Nov. 7, 1939. W. P. MASON 2,179,098

ELECTRO-OPTICAL APPARATUS

Filed Aug. 11, 1937

FIG. 1

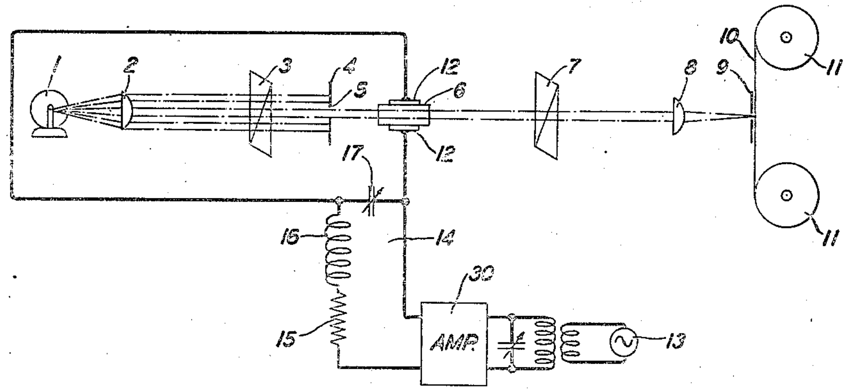
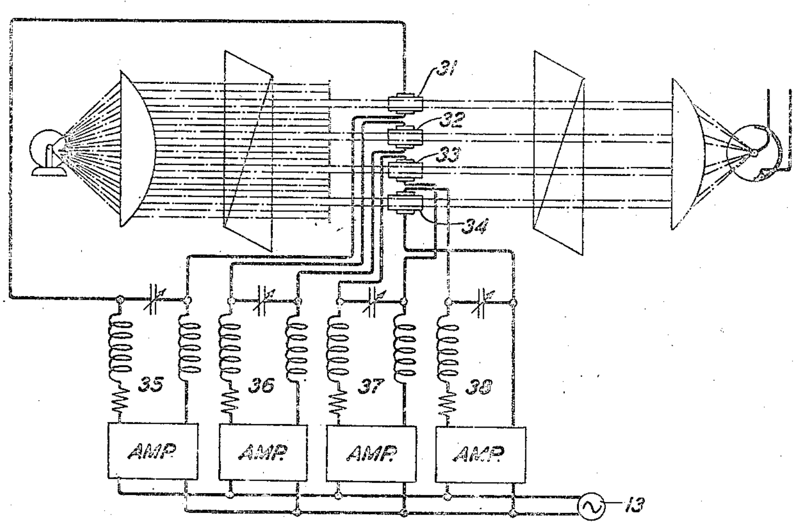


FIG. 2



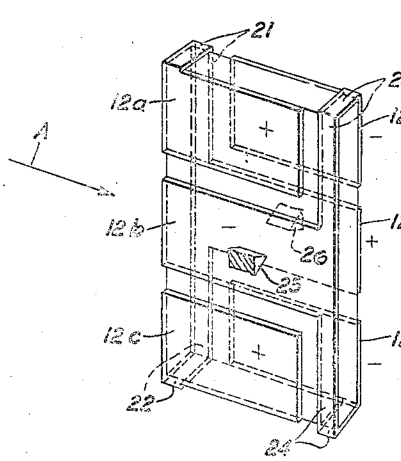


FIG. 3

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ELECTRO-OPTICAL APPARATUS

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18 Claims. (Cl. 179—100.3)

This invention relates to light valves and more particularly to devices of this type including piezoelectric crystals.

While it has heretofore been proposed to utilize piezoelectric crystals as light valves in sound recording and for similar purposes where the signal current comprises a continuous band of current variations extending over a very narrow frequency range, they have not gone into practical use even for these purposes, because the frequency band width, to which the response of a crystal will be substantially uniform when actuated by driving potentials of the same magnitude, is only a very small fraction of one per cent of the resonant frequency of the crystal.

An object of this invention is to provide a light valve comprising a piezoelectric crystal the response of which is substantially uniform over a band of frequencies corresponding to several per cent of the resonant frequency of the crystal.

Another object is to provide a piezoelectric crystal light valve having a substantially uniform response over a wide band of frequencies.

