United States Patent [15] **3,684,350**
Wentz [45] **Aug. 15, 1972**

[54] LIGHT BEAM POLARIZATION MODULATOR

[72] Inventor: **John L. Wentz,** Ellicott City, Md.
[73] Assignee: **Westinghouse Electric Corporation,** Pittsburgh, Pa.
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[52] **U.S. Cl.** **350/150,** 350/147, 350/157, 350/DIG. 2
[51] **Int. Cl.** **G02f 1/26**
[58] **Field of Search**..350/147, 150, 157, 160, DIG. 2

[56] **References Cited**

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Rowe, " Light Intensity Modulator" IBM Technical Disclosure Bulletin Vol. 12, No. 7 (Dec. 1969) p. 910,

Primary Examiner—David Schonberg
Assistant Examiner—Paul R. Miller
Attorney—F. H. Henson, E. P. Klipefel and J. L. Wiegreffe

[57] **ABSTRACT**

A parallel cell electro-optical phase modulator is used in combination with two birefringent crystals and a half wave plate to produce polarization modulation of an incident light beam. A first birefringent crystal provides a lateral relative displacement between the two orthogonal components of the incident light beam to form two spaced light paths, one through each of the respective electro-optical crystals. The half wave plate rotates the linear polarization of the orthogonal components to allow a second birefringent crystal to recombine the orthogonal components into a single light beam.

5 Claims, 6 Drawing Figures

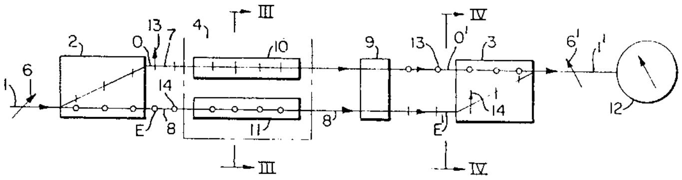
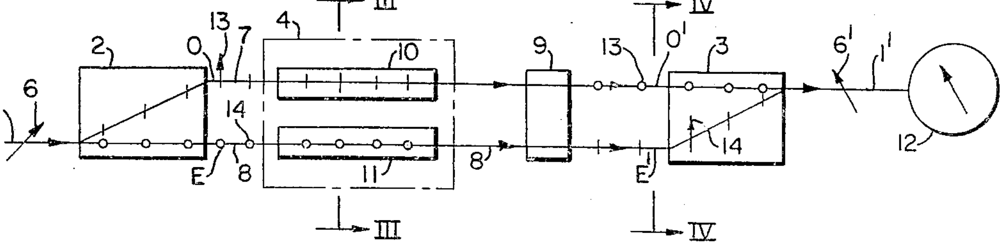


FIG. 1



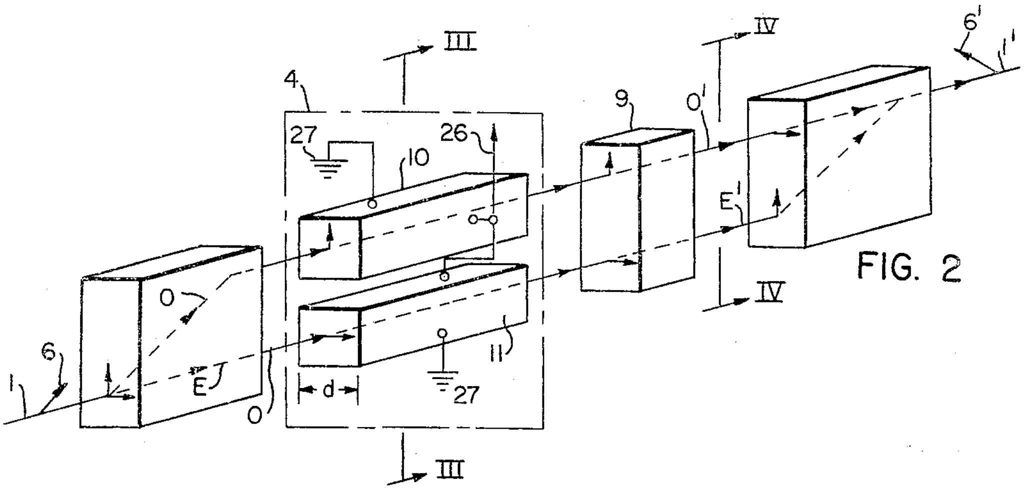


FIG. 2

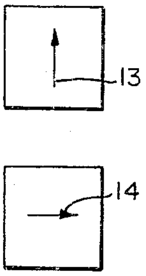


FIG. 3

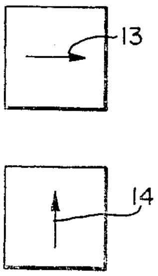


FIG. 4

WITNESSES

Alfred N. Colaizzi

James F. Young

INVENTOR

John L. Wentz

ATTORNEY

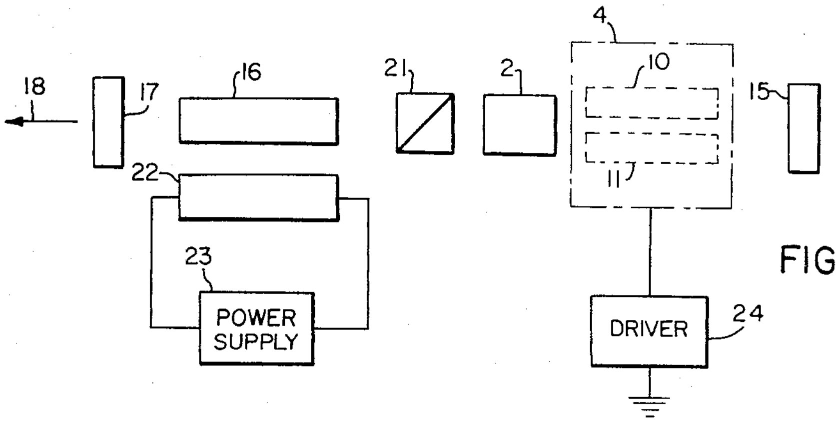

18
17
16
22
23
POWER SUPPLY
21
2
4
10
11
15
DRIVER
24

FIG. 5

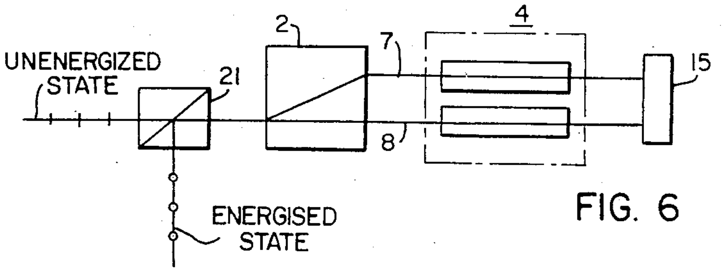

UNENERGIZED STATE
21
2
7
8
4
15
ENERGISED STATE

FIG. 6

LIGHT BEAM POLARIZATION MODULATOR

CROSS REFERENCE TO RELATED APPLICATION AND PATENT

In applicant's U.S. Pat. No. 3,429,636 issued Feb. 25, 1969 there is disclosed and claimed a light modulation apparatus for electronically controlling the passage of polarized light. The modulation apparatus is there disclosed as applied to the resonant optical cavity of a stimulated emission of radiation device as well as to a simple light valve or shutter.

That system has gone into very wide usage because of its capability of very high frequency operation and its capability of operating at what is considered in the art as relatively low modulation voltages. In both that system and in the present application the light modulation is effected by direct polarization modulation. In the patented system the type and/or degree of polarization must be known in order to make the proper adjustments to make the system effective. In applicant's copending application Ser. No. 067,930, filed Aug. 28, 1970 for Polarization Independent Light Modulation Means Using Birefringent Crystals, there is described and claimed a light modulation system for modulating light which system is independent of the polarization of the incident light. In other words, the system of the copending application is capable of modulating light energy having random polarization. The electro-optical modulator component of that system may be identical with that of the patented device as the improvement there resides in combining with the electro-optical crystals of the modulator a birefringent crystal, similar to the birefringement crystal of this invention between the incident light and the first electro-optical crystal. The birefringent crystal resolves any incident light into two orthogonal components and simultaneously produces a lateral displacement between the orthogonal components to produce two parallel light beams which pass through the electro-optical components. In the copending patent application the incident beam may be randomly polarized but in the patented system and as in the present system the incident light beam must be polarized either linearly, circularly, or elliptically.

The single light path of the patented system and the two light paths of the copending application each have two electro-optical crystals in series for the purpose of cancelling any natural birefringence, however, each crystal operates, respectively, on only one of the orthogonal polarization components; passage of an orthogonal polarization component through a crystal which does not operate on that particular component represents an unnecessary attenuation of the light beam.

SUMMARY OF THE INVENTION

This invention relates to an improvement over the modulation system of the single path patented construction which is intended to be used with polarized light, that is, light in which the degree and type of polarization is known. The object of the invention is to provide an optical modulation system which has the advantages of the patented construction without the light energy attenuation of the patented system. The present invention provides a means for reducing the optical transmission losses in a polarized light modulation system of the type disclosed in applicant's aforementioned patent. It provides two parallel paths for the orthogonal components of known polarized light so that the transmission losses are decreased by a factor of two or allows a reduction in modulation voltage required by a factor of two for no reduction in transmission losses. Alternatively, with the same modulation voltage, it reduces the required length of the electro-optical modulator by a factor of two.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration for the purpose of explaining the invention;

FIG. **2** is a diagrammatic illustration showing the components of FIG. **1** but in addition illustrating the manner in which the electro-optical crystals are energized;

FIGS. **3** and **4** are cross-sectional elevational views of FIG. **2** at the respective sections indicated and looking in the direction indicated by the arrows for two respective conditions and positions of the light vectors as they progress through the modulator from left to right in FIGS. **1** and **2**;

FIG. **5** is a diagrammatic illustration of an embodiment of the invention applied as a light intensity modulator; and

FIG. **6** is a diagrammatic illustration of an embodiment of the invention applied as a Q-switch for a Fabry-Perot cavity of a stimulated emission of radiation amplifier or oscillator.

Briefly, the present invention provides an improved electro-optical light modulation system which may be used as a light valve, in general, and specifically as a light modulating device and is particularly adapted for use in modulating the Q of a Fabry-Perot cavity of a stimulated emission of radiation amplifier or oscillator. The system is capable of effecting continuous variation in the transmission of light or of effecting pulse modulation thereof. The system is capable of operating at very high speeds in the manner of an "on-off" switch to abruptly cut-off, or on, light energy reflected back and forth in the resonant optical cavity of a stimulated emission of radiation amplifier or oscillator.

An illustrative embodiment of the present invention utilizes the components of a modulation system described and claimed in applicant's aforesaid patent in combination with double refracting birefringent crystals and suitable means such as a half-wave plate, to provide two optical transmission paths of equal optical path length for selected portions of the light energy and to thereby reduce the transmission losses for light energy having a selected polarization. Whereas the system of applicant's copending patent application is adapted to control light energy of any polarization, the present invention contemplates an improved electro-optical system in which the optical transmission losses, or the modulation voltage, are reduced by a factor of two when the polarization of the light energy is known.

Referring to FIG. **1**, there is shown an embodiment of the present invention wherein the system is to be used where it is merely desired to modulate the polarization of a light beam passing in a single direction. A later embodiment is described in which the system is designed to control the light energy in a multi-reflected path. The similarities and the differences between the present invention and that described and claimed in applicant's copending patent application for controlling randomly polarized light will be immediately pointed up by comparing FIGS. 1 of the respective patent applications.

The essence of the present invention resides in the association of birefringent crystals, such as crystals 2 and 3, having characteristics well known but not heretofore used in the combination disclosed herein and in the use of a half wave polarization rotator in conjunction with the birefringent crystals to obtain equal optical path lengths through the modulator (zero retardation) for both orthogonal polarization components of the incident light.

In optical modulation systems of the type under consideration here, uniaxial electro-optical crystals are commonly used to polarization modulate light beams. Specific preferred examples are the dihydrogen phosphate type, such as potassium dihydrogen phosphate (KDP). These crystals which are normally uniaxial become biaxial when an electric field is applied along one of the principal optic axes. Such crystals have one axis, namely, the Z axis, along which the index of refraction is not altered by an applied voltage. The electro-optic effect is the result of changes in the index of refraction which occur along the other axes when a modulating electric field is applied along the Z axis.

Still referring to FIG. 1, an incident light beam indicated at 1, linearly polarized as indicated by the vector 6, will be doubly refracted by the crystal 2 to give two orthogonal components in the light paths 7 and 8. The axis of component 7 will be displaced in a direction normal to the axis of the incident light beam 1 by an amount which is a function of the birefringence and length of the crystal 2. Thus, the crystal 2 resolves the linearly polarized beam 1 into two laterally spaced orthogonal components in two respective parallel optical paths. The light energy of the light paths 7 and 8 may be passed through an optical phase modulating device 4 which includes electro-optical crystals 10 and 11 arranged to impart a phase retardation in the paths 7 and 8, respectively. The light energy emerging from the phase modulator 4 along paths 7 and 8 can be combined into a single emergent light beam having the same polarization as the incident beam by means of a half wave plate 9 and a crystal 3 which has the same characteristics as that of crystal 2 and performs the inverse of the operation performed by crystal 2. Since the crystals 2 and 3 pass orthogonal components of an incoming light beam their respective optical axes are arranged orthogonal to each other. The half wave plate 9 is used to equalize the optical path lengths for the paths 7 and 8 in order to obtain zero retardation at zero modulation voltage.

By applying a modulation voltage to crystals 10 and 11, sufficient to produce a 180° phase shift between the polarization vectors of the light along paths 7 and 8, the emergent vector 6′ can be rotated 90° with respect to incident vector 6.

When the present invention is being used as a light modulator or light shutter, as illustrated in FIG. 1 of the drawings, the emergent beam 1′ is directed through an appropriate analyzer 12 to effect intensity modulation of the light beam. The intensity modulation is effected by polarization modulation of the resultant emergent light vector 6′ relative to the plane of polarization of the analyzer. However, if as shown in another embodiment, the invention is used as a Q-switch for a stimulated emission of radiation device, the electro-optic modulator is operably associated with the optical cavity of a laser wherein the laser medium is polarized. Since the laser amplifies and oscillates for only a particular plane of polarization the electro-optic modulator of the present invention is able to control the amount of light which is regeneratively coupled back into the laser medium. The crystals 10 and 11 correspond, respectively, to the electro-optical crystals 10 and 11 of applicant's patent and also corresponds to crystals 17 and 18 of said copending patent application as regards to their characteristics. However, it should be carefully noted here that the patented construction is adapted to modulate or control all the light having a known degree of polarization; the system of said patent application is capable of operating on all of the energy of a light beam having random polarization; and the present invention is capable of reducing the optical transmission losses only when the incident light energy is polarized. These differences must be kept clearly in mind in order to understand the distinctions between the three systems and to appreciate the novelty of the present invention.

In the polarized light system of the patent and the randomly polarized light system of said copending application, both orthogonal components of the light energy must pass through both of the electro-optical crystals in series. In the present invention only one-half of the light energy, that is, the light energy in the component to be operated upon, passes through one electro-optical crystal and the other half passes through the other crystal resulting in a reduction of the optical transmission losses for the system by a factor of two as compared to the system of applicant's patent and that of the copending patent application.

Referring again to detailed description of the invention, the crystals 2 and 3 serve as means for generating, separating and recombining, respectively, the orthogonal components of the energy in the light beam 1, the plane of polarization of which is indicated by the vector 6. In order to obtain sufficient spatial separation to carry out the objectives of the invention and have one of the components pass through one of the electro-optical crystals 10 while the other one passes through the electro-optical crystal 11 it is necessary to choose the proper material for the crystals 2 and 3. Furthermore, the crystal geometry must be optimized by carefully orienting the incident light beam with respect to the optic axis of the said crystals. This requirement for the present invention is substantially the same in this respect as for the system in said copending application and it has been found that a biaxial crystal which gives an angle separation of approximately 9.5° for a light beam having a wavelength in the neighborhood of from 4,000 to 15,000 Angstroms can provide sufficient separation within the practical limits of the crystal to carry out the objectives of the invention. The separation of the orthogonal components of the light beam, illustrated in FIG. 2 and FIG. 3, indicates that the light beam 1 which is shown polarized at 45° with respect to the horizontal and vertical axes is resolved into two orthogonal components, one of which is the ordinary ray (O ray). The polarization vector **13** is vertical. The other is the extraordinary ray (E ray) which is horizontal and indicated by the vector **14**.

From FIGS. **2** and **3** it will be seen that with the physical axis of the crystal **2** properly oriented with respect to the incident light beam **1** the extraordinary ray E will not be deviated as it passes through the crystal **2** but it will contain the horizontal component indicated by the vector **14**. The extraordinary ray E will coincide with the optical axis of path **8** through the electro-optical crystal **11**. The extraordinary ray E will emerge parallel to the ordinary ray O (path **8**) and will follow the path **7**. The deviation of the extraordinary ray E to make it parallel to the ordinary ray O is caused by the bi-axial crystal **2** by virtue of its double refraction properties. The extraordinary ray E and the ordinary ray O will emerge from the right-hand side of the electro-optical crystals **10** and **11**, respectively, parallel to each other and pass through the half wave plate **9**. The half wave plate **9** rotates the plane of polarization of the E and O rays to produce the polarization of the emergent rays O′ and E′, respectively, with respect to crystal **3** as illustrated in FIG. **4**. The emergent rays O′ and E′ are then recombined in crystal **3**, inverse to the manner in which separation of the rays was obtained in crystal **2** and emerge as an output light beam indicated at **1′**.

Assuming that there is no energization of the electro-optical phase modulator **4**, the electric vectors **13** of the ordinary ray O and the vector **14** of the extraordinary ray E will remain in the same orthogonal relative positions in which they are shown in FIG. **3**. Both of the rays O and E will pass straight through the crystals **10** and **11**, respectively, without any additional lateral axis deviation. As the extraordinary ray E′ enters the crystal **3** it will be deviated back to the optical axis of the ordinary ray O′ and the output beam represented at **1′** will have the same polarization as the incident beam represented by the vector **6** which is at 45° with respect to the horizontal and vertical axes. Now assume that the electro-optical phase modulator **4** is energized, that is, it is in what may be called the closed position as far as the light valve action is concerned. As in the copending patent application, the incident light beam will be split into the two spaced rays E and O with paths spaced as indicated in FIGS. **1** and **2**. The linear polarization of the incident beam **1** will be resolved into two orthogonal components, one of which will be the ordinary ray O along path **7** with vertical polarization, and the other will be the extraordinary ray E along path **8** and this component will be horizontal. As the two rays pass through the electro-optical phase modulator **4** the phase difference between the E and O rays will be modified to an extent dependent upon the magnitude of the applied modulating voltage. Upon recombing the O′ and E′ rays in crystal **3**, the resultant **6′** will be polarization modulated. For an induced phase difference of 180° between the E and O rays, the polarization of the resultant **6′** will be orthogonal to the polarization of the incident beam **6**. Therefore, light valve action can be obtained by placing an analyzer **12** in the emergent light beam **1′** with the analyzer having its polarization vector orthogonal to that of the incident light beam **1**, or in other words, parallel to the polarization modulated vector **6′**.

Now if a mirror **15** were placed with its reflecting surface at the left end surface **15** and if the electro-optical crystals **10** and **11** of the phase modulator **4** were not energized the O ray and the E ray on paths **7** and **8**, respectively, will be reflected back without change of phase through the electro-optical crystals and to the birefringent crystal **2** where the orthogonal components will be recombined with the incident light beam **1** and with the same polarization as the incident beam. This would adapt the invention to use in the Fabry-Perot cavity of an optical stimulated emission radiation device, schematically illustrated in FIGS. **5** and **6** show the optical paths for such a reflected light system for creating regenerative action in an optical maser.

With the invention applied to the Fabry-Perot cavity of a stimulated emission of radiation amplifier as indicated in FIG. **6**, the reflected light from the mirror **15** proceeding to the birefringent crystal **2** from the right to the left would pass through the laser rod **16** and strike the mirror **17** and would be reflected back through the rod **16** to the point corresponding to the incident ray which has been described in connection with FIG. **1**. As long as the electro-optic crystals **10** and **11** are unenergized the light can repeat the cycle of reflecting back and forth between the two mirrors **15** and **17**. When the electro-optic crystals **10** and **11** are energized with a half-wave voltage pulse, the resultant vector of the two components through the electro-optic crystals **10** and **11** will be rotated 90° so that light reflected from the mirror **15** cannot pass through the crystal **3** from right to left by virtue of the linear polarizer **21** and thus the oscillation of the laser will be stopped.

When the present invention is utilized in of radiation system using the present invention includes the two mirrors **15** and **17**, the laser rod **16**, a linear polarizer **21**, and the optical phase modulator **4** which is identical to the one previously disclosed. One of the mirrors such, for example, mirror **17** may be partially reflective so that the coherent light output would be from the mirror **17** from right to left as indicated by the arrow **18**. The system also includes a suitable source of light, such as the flash tube **22**, energized from a suitable power supply source **23** in a manner well known in the art. The control of the modulation of the output light beam **18** may be controlled by the voltage applied to the electro-optical crystals from the driver **24**.

The operation of the phase modulator **4** is best illustrated by reference to FIG. **2** which illustrates the manner in which the voltage is applied between terminal **26** and ground **27**. The control voltage is supplied by the output of the driver **24**. The voltages are applied in parallel to the electro-optical crystals **10** and **11** along their Z axes which are orthogonal with respect to each other.

The electro-optical effect is the result of induced birefringence which occurs when an electric field is applied to the crystal along a particular axis. As an example a particular type of crystal which may be used is the dihydrogen phosphate type of crystals which have been found to be very satisfactory for operation in this device. The electro-optic effect in these crystals occurs as a result of field induced anisotropy of the index of refraction along their principal crystal axes. The characteristics of electro-optical crystals can best be described in terms of the Fresnel index ellipsoid which has axes proportional to the principal indexes of refraction in the crystal. Plane polarized light upon such a crystal will produce double refraction and phase retardation between the orthogonal components of the incident light vibrating along the principal optical axis in the crystal.

In uniaxial crystals, two of the indices of refraction in the ellipsoid are equal. Therefore, no phase retardation occurs for light propagating perpendicular to the plane of equal indices. This propagation direction determines the optical axis of the crystal. Crystals in which the principal indices are unequal are termed biaxial, that is, they have two optic axes. Electro-optic crystals, which are normally uniaxial become become biaxial when the electric field is applied parallel to the Z axis. As is clear from the drawing in the present instance, the indices of refraction for a light vibrating parallel to the X and Y axis is altered by applied voltages along the Z axis and under this condition the X and Y indices are no longer equal.

It has been pointed out previously that the optical transmission losses are reduced by this invention for light of a known polarization since the light energy is divided into two separate paths so that it is not necessary that the component which is not being operated upon in a given crystal need pass through that crystal. The operation of the invention when it is used as a simple light valve has already been described. In the operation of the devices applied to the optical cavity of the stimulated emission of radiation device it can be assumed that the laser rod **16** is made of a material which produces a polarized output. If a rod is used which does not produce a polarized output it would be necessary to insert the polarizer **21** between the right hand end of the rod **16** and the birefringent crystal **2**.

Then we can assume that the incident light beam **1** is polarized as it enters the birefringent crystal **2**. The extraordinary ray E and the ordinary ray O will be generated as a result of crystal **2** and if the phase modulator **4** is adjusted for zero phase retardation, the two orthogonal components will proceed through the electro-optic crystals **10** and **11** without any change of phase and then be reflected back through the electro-optical crystals **10** and **11** and will be returned to the right hand side of the electro-optical crystal **2**. Then as the reflected light beams proceed to the left the E and O rays will be refracted in a manner illustrated in detail in FIG. **6**, which of course is the reverse of the operation when the incident light beam **1** propagates from left to right to the system and will emerge from **2** with the same polarization as the incident beam.

Considering the incident light beam **1** proceeding from an external source having a polarization vector indicated at **6**, the two orthogonal components will be generated with the orthogonal polarization as indicated in FIG. **3** in separate paths indicated in FIG. **1** at **7** and **8**, respectively. Assuming that the phase modulator **4** is unenergized the ordinary ray along path **7** and the extraordinary ray along path **8** will proceed to the right, unaffected by the phase modulator, where they will be incident upon the half wave plate **9** and birefringent crystal **3** which by combined action will recombine the orthogonal components to produce an output light beam indicated at one time with the same polarization as that indicated by the arrow **6** on the incident beam. Assuming that the polarization of the polarizer **21** is parallel to the polarization vector **6** the light will pass through the polarizer.

Now assume that the phase modulator **4** is energized. The same light beam **1** with the polarization indicated by the vector **6**, regardless of whether the light is coming from the source of unpolarized light passing through a filter or from the output of a laser rod which is polarized and having polarization indicated by the vector **6**, will be incident on **2** and again the two orthogonal components will be generated as previously described with the extraordinary ray E taking the path **7** and the ordinary ray taking the path **8**. These two rays will then pass through the electro-optical crystals **10** and **11**, respectively, but as they pass through these latter crystals their phase difference will be modified, the degree of which is dependent upon the magnitude of the modulating voltage. At the same time, the half wave plate **9** and birefringent crystal **3** will recombine the component in the path **8** with the component in the path **7** to give the emergent beam **1'** with the polarization indicated by the vector **6'**. This polarization is at 90° with respect to the previously assumed polarization of the polarizer **21** blocking the light for a 180° phase retardation between components which would result when half-wave voltage is applicating the modulator **4** and, effectively, producing a light shutter which is closed.

In the case of the invention being applied to the Fabry-Perot cavity of a stimulated emission of radiation device and assuming the above same conditions for the incident light beam **1** with the polarization indicated by the vector **6** the crystal **3** and half wave plate **9** would not be present and in its place would be a mirror such as indicated at **15** in FIG. **6**. The two orthogonal components in the two paths **7** and **8** would be reflected by the mirror and if the phase modulator **4** was at the zero phase retardation bias the two components would return to the electro-optical crystals **10** and **11** and be recombined in crystal **2**. When the phase modulator **4** is set to the 180° phase retardation bias the resultant polarization would be orthogonal to the polarization of the original incident beam represented by the arrow **6**. Therefore, the regenerative coupling between the output energy of the laser rod **16** and the excited particles of the laser medium would be cut off by action of the polarizer **21**.

Preferably, although not necessarily, the elongated electro-optical crystals **10** and **11** may have a square cross section. They may have a rectangular cross section, so long as the dimensions along the respective Z axes are the same. The physical axis of each rod should lie in or be perpendicular to the **110** plane of the crystal and also be parallel to the X-Y plane.

Since there are two separated linearly polarized orthogonal beams which are acted upon separately by the phase modulator **4**, it is important that the geometry of the electro-optical crystals **10** and **11** be such that the extraordinary ray E and the ordinary ray O be absolutely parallel to one of the principal optic axes of the respective crystals. When this is true the following phase relationships are characteristic of the polarization of the orthogonal components of the plane polarized light in both rays propagating parallel to the axis of the present system.

Let N_x, N_y and N_z be the principal indices of refraction for the X, Y and Z crystal axes and let L be the length of the crystals along the light path. Also let d represent the dimension of the crystals traverse to the longitudinal axis. Since the crystals have a square cross section, the dimension d will always be parallel to the Z axes of the respective crystals. Let λ be the wavelength of the incident radiation represented by the light beam **1**.

In passing through the crystal **10**, along the X axis of that crystal, the Y component of the polarization undergoes a phase change of

$$\Phi_y=(2\pi L)/(\lambda)\,(N_y) \qquad 1.$$

radians and the component parallel to the Z axis undergoes a phase change of

$$\Phi_z=(2\pi L)/(\lambda)(N_z) \qquad 2.$$

radians. The phase change resulting from the air gap between the two crystals **2** and **3** is the same for each component and will be expressed as a constant, α . In passing through crystal **11** along the Y axis of the latter, the X component of the polarization undergoes a phase change of

$$\Phi_x=(2\pi L)/(\lambda)(N_x) \qquad 3.$$

radians and the component parallel to the Z axis undergoes a phase change of

$$\Phi_z=(2\pi L)/(\lambda)(N_z) \qquad 4.$$

radians. The total phase change for the X and Y components in passing through both crystals is

$$\theta_x=\Phi_x+\Phi_z+\alpha=(2\pi L)/(\lambda)(N_x+N_z)+\alpha \qquad 5.$$

and

$$\theta_y=\Phi_y+\Phi_z+\alpha=(2\pi L)/(\lambda)(N_y+N_z)+\alpha \qquad 6.$$

respectively. The phase difference between the two components is

$$\Delta\theta=\theta_x-\theta_y=(2\pi L/(\lambda)[N_x+N_z]-(N_y+N_z)] \qquad 7.$$

This then becomes:

$$\Delta\theta=(2\pi L)/(\lambda)\,[N_x-N_y] \qquad 8.$$

If no electric field is applied to the Z-axes of the respective crystals **10** and **11**, the indices of refraction N_x and N_y are equal, that is N_x, that is $N_x=N_y=N_o$. The phase difference between the emerging perpendicular components of each linearly polarized input ray, is then zero, that is,

$$(\Delta\theta=O) \qquad 9.$$

The original polarization of each incident light ray O and E is preserved.

When an electric field is applied along the Z-axis of the two respective crystals, that is, when electric potential is applied to the electrodes **10***a* and **10***b* of crystal **10** and **27***a* and **27***b* of crystal **11**, the index of refraction N_x and the index of refraction N_y of the two crystals are no longer equal. But significantly, the index of refraction N_z along the Z axis of the crystal remains unchanged. When the electric field is applied to these crystals, one of the indices increases while the other decreases. This may be represented as

$$N_x=N_o\pm\Delta N \qquad 10.$$

and

$$N_y=N_o\mp\Delta N \qquad 11.$$

where ΔN is the change in index of refraction brought about about by application of the electric field. It has been determined by others that

$$\Delta N=(r_{63}V_zN_o3)/(2d) \qquad 12.$$

Substituting the value of N_x and N_y in Equation 8 gives

$$\Delta\theta=(2\pi Lr_{63}V_zN_o)/(\lambda d) \qquad 13.$$

where r_{63} is an electro-optic constant and where V_z is a voltage applied along the Z axis.

By the application of the proper voltage to the Z axes of the two respective crystals **10** and **11** and the voltage being properly related to the longitudinal and transverse dimensions of the crystals, it is possible to cause the linear components of the input light ray emerging from the right-hand end of the crystal **11** to have a π radians phase difference, that is,

$$\Delta\theta=\pi \qquad 14.$$

In this latter condition, the incident ray **1** will have its plane of polarization, indicated by vector **6**, rotated 90° when it emerges from the right-hand end of crystal **11**.

The required voltage to cause a 90° rotation of the input polarization ray may be determined by substituting the values $N_x=N_o+N$ and $N_y=N_o-\Delta N$ in Equations 10 and 11, respectively, and the value of $\Delta\theta=\pi$ in Equation 14 into Equation 8. Solving this, gives

$$V_2=(\lambda d)/(2r_{63}N_03L) \qquad 15.$$

The factor

$$(\lambda)/(2r_{63}N_o3)$$

is called the half wave voltage, that is, the voltage necessary to produce a π radians phase displacement between the emergent components of the incident ray, resulting in a 90° change between the polarization of the incident and emergent ray when an electric field is applied parallel to the Z axis and when the light is also parallel to the Z axis. It will be noted that the half-wave voltage is a function of L/d and therefore the modulation voltage can be adjusted within practical limits by selecting the desired value for this ratio. Since it is possible to produce a polarization rotation between the incident and emergent rays of 90° by appropriate voltages, a complete light shutter effect can be produced. It is obvious that modulation of light in a continuous manner from a maximum to a minimum is possible.

Since the incident light energy is resolved into two orthogonal components, each of which is restricted to a single light path that includes only a single electro-optical crystal for operating on that particular component the optical transmission losses are reduced by a factor of two over those systems in which both components must pass through both electro-optical crystals in series.

What is claimed is:

1. Light modulation apparatus for a source of polarized light comprising a birefringent element oriented for receiving an incident light beam parallel to an optic axis to resolve said beam into two orthogonal components in spaced parallel lights paths, first and second birefringent electro-optical crystals having substantially the same index of refraction arranged, respectively, in said parallel light paths, half-wave plate arranged across said light paths a second birefringent element having the same characteristics as said first birefringent element and having its principal axis orthogonal to the principal axis of said first birefringent element for receiving light from said parallel paths and recombining them into a single light beam substantially colinear with said incident light beam, said birefringent elements being so disposed about the axis of the incident light that their respective optic axes are 45° with respect to the electric vector of said incident light beam and means for applying a D.C. potential across said electro-optical elements to vary the index of refraction of said crystal.

2. A combination as set forth in claim **1**, in which said electro-optical crystals has substantial the same index of refraction and have the respective principal optic axes effectively optically optically perpendicular to each other, said crystals having substantially the same length and being subjected to the same environmental conditions, and means for supplying a modulation voltage to said crystals with the electric fields parallel to the respective *z* axes of said crystals.

3. The combination as set forth in claim **2** and means for converting polarization modulation of said orthogonal light components into intensity modulation of the light from said combined orthogonal components.

4. The combination as set forth in claim **2** in which the *x* axis of one of said electro-optical crystals is parallel to the *y* axis of the other of said crystals and the *z* axis of both crystals are perpendicular to each other.

5. The combination set forth in claim **4** with means for converting polarization modulation of said orthogonal light components into intensity modulation of the light from said combined orthogonal components.

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