

[54] **PIEZOELECTRICALLY ACTUATED LIGHT DEFLECTOR**

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[22] Filed: **Nov. 22, 1971**

[21] Appl. No.: **200,672**

[52] U.S. Cl. **350/285, 350/6, 350/299**

[51] Int. Cl. **G02f 1/34**

[58] Field of Search. **350/285, 299, 6**

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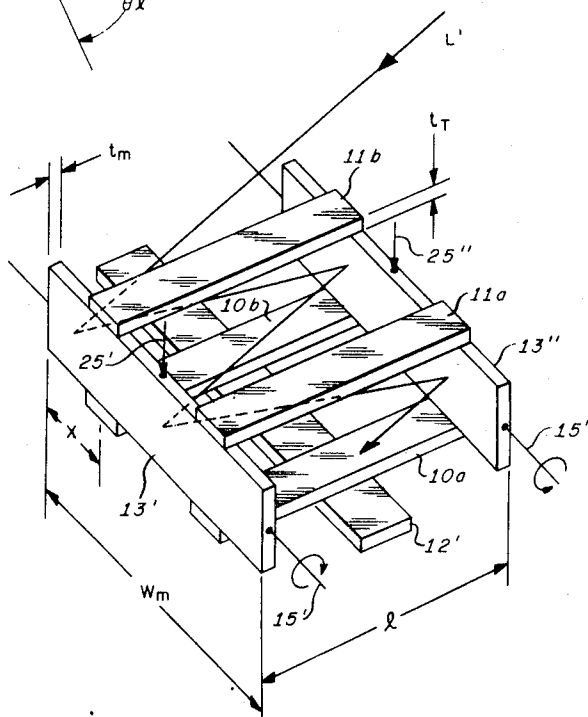
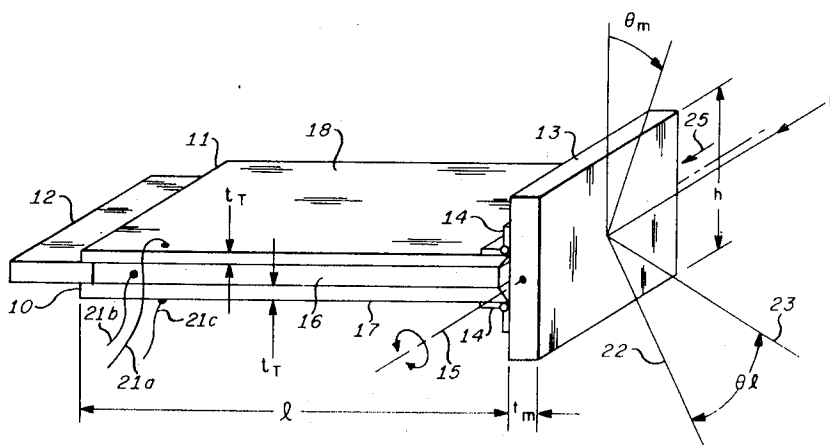
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ABSTRACT

A piezoelectrically actuated type light deflector comprising a pair of piezoelectric transducers rigidly cantilevered at one end from a support member and articulately connected at the other end to a mirror. Electrodes affixed to the transducers provide for application of electrical signals in a manner to utilize an extensional mode of the transducers in which one transducer elongates and the other contracts, or conversely, so as to rotate the mirror about an axis passing therethrough and thereby produce deflection of a light beam impinging on the mirror.

9 Claims, 5 Drawing Figures



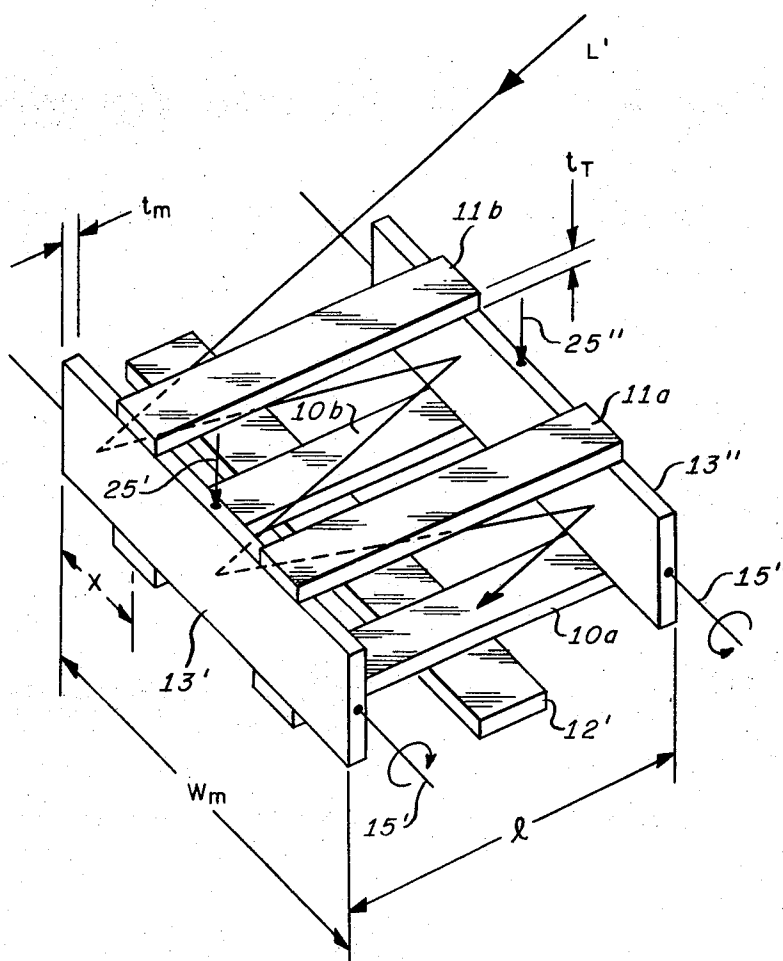


FIG. 3.

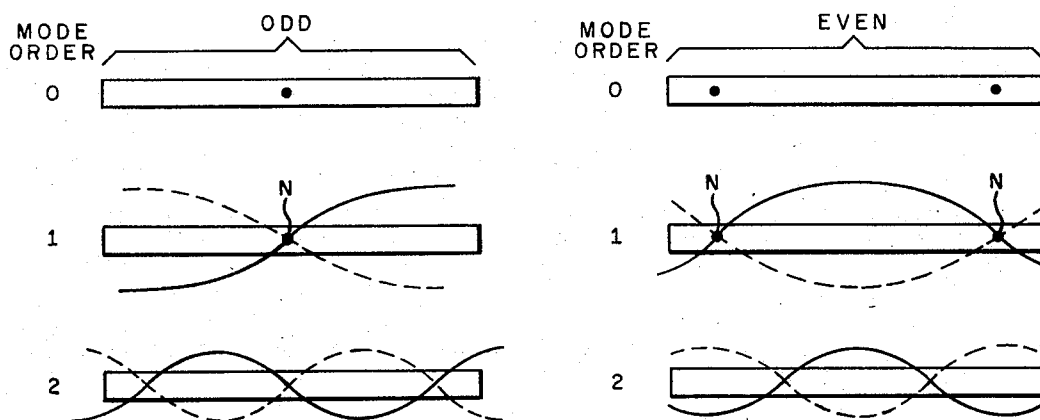


FIG. 3a.

PIEZOELECTRICALLY ACTUATED LIGHT DEFLECTOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to electromechanical light deflector apparatus of the type including a piezoelectrically actuated mirror for reflecting incident light in different directions in accordance with an electrical drive signal applied to a pair of piezoelectric transducers.

2. Description of the Prior Art

A variety of electrically operated devices utilizing electrooptic, acousto-optic and piezoelectric techniques have been extensively investigated in the prior art pursuant to the development of light deflectors for general scanning and random access purposes as required, for instance, for optical memory addressing. Each type of deflector is characterized by certain advantageous features while simultaneously being limited in one or more respects. Electro-optic devices, for example, constructed with presently known suitable materials require extremely high voltage excitation involving thousands of watts of reactive power. Drive requirements are not as stringent in the case of acousto-optic devices, but nevertheless usually cause serious heat dissipation problems. Another characteristic of acousto-optic deflectors which is objectionable in some applications is the beam distortion that occurs while the beam is deflecting from one location to another. In an acousto-optic device, deflection is produced by deflection of a light beam transmitted through a compressional wave established in an optically transparent acoustic line. As a result, the resultant deflection is determined in accordance with the frequency of the acoustic wave and, consequently, during the interval immediately after a frequency change is introduced to alter the beam deflection angle, the deflector apparatus contains acoustic wavelengths corresponding to both the previous and the new beam positions. Hence, all of the wavelengths present in the aperture at any instant act to diffract the beam and thus cause a transient distortion. Electro-optic and acousto-optic light deflectors also produce considerable insertion loss resulting from the high absorption attendant to electro-optic materials and the poor diffraction efficiency experienced with acousto-optic elements.

Piezoelectric deflectors, on the other hand, are inherently low insertion loss devices by virtue of operating on the principal of reflection rather than transmission as in the case of the electro-optic and acousto-optic deflectors. In addition, considerably less power excitation is required and heat losses are significantly diminished. Piezoelectric deflectors also offer substantial benefit with regard to fabrication complexity, cost, and size; factors which presently preclude general acceptance and use of light deflectors. The well known piezoelectric light deflector of the prior art comprises a pair of piezoelectric transducers constructed in the form of thin elongated strips rigidly affixed at one end in cantilever fashion from a supporting block and secured together along their length. Upon application of an appropriate excitation signal, one strip lengthens while the other shortens thereby resulting in bending of the composite structure relative to the support block so as to deflect a mirror mounted on the free end of the piezoelectric strips.

Two fundamental parameters which must be considered in the design of a practical light deflector are the number of resolvable beam positions and the bandwidth or access time to a given position. Aside from the previously discussed parameters of complexity, cost, insertion loss, etc., the performance of a light deflector can best be described in terms of a speed-capacity product. Capacity is defined as the number of distinguishable diffraction limited or resolvable beam positions which can be addressed. Speed relates to how rapidly the beam can be directed to any one of the addressable positions, or the number of positions the deflector can address per unit time. Unfortunately, the piezoelectric bender apparatus of the prior art has a very slow operating speed compared to electro-optic and acousto-optic deflectors and because of this limitation is rendered unsuitable for many applications. The piezoelectric deflector constructed according to the principles of the present invention, however, is capable of substantially higher speed operation and therefore overcomes the primary limitations of the prior art piezoelectric bender configuration. Moreover, the high speed operation is achieved without degradation of resolution or reduction in deflection angle, that is, diffraction limited resolution is retained, thereby providing a significantly higher speed-capacity product than is attainable with a bender apparatus for applied voltages of equivalent magnitude.

SUMMARY OF THE INVENTION

The piezoelectric deflector of the present invention operates on an extender principal as opposed to the bender mode of operation employed in the prior art piezoelectric deflector. The invention deflector comprises a pair of strip piezoelectric transducers, which in a single mirror embodiment, are secured at one end in cantilever fashion from a support block as in the prior art device. The transducers, however, are not secured to one another along their length as in the prior art devices but instead are free to move longitudinally with respect to one another. In addition, the mirror is not rigidly secured to the free end of the transducers but rather is articulately connected, as by hinges, to enable pivotal motion of the mirror relative to the transducers. As a consequence of this arrangement, the applied excitation rather than producing a bending action of the transducers instead causes extension of one and contraction of the other for the purpose of rotating the mirror about an axis passing through the mirror plane. This unique arrangement of the transducers and articulated connection to the mirror enables operation at speeds orders of magnitudes higher than is achievable with the prior art bender configuration without degradation of capacity or any of the other previously mentioned characteristics.

The speed limitation of the bender configuration arises from the relatively low resonant frequency associated with the bending mode. The resonant frequency of the extensional mode, on the other hand, is considerably higher and since the lowest frequency resonant mode of the transducer, that is excited by the drive signal and also causes mirror rotation, determines the highest frequency at which the deflector will operate, a substantial increase in speed is obtained, for a given operating voltage and position capacity, by utilizing the extensional mode as compared to the bending mode.

Another embodiment of the invention incorporates two mirrors, one at each end of the piezoelectric transducers, for increased angular deflection at the optical beam. The principle of operation of this two-mirror embodiment is based on extensional mode vibration of the piezoelectric transducers in the same manner as for the single mirror embodiment.

An additional feature of the invention pertains to the placement of the transducers along the mirror in a manner to inhibit torsional motion thereof as will be understood more fully from the subsequent detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a single mirror piezoelectrically actuated light deflector constructed according to the principles of the present invention.

FIG. 1a illustrates flexural mirror motion which can occur in the case of a thin mirror used in the embodiment of FIG. 1.

FIG. 2 is an electrical schematic illustrating the manner of energizing the embodiment of FIG. 1.

FIG. 3 is a perspective illustration of an alternative embodiment of the invention incorporating two mirrors for deflecting a beam through larger angles.

FIG. 3a illustrates torsional mirror motion which can occur in the case of a thin mirror used in the embodiment of FIG. 3.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, a light deflector apparatus of the present invention comprises strip piezoelectric transducers 10 and 11 of poled ceramic or suitable crystalline material rigidly secured at one end by epoxy cement to insulator block 12 which may be constructed of PZT ceramic. Mirror 13 is articulately connected as by hinges 14 to enable pivotal motion of mirror 13 relative to the piezoelectric transducers about axis 15 passing through the plane of the mirror. Connection of the hinges to the mirror and transducers may also be made by epoxy cementing. Alternatively, the transducers may be epoxy cemented directly to the mirror without any intervening hinge components, the epoxy connections serving in this case as elastic hinges to enable pivotal motion of the mirror relative to the transducers. A plate 16 of thermally conductive material is secured to the block 12 and disposed in sliding engagement between the piezoelectric strips to function both as an electrode coupled to the top and bottom of strips 10 and 11 respectively and as a heat sink for power dissipated in the piezoceramic members. It is to be understood, however, that satisfactory operation of the deflector can generally be achieved without the use of the heat sink, in which case individual electrodes can be affixed to the top and bottom of strips 10 and 11. Additional electrodes 17 and 18 connect respectively to the bottom and top of strips 10 and 11 for application of an electric potential thereacross by way of leads 21a, a, b and c connected to the respective electrodes.

Upon application of an electric potential one of the piezoelectric strips extends along its length between block 12 and mirror 13 while simultaneously the other piezoelectric strip contracts, in accordance with the spontaneous polarization of the piezoelectric strips and the polarity of the applied potential. The illustrated embodiment depicts a situation in which the upper strip

has lengthened and the lower strip has shortened whereby the mirror is rotated clockwise about axis 15 through an angle θ_m . This action causes the incident light beam L to be deflected along path 22 which is angularly displaced by an angle $\theta_r = 2\theta_m$ from the undeviated path 23 corresponding to the quiescent position of the mirror.

The electrical schematic of FIG. 2 shows the manner of biasing and driving the piezoelectric transducers 10 and 11 connected to the mirror 13. For simplicity of illustration, the support block which rigidly holds the ends of the transducers remote from the mirror is not shown in this figure. In addition, the heat sink/electrode member has been replaced by individual electrodes 17' and 18' affixed to the top and bottom surfaces of transducers 10 and 11, respectively. Batteries B1 and B2 are poled and serially connected so as to polarize the transducers parallel to their thickness dimension (t) as indicated by the arrows designated P. The alternating current signal source (S_s) then operates on alternate half cycles to tend to de-polarize one of the transducers while simultaneously further polarizing the other. Thus, at the instant when the top terminal of the signal source has a relative positive polarity, transducer 10 is further polarized causing it to contract whereas transducer 11 is de-poled somewhat, depending on the relative amplitude of the bias and signal voltages, causing it to elongate. On the next half cycle a converse action occurs whereupon transducer 10 elongates while transducer 11 contracts with the result that mirror 13 alternately tilts back and forth about axis 15 causing a repetitive vertical scanning motion of the light beam L incident on the mirror surface, the extremities of the light beam deflection being represented by lines 22_i and 22_v. It should be understood that the initial poling direction of the transducers, up or down, is immaterial. The essential requirement is that the signal source must operate to increase the polarization of one of the transducers and decrease the polarization of the other but without completely de-polarizing either transducer or actually reversing the polarization. Consequently, the signal voltage amplitude should be held to a level less than that of the battery voltages.

At this point consider the frequency response, that is the speed limit capability of the extensional mode piezoelectric light deflector. As previously explained, the resonant frequency of the extensional mode is considerably higher than that associated with the bending mode and thus higher frequency or faster speed operation is attainable with an extender configuration. In general, the upper frequency limit of the extender will be determined by the lowest longitudinal resonant frequency of the transducer and this will increase as the length (l) of the transducer decreases; but for other reasons which will be explained subsequently, it is advisable to increase the length (l) to thickness (t) ratio of the transducers thus necessitating a compromise in accordance with the requirements of various applications. It must be recognized, however, that the mirror thickness (t_m) also enters into a determination of the operational speed. FIG. 1a illustrates the even and odd first order vibrational modes which may occur in a free mirror in the vertical direction along the height (h) dimension as viewed from the side in the direction of arrow 25 in FIG. 1. When the mirror thickness is approximately the same as or less than the mirror height, the frequency of these flexural mirror vibrations are

likely to be less than the frequency of the longitudinal transducer vibrations and thus impose the upper limit on the operational speed of the deflector. The even order modes are inhibited as a consequence of the upper and lower transducers operating 180° out of phase. The lowest frequency odd order mode is also inhibited in accordance with the present invention by connecting the transducers to the mirror at the nodal points N of the mirror vibration for this mode.

Placement of the transducers relative to the mirror in a manner to preclude certain mirror vibrational modes is determined in accordance with the reciprocal theorem of mechanics. In general this theorem states that when a force is applied at a first point of a mechanical system and the resultant displacement measured at some other point, subsequent application of the force to the other point will produce a corresponding displacement at the first point. Now since the mirror does not move at the nodal points of the vibrational modes, the application of a force to the mirror at those points will not produce displacement of this mode configuration at any other points along the mirror.

On the other hand, where the mirror thickness is equal to or greater than the mirror height, the frequency of the mirror flexure vibrations become substantially higher than the extensional vibration modes of the transducer and are therefore immaterial with regard to a determination of the maximum deflector speed. The use of a thin, lightweight mirror in conjunction with a judicious placement of the transducers, however, enhances the overall deflector performance. Typical constraints on relative dimensional sizes of the various components comprising the extensional mode deflector to achieve a substantial improvement in speed-capacity product compared to the bender configuration of the prior art generally stipulates a transducer length at least about 10 times greater than the transducer thickness and a mirror thickness approximately equal to or greater than the thickness of the transducer.

The speed (S) of the deflector is defined as the rapidity with which the mirror/transducer system can switch a light beam from one point to another without overshoot or without other spurious vibrations being introduced into the mechanical system and is taken as the reciprocal of the switching time T_s which is related to the mechanical bandwidth of the transducer system by the equation

$$S = 1/T_s = 2 \pi f_r \quad (1)$$

where f_r refers to the lowest frequency mechanical resonance of the transducer/mirror system excited by the driving signal and which results in rotational movement of the mirror about the axis 15.

The number of resolvable positions obtainable by the deflector in one plane of deflection is called the linear capacity (N_L). This quantity can be determined by considering the diffraction from an aperture, which in this case is the mirror. A circular mirror of diameter (d) illuminated by light of wavelength (λ) has a diffraction limited angle of beam spread $\theta_d = \lambda/d$. If the maximum angle of deflection is θ_d then the linear capacity

$$N_L = \theta_d/\theta_d = 2\theta_d d/\lambda \quad (2)$$

where θ_d is the maximum mirror deflection. Combining equations 1 and 2 provides a linear speed capacity product

$$SN_L = 4\pi\theta_d f_r/\lambda \quad (3)$$

For this product to be large, both f_r and $\theta_d d$ must be large, but these conditions cannot be independently satisfied inasmuch as the resonant frequency f_r is inversely related to the linear dimensions d and θ_d . These facts imply a limiting value of the speed capacity product for a given deflector geometry.

An analysis of a bender type deflector considered as a cantilevered bending beam with a load (the mirror) at the free end leads to a mathematical expression for the speed of the bender configuration as follows:

$$S_B = 2 \pi f_{rB} = K_1 V_l / l^2 \quad (4)$$

where K_1 is a constant related to the lowest frequency bending mode, V_l is the velocity of a compressional sound wave in the material measured in the direction of its length and l and t are the length and thickness of the transducer as previously indicated. The linear capacity, that is the number of resolvable positions to which the beam can be directed, is determined for the bender configuration to be

$$N_{LB} = K_2 l V / \lambda t \quad (5)$$

where again l and t are the length and thickness of the transducer, λ is the light wavelength, V is the applied voltage and K_2 is a constant related to the diameter of the mirror relative to its thickness and the piezoelectric coefficient applicable to a ceramic transducer polarized parallel to its thickness dimension. By combining equations 4 and 5 it is seen that the speed capacity product of the bender configuration is

$$(SN_L)_B = (K_1 K_2 / \lambda) \cdot (V/t) \cdot (t/l) \quad (6)$$

In the case of an extender type deflector, assuming that the mirror vibrational modes are of no consequence, and that the extensional modes of the transducers determine the frequency response of the deflector, the speed can be represented mathematically as

$$S_E = 2 \pi f_{rE} = (\pi V_l) / (2 l) \quad (7)$$

and likewise the capacity N_E can be represented as

$$N_{LE} = K_3 / \lambda \cdot l V / t \quad (8)$$

whereupon the speed capacity product becomes

$$(SN_L)_E = (K_3 V_l V) / (2 \lambda t) \quad (9)$$

From equations (5) and (8) it is seen that both the bender and extender type apparatus have approximately the same linear capacity for devices of compa-

rable geometry and size. These equations also indicate that lower voltage operation is achieved, for a given linear capacity, if the ratio of l to t is made large. In many applications, both a low operating voltage and large capacity will be desired in which case l/t can be made as large as speed considerations permit. A determination of the ratio of speed of the extender device to that of the bender obtained by combining equations 4 and 7 yields

$$(S_E)/(S_B) \approx l/t \quad (10)$$

It is therefore seen that the large l to t ratio necessary for low voltage operation also improves the relative speed advantage of the extender configuration.

FIG. 3 depicts an alternate embodiment of the invention in which a pair of mirrors are articulately secured, as by epoxy cementing, to the respective ends of transducers 10a, 10b, 11a, and 11b and a support point is provided at any convenient point such as at the bottom of the mirrors 13', 13'' by means of a flexible rubber-like support or somewhere between the mirrors, for instance at the center point of the lower transducers 10a, 10b by epoxy cementing to a support plate 12'. For simplicity of illustration, the electrodes associated with the transducers have not been shown in the figure but it will be appreciated that the manner of electrode connection and excitation of each pair of transducers 10a, 11a and 10b, 11b may be the same as explained with respect to the previously described embodiment. The points of attachment of the transducers 10a and 10b to the support plate provide a reaction point about which the transducers are free to extend and contract for the purpose of rotating the mirrors about their respective axes 15', 15''. For the case where both pairs of transducers 10a, 11a and 10b, 11b are poled as shown in FIG. 2, namely vertically upward parallel to the thickness dimension, an applied alternating current signal will alternately cause extension and contraction of the lower transducers 10a and 10b and likewise for the upper transducers 11a and 11b except for a phase shift of 180° relative to the lower transducers, thereby causing the mirrors to oscillate back and forth about their respective axes.

It will be noted that the transducers are connected to the upper and lower edges of the mirrors in this embodiment. This is not essential but is done merely to allow more space for passage of the light beam L' which is deflected as a consequence of multiple reflection from the interior surface of the mirrors. As a consequence of this construction, the degree of mirror rotation per unit of applied voltage is not as large as in the FIG. 1 embodiment where the transducers were located closer to the mirror rotational axis; but the overall beam deflection is nevertheless greater by virtue of the multiple reflections.

Again as in the case of the FIG. 1 embodiment, the possibility of mirror vibrations must be considered as a factor which may limit the frequency response of the deflector. In this instance, since the transducers are connected to the mirror edges, the mirror thickness t is selected to be sufficient with respect to its height (h) to assure that the vibrational modes extending vertically between the lower and upper transducers are of substantially higher frequency than the transducer extensional mode vibrations. However, since the mirror

width (W_M) is greater than its height, there is a likelihood of vibrational modes developing along the width dimension. Looking down on the mirror edges in the direction of arrows 25' 25'', the odd and even order torsional vibrational modes that can occur in a free mirror would be as shown in FIG. 3a. Excitation of the odd modes is inhibited inasmuch as the two top transducers operate in phase and likewise for the two bottom transducers. The even order modes, however, remain to be contended with. These modes can be inhibited as explained with reference to the FIG. 1 embodiment by judicious placement of the transducers relative to the mirror. The first order even mode, for instance, is inhibited by locating the center line of the transducers at the nodes of this vibrational mode which in this case are located about one-quarter of the mirror width from the edges of the mirrors, that is $X = W_M/4$ as shown in FIG. 3. Hence, the lowest frequency vibrational mode which is able to develop is the second order even torsional mode which is about three times the frequency of the first order even mode. Thus, by appropriate positioning of the transducers relative to the mirrors it can be assured that the frequency limit of the device is determined by the transducer dimensions irrespective of the tendency for first order mirror vibrational modes to develop. The other characteristics of the deflector concerning speed, capacity, the speed-capacity product, length of the mirrors relative to their thickness and the desirability of increasing the length to thickness ratio of the transducers in the interest of achieving lower voltage operation and greater capacity are all applicable as explained with reference to the prior embodiment.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

I claim:

1. A light deflector of the piezoelectrically actuated reflector type comprising

first and second light reflectors having respective height and width dimensions,

a pair of piezoelectric strips having substantially greater length than thickness extending generally parallel to one another lengthwise and each articulately connected at one end in spaced apart relation along the height dimension of the first reflector and connected at the other end spaced apart relation along the height dimension of the second reflector,

means for fixedly supporting the reflector-strip structure at a point with respect to which the strips can extend and contract in response to an electrical drive signal applied thereto, and

electrode means connected to the strips for receiving the applied signal to produce extension of one strip and contraction of the other in accordance with the spontaneous polarization of the strips and the magnitude and polarity of the applied signal whereby each reflector rotates about a respective axis passing therethrough oriented transversely of the length of the strips and parallel to the width dimensions of said reflectors, for deflecting a light beam reflected from one reflector to the other.

2. The apparatus of claim 1 including means for applying a bias voltage to the strips to establish a predetermined quiescent polarization therein oriented transverse to the strip length whereby repeatability of reflector rotation is obtained in response to a drive signal of given amplitude applied to the strips for increasing the polarization of one strip to cause elongation thereof and decreasing the polarization of the other strip to cause contraction thereof.

3. The apparatus of claim 1 wherein the length to thickness ratio of the strips is on the order of ten to one or more.

4. The apparatus of claim 3 wherein the light reflectors have height in the direction of the spacing between the strips and thickness lengthwise of the strips proportioned so that the height to thickness ratio of each reflector is at least equal to the length to thickness ratio of the strips, and the strips are connected to the reflectors along the height dimension thereof at points corresponding to the nodes of the lowest order flexural vibration mode which could occur along the height dimension of a free reflector whereby motion associated with said flexural mode is inhibited.

5. The apparatus of claim 4 including means for applying a bias voltage to the strips to establish a predetermined quiescent polarization therein oriented transverse to the strip length whereby repeatability of reflector rotation is obtained in response to a drive signal of given amplitude applied to the strips for increasing the polarization of one strip to cause elongation thereof and decreasing the polarization of the other strip to cause contraction thereof.

6. The apparatus of claim 3 including an additional pair of piezoelectric strips having a length to thickness ratio on the order of ten to one or more extending generally parallel to one another lengthwise in spaced apart relation with the ends thereof articulately connected to the reflectors and disposed in side by side relation with said pair of piezoelectric strips, and wherein the light reflectors have width in the direction of the side by side disposition of the strips and thickness lengthwise of the strips proportioned so that the width to thickness ratio of each reflector is at least equal to the length to thickness ratio of the strips, and the strips are connected to the reflectors along the width dimension thereof at points corresponding to the nodes of the lowest even order free torsional vibration mode which could occur along the width dimension of a free reflector whereby said torsional mode is inhibited.

7. The apparatus of claim 6 including means for applying a bias voltage to the strips to establish a predetermined quiescent polarization therein oriented transverse to the strip length whereby repeatability of reflector rotation is obtained in response to a drive signal of given amplitude applied to the strips for increasing the polarization of one strip to cause elongation thereof and decreasing the polarization of the other strip to cause contraction thereof.

8. A light deflector of the piezoelectrically actuated reflector type comprising

a pair of piezoelectric strips having a length to thickness ratio on the order of ten to one or more extending generally parallel to one another lengthwise in spaced apart relation,

a light reflector having height in the direction of the spacing between the strips and thickness lengthwise of the strips proportioned so that the reflector height to thickness ratio is at least equal to the length to thickness ratio of the strips, and articulately connected to one end of the strips at points along the height dimension of the reflector corresponding to the nodes of the lowest order flexural vibration mode which could occur along the height dimension of a free reflector whereby motion associated with said flexural mode is inhibited, and means for fixedly supporting the reflector-strip structure at a point with respect to which the strips can extend and contract in response to an electrical drive signal applied thereto

electrode means connected to the strips for receiving an applied drive signal to produce extension of one strip and contraction of the other in accordance with the spontaneous polarization of the strips and the magnitude and polarity of the applied signal whereby the reflector rotates about an axis passing therethrough oriented transversely of the length of the strips for deflecting a light beam incident on the reflector.

9. The apparatus of claim 8 including means for applying a bias voltage to the strips to establish a predetermined quiescent polarization therein oriented transverse to the strip length whereby repeatability of reflector rotation is obtained in response to a drive signal of given amplitude applied to the strips for increasing the polarization of one strip to cause elongation thereof and decreasing the polarization of the other strip to cause contraction thereof.

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