According to one embodiment to be hereinafter described in detail a resistance and an inductance are connected in series with a piezoelectric crystal, the value of the inductance being so chosen that the circuit resonates at two limiting frequencies about equidistant from the anti-resonant frequency of the crystal, whereby the voltage across the crystal is approximately equal to the input voltage at the anti-resonant frequency and becomes greater at the two limiting frequencies depending upon the value of the resistance. Since the mechanical resonant frequency of the crystal occurs very nearly at the anti-resonant frequency of the circuit, the voltage required to cause a given amount of strain in the crystal is a minimum at this frequency and increases rapidly on either side thereof. By properly adjusting the value of the series resistance, the amplitude of response of the crystal may be made equal at the three frequencies under consideration, whereby the deformation of the crystal will be substantially uniform over the range identified by the limiting frequencies, the variation of the plane of polarization of light passing through the crystal will be substantially the same and hence the amount of light transmitted therethrough will be substantially constant.

The maximum band width which may be obtained is directly proportional to the coefficient of coupling between the electrical and mechanical system and may be expressed as the square root of the value of the series capacity of the equivalent crystal circuit divided by the sum of the values of the series and shunt capacities of this equivalent circuit. However, since the shunt capacity is much greater than the series capacity, the coefficient of coupling is substantially equal to the value of the series capacity divided by that of the shunt capacity.

The series capacity of the crystal being dependent upon the piezoelectric constants of the quartz and other factors which are not readily determined, it is more convenient to express the coefficient of coupling in terms of the anti-resonant and the resonant frequencies. This coefficient is equal to the square root of twice the difference between the anti-resonant and the resonant frequencies of the crystal, divided by its anti-resonant frequency.

The invention also contemplates the idea of connecting in shunt to the crystal a variable condenser, the capacity of which may be adjusted to vary the frequency band width over which a uniform response may be obtained. The coupling coefficient and the band width being a maximum when the series capacity is a maximum, it is preferable to plate the crystal with metal to reduce the air-gap to a minimum and to make contact with the coatings at points which clamp the crystal at the nodes. Again, since secondary modes of vibration over the frequency range applied to the crystal seriously alter its response and may cause the crystal to shatter and the third harmonic longitudinal vibration along the length (Y axis) is free from secondary frequencies when the dimensions of the crystal are kept within certain limits, it is preferable to employ low frequency modes of vibration, to divide the metal plating applied on each side of the crystal into three sections and to connect the alternate sections together, in order to obtain maximum coupling at the third harmonic.

While the apparatus described above may be used for sound recording and picture transmission, the invention contemplates the use of such apparatus to be controlled by signal variations now in use for television transmission. This may be effected by providing a series of circuits of the type described above, each including a crystal which resonates at a different but nearby frequency and having the impedances of the circuit so related that they operate as filter circuits to respectively concentrate practically all of the energy in a given frequency range in the proper crystal, and connecting these circuits in parallel with each other; whereby there is provided a combination which responds to driving potentials which extend over a wide frequency range, such as, for example, of the order of a million cycles or more. A detailed description of the invention follows and is illustrated in the attached drawing in which:

Fig. 1 is a diagrammatic representation of an electro-optical system embodying the invention;

Fig. 2 diagrammatically illustrates a system comprising a plurality of piezoelectric crystal light valves controlled by a signal current including variations extending over an extremely wide frequency band; and

Fig. 3 is a perspective view of a crystal structure which may be used in either of the arrangements illustrated in the preceding figures.

Referring to Fig. 1 there is shown, by way of example, a signal recording system comprising a source of chromatic light 1, a lens 2, a polarizer 3, a mask 4 having an aperture 5, a vibrating crystal 6 axially aligned with the aperture 5, an analyzer 7, a lens 8, an apertured screen 9, and a light sensitive film 10, mounted on reels 11 adapted to be driven by a motor drive (not shown) but which operates in the manner now commonly used in the sound recording art, so as to move the film transversely of the path of the light beam supplied by lens 8. The crystal 6 is provided with a pair of electrodes 12 supplied from a source of signal modulated carrier current 13 over a circuit 14, including an amplifier 30 provided with a tuned input circuit, an adjustable resistance 15 and an inductance 16 connected in series with the crystal electrodes, and an adjustable condenser 17 connected in shunt to these electrodes.

Light radiated from the source 1 is focused upon the recording film 10 through the aperture in screen 9 by lenses 2 and 8 after passing through the polarizer 3, the analyzer 7 and the transparent crystal 6. The effect of the signal modulated carrier current, supplied over the circuit 14, is to cause the crystal to vibrate at an amplitude proportional to the voltage of the impressed current. During such vibration, the plane of the polarized light received from the polarizer 3 is rotated so that an amount of light proportional to the amplitude of the vibration of the crystal 6 passes through the analyzer 7 to control a record on the film 10.

The Nicol prisms, i. e., the polarizer 3 and analyzer 7, and the electrically energized crystal 6 function as a shutter or light valve to control the passage of light from the light source 1 to the light record film or blank 10. The capacity of this shutter or valve to pass light therethrough is dependent on the electro-activity of the crystal.

Light valves or shutters of the type described above have been disclosed in the prior art. However, they depend for their operation on the resonant response of the crystal per se. As is well known, the characteristic impedance of a crystal, for applied driving potentials, is such that its response is a maximum when a driving potential of anti-resonant frequency is applied to it, but the response drops to an extremely low value, when the frequency of the applied potential differs from that of the anti-resonant frequency of the crystal by an extremely small amount. As a matter of fact, the response of the crystal will only be substantially uniform, provided the frequency of the applied driving potential does not exceed a small fraction of one per cent of the anti-resonant frequency of the crystal.

According to the present invention, the value of the inductance 16 should be so chosen that the combined circuit, including the crystal, is caused to resonate at two limiting frequencies about equidistant from the anti-resonant frequency of the crystal, with the result that the voltage across the crystal is approximately equal to the input voltage at the anti-resonant frequency and is of a much greater value at the two limiting frequencies.

The mechanical resonant frequency of the crystal being substantially the same as the anti-resonant frequency of the circuit, the driving voltage required to produce a given amount of strain in the crystal is a minimum at this frequency and increases rapidly on either side thereof. By properly adjusting the value of resistance 15, the magnitude of the voltages applied to the crystal may be so regulated that the amplitude of the response of the crystal may be made equal at the three frequencies under consideration and hence the crystal will be deformed substantially uniformly over the frequency range identified by the limiting frequencies, and hence the variation of the plane of polarization of light passing through the crystal will be substantially the same and the amount of light transmitted therethrough will be substantially constant.

It can be shown that the maximum band width which may be obtained is directly proportional to the coefficient of coupling between the electrical and mechanical systems. This may be expressed by the equation,

$$\frac{f_3-f_1}{f_2}=K$$

in which f_3 and f_1 are the maximum and minimum limiting frequencies, respectively and f_2 is the anti-resonant frequency. The left-hand member of the equation therefore defines the ratio of the band width to the anti-resonant frequency and K is the coefficient of coupling.

K may also be expressed in terms of the constants of the equivalent electrical circuit of the crystal as follows:

$$K=\sqrt{\frac{C_3}{C_3+C_4}}$$

where

C_3=the series capacity of the equivalent crystal circuit, and

C_4=the parallel capacity of the equivalent crystal circuit.

Since C_4 is very large compared with C_3, the ratio of values being substantially equal to 125, the above equation may be reduced to:

$$K=\sqrt{\frac{C_3}{C_4}} \qquad (1)$$

The capacity C_4 may be measured or computed to a fair degree of accuracy, but C_3 depends upon the piezoelectric constants of the quartz and other factors which are not readily determinable. For this reason, it is more convenient to express K by the equation

$$K=\sqrt{\frac{2(f_A-f_R)}{f_A}}$$

where

f_A=the anti-resonant frequency of the crystal, and

f_R=the resonant frequency of the crystal.

These two frequencies may be readily determined by measuring the current through the crystal as the frequency of the applied potential is varied and noting the maximum and minimum current values.

From Equation 1, it will be evident that the coefficient of coupling, and hence the band width, is a maximum when the series capacity is a maximum. In order to secure a maximum series capacity, the crystal 6 is provided with electrodes 12 as shown in Fig. 3. These electrodes are applied to the large faces of the crystal, i. e., to the surfaces perpendicular to the electrical axis, by depositing a layer of silver, or other conductive metal, to secure an intimate contact over the whole surface, whereby the gap between these electrodes and the crystal is reduced to a minimum, and contact is made with the respective electrodes by point or knife edge contacts 25 and 26 which clamp the crystal at a nodal point on its optical axis. The electrode coating may be applied by electrical deposition, or in any other manner adapted to insure an intimate contact with the crystal.

In the operation of the crystal for the purposes of this invention, it is important that the crystal be free from secondary modes of vibration over the transmission band of uniform response, as secondary vibrations seriously alter the transmission characteristics of the crystal and may cause it to shatter. In general the number of secondary frