the anti-parallel domains, formed within the electro-optic material 2.

Many methods exist to create a spatially varying domain structure, i.e. a domain inversion pattern, within the electro-optic material 2. These include direct field reversal (polarising), electron beam written inversion, ion exchange reversal and optically written domains through internal fields induced by charge separation in photorefractive materials. Ion exchange in non-centrosymmetric crystals may be used to lower the Curie temperature for domain inversion along the optic axis in ion exchanged regions of the electro-optic material 2. Thus lithographically defined domain inversion may be performed to create the domain inversion pattern. Fabrication of a domain inversion pattern is described in a paper entitled "Quasi-phase-matched second harmonic generation in a $LiTaO_3$ waveguide" Kazuhisa Yamamoto, Kiminori Mizuuchi and Tetsuo Taniuchi, IEEE journal of quantum electronics, vol 28, no 9, September 1992. Variations in refractive index formed between ion exchanged and non-ion exchanged regions may be reduced or removed by annealing. Direct writing of inverted domains using electron beam lithography has the advantage of avoiding the changes in refractive index associated with ion exchange techniques and also allows relatively deep inverted regions to be formed. For example, lithium niobate substrates 1mm thick have been completely inverted by electron beam writing of one surface of the substrate.

Assuming that the refractive indices of the regions 4 and 6 are the same,

there is no discernable optical difference for light travelling in the first regions 4 compared to light travelling in the second regions 6. However, when the regions 4 and 6 are subjected to an electric field, the refractive indices of the regions change and diverge, thereby giving rise to a difference between the refractive index of the first regions and the refractive index of the second regions.

For light incident normal to the plane of the layer of electro-optic material 2, as indicated in Figure 1, the direction of the polarisation of light is perpendicular to the optic axes of the first and second regions 4 and 6. With the optic axis defined in a conventional manner as along the z axis for an electro-optic material such as lithium tantalate or lithium niobate which has a 3m type crystal structure, the change in refractive index along the x, y and z crystallographic directions for a field applied along the z direction is given by:

$$\Delta(1/n_x^2) = r_{13}E_z \qquad (1a)$$

$$\Delta(1/n_y^2) = r_{23}E_z \qquad (1b)$$

$$\Delta(1/n_z^2) = r_{33}E_z \qquad (1c)$$

where n represents refractive index, and r_{p3} represent a coupling coefficient between an effect along the p direction where p represents x,y, and z and a field along the z direction.

For this specific case, $r_{13} = r_{23}$ so that the polarisation of the input light is unimportant. The difference in refractive index between the regions 4 and 6 for light incident normal to the plane is given by:

$$|\Delta n| = n_o^3 . r_{13} . E_z \quad (2)$$

where n_o represents the refractive index of the electro-optic material with no applied electric field.

Similar equations describing the electro-optic effect can be written for crystals belonging to other crystallographic groups and/or having other orientations.

For a device of the type shown in Figure 1, fabricated from z-cut lithium niobate 300 microns thick, r_{13} has a value of 8.6pm/V . With the application of a voltage between the first and second electrodes 8 and 10, a phase difference will occur between light travelling in the first regions 4 and in the second regions 6. For use as an electrically controllable phase grating, for instance in the reproduction of phase holograms, it is desirable that a phase difference of π radians can be introduced between the light travelling through the first and second regions. This phase change is produced when the condition $\Delta nl/\lambda = 0.5$ is satisfied, where l is the thickness of the electro-optic material. For $\lambda = 600nm$, $n_o = 2.3$, and $l = 300$ microns, a field of approximately 10^7 Vm^{-1} is required. This corresponds to a voltage of approximately 1500V across the device.

The pattern of the first and second regions 4 and 6 may be arranged to form a phase hologram which is arranged to act as a lens, a beam steering device, Fourier plane filters, a Fresnel type zone lens, or which forms a binary optic device.

An alternative arrangement is shown in Figure 2. The first and second regions 4 and 6 are optically in series. A planar first region 4 has a pattern of domain inverted (anti-parallel) second regions 6 formed

therein. The second regions 6 have profiled interface regions with the first region, thereby giving rise to a boundary 12 at which refraction occurs. Additionally regions having interfaces 14 which are perpendicular to the direction of propagation of light through the device may be formed to provide phase changes, in a manner similar to that described hereinabove. The refractive boundaries 12 form a microlens array when a potential difference exists between the electrodes 8 and 10. However, other profiles may be formed in order to form other optical elements such as prism or wedge arrays. The first and second regions 4 and 6 may be arranged such that, in the absence of an electric field, the regions have equal refractive indices. Thus the refractive elements are only formed when an electric field is applied. Alternatively the first and second regions 4 and 6 may have different refractive indices (for example due to fabrication using ion exchange processes) such that the refractive interfaces exist in the absence of an electric field and are modified by the application of an electric field. Thus, for instance, the device shown in Figure 2 may provide a microlens array having a controllable focal length.

Figure 3 shows a controllable focal length lens comprising two of the devices described with reference to Figure 1 arranged in series. Each device 20 and 22 is controlled to be either on or off and has a phase grating formed therein arranged to act as a Fresnel lens. Thus the series combination of the devices provides a lens 24 controllable to have any one of four possible focal lengths. Light from a light source 26, such as a laser diode, is collected by a collimating lens 28 and directed towards the controllable lens 24. When both devices 20 and 22 are in an off state, the lens 24 has no effect and the light passes therethrough and remains collimated. Switching on the first device 20 gives the lens 24 a first focal length, and focuses the light to a first point C. Switching on

the second device 22 with the first device in an off state gives the lens 24 a second focal length, thereby focusing the light to point B. The lens 24 has a third focal length when both devices 22 and 24 are switched on, thus focusing the light to point A.

The domain inversion effect can be enhanced, thereby allowing thinner slabs of electro-optic material to be used, if the electro-optic material is used to define one wall of a liquid crystal cell, as shown in Figure 4. A ferroelectric liquid crystal cell 30 having one side formed using conventional aligning film 32 and the other side formed of electro-optic material 34 having a domain inversion pattern formed therein causes the liquid crystal 36 to align in one of two states at the surface of the electro-optic material in accordance with the domain inversion pattern. Application of an electric field across the cell, via transparent electrodes 38 and 40, aligns the liquid crystal 36 with the electric field, and thereby switches off the pattern of phase shifts. Cells of only a few microns thickness and having slabs of electro-optic material patterned to a depth of approximately 1 micron thickness or less are thus able to provide electrically controllable spatial light phase modulators.

Additionally the first and second regions 4 and 6 may be regularly arranged along a direction of light propagation so as to form an electrically controllable grating, as shown in Figure 5, which can be switched on and off, the strength of the grating being determined by the magnitude of the voltage. Such a grating may be used, for example, to form a distributed Bragg reflector.

In a further embodiment, the first and second regions 4 and 6 are periodically arranged in series to form a periodically inverted waveguide 50, as shown in Figure 6. The first and second regions are arranged so

as to approximately match the velocity of propagation of light within the waveguide 50 with the velocity of propagation of electrical signals along strip electrodes 52 formed adjacent the waveguide 50.

In use, an RF signal is supplied to the electrodes 52. The regions 4 and 6 are arranged such that the change from one region to the next occurs when the velocity difference between the electrical and optical signals has resulted in the electrical and optical signals being substantially 180° out of phase.

The amplitude of the RF signal can be varied to control the transit time of the light along the waveguide 50. It is thus possible to use this arrangement as a phase modulator. The electrodes 52 appear electrically as a transmission line and consequently the maximum modulation frequency is not limited by the electrode charging time. The transmission line is terminated by a resistor 54 matched to the characteristic impedance of the line so as to substantially eliminate reflections.

Two phase modulators may be combined so as to form an interferometer, as shown in Figure 7. Light is divided between first and second paths 60 and 62, each containing a phase modulator. The phase modulators may be controlled so that interference between light travelling along the first and second paths causes the light to be intensity modulated.

It is thus possible to provide a very versatile electrically controllable optical device.

CLAIMS

1. An optical apparatus, comprising an electro-optic material having at least one first region having a crystal axis along a first direction, at least one second region having a crystal axis along a second direction, and means for applying an electric field across the at least one first region and the at least one second region.

2. An optical apparatus as claimed in Claim 1, in which the first direction makes an angle of 180° with respect to the second direction.

3. An optical apparatus as claimed in Claim 1 or 2, in which the electro-optic material is planar and the first and second directions are perpendicular to the plane of the electro-optic material.

4. An optical apparatus as claimed in any one of the preceding claims, in which the means for applying the electric field is arranged to apply the electric field parallel to the first direction.

5. An optical apparatus, as claimed in any one of Claims 1 to 4, in which the means for applying the electric field is arranged to apply the electric field perpendicularly to the first direction.

6. An optical apparatus as claimed in any one of the preceding claims, in which, in use, a direction of light propagation is parallel to the first direction.

7. An optical apparatus as claimed in any one of Claims 1 to 5, in which, in use, a direction of light propagation is perpendicular to the first direction.

8. An optical apparatus as claimed in any one of the preceding claims, in which the means for applying an electric field comprises first and second electrodes.

9. An optical apparatus as claimed in Claim 8, in which the electrodes are formed on opposite surfaces of the electro-optic material.

10. An optical apparatus as claimed in Claim 8 or 9, in which the electrodes are translucent.

11. An optical apparatus as claimed in Claim 8 or 9, in which the electrodes are transparent.

12. An optical apparatus as claimed in any one of the preceding claims, in which the refractive index of the at least one first region is substantially equal to the refractive index of the at least one second region for a first value of the electric field.

13. An optical apparatus as claimed in Claim 12, in which the first value of electric field is substantially zero.

14. An optical apparatus as claimed in any one of the preceding claims, in which a magnitude of a difference in refractive index between the at least one first region and the at least one second region is a function of the electric field.

15. An optical apparatus as claimed in any one of the preceding claims, in which the at least one first and the at least one second regions are arranged optically in parallel to provide a spatial phase modulator.

16. An optical apparatus as claimed in Claim 15 when dependent on Claim 3, in which, in use, the direction of light propagation is substantially perpendicular to the plane of the electro-optic material.

17. An electrically controllable phase plate comprising an optical apparatus as claimed in Claim 15 or 16.

18. A phase plate as claimed in Claim 17 arranged to introduce a phase difference of π radians.

19. An optical apparatus as claimed in any one of Claims 1 to 14, in which at least one of the at least one first region is optically in series with at least one of the at least one second region and has an interface therewith having a region which is inclined with respect to the direction of propagation of light therethrough.

20. An optical apparatus as claimed in Claim 18, in which the or each interface forms an electrically controllable lens.

21. A beam steering device comprising an optical apparatus as claimed in Claim 20 or 21.

22. An electrically controllable refractive index grating comprising an optical apparatus as claimed in any one of Claims 1 to 14, comprising a plurality of parallel first regions separated by second regions.

23. A liquid crystal device having a side comprising an optical apparatus as claimed in Claim 1.

24. A liquid crystal device as claimed in Claim 23, in which the

means for applying an electric field is also arranged to apply an electric field to the liquid crystal of the liquid crystal device.

25. An electrically controllable optical phase modulator comprising an optical apparatus as claimed in Claim 1, the first and second regions being in series and defining a waveguide.

26. An electrically controllable optical phase modulator as claimed in Claim 25, in which the means for applying an electric field comprises at least one elongate electrode adjacent the waveguide.

27. An electrically controllable optical phase modulator as claimed in Claim 26, in which the velocity of propagation of a signal of a first frequency along the at least one elongate electrode is substantially equal to the average velocity of light propagating along the waveguide.

28. An optical intensity modulator comprising first and second optical paths, at least one of the optical paths comprising an electrically controllable optical phase modulator as claimed in any one of Claims 25 to 27, the light from the first and second paths being arranged to be combined such that the intensity of the combined light at a first wavelength is a function of the phase shift between the first and second optical paths.

29. An optical apparatus substantially as hereinbefore described with reference to and as illustrated in each of Figures 1 to 7 of the accompanying drawings.

Patents Act 1977
E niner's report to the Comptroller under Section 17
(The Search report)

Application number
GB 9404001.1

..elevant Technical Fields

(i) UK Cl (Ed.M) G2F(FCE)

(ii) Int Cl (Ed.5) G02F 1/03 1/05 1/055

Search Examiner
G M PITCHMAN

Date of completion of Search
19 MAY 1994

Databases (see below)
(i) UK Patent Office collections of GB, EP, WO and US patent specifications.

(ii) ONLINE DATABASE: WPI

Documents considered relevant following a search in respect of Claims :-
1 TO 29

Categories of documents

X: Document indicating lack of novelty or of inventive step.

Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.

A: Document indicating technological background and/or state of the art.

P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 2173605 A	(CANON) see abstract, Figure 7 and page 3 lines 13 to 45	1
X	GB 1024330	(HORLOGERE) see page 2 line 68 to page 3 line 86	1
X	EP 0486769 A2	(SONY) see abstract	1-3

Databases: The UK Patent Office database comprises classified collections of GB, EP, WO and US patent specifications as outlined periodically in the Official Journal (Patents). The on-line databases considered for search are also listed periodically in the Official Journal (Patents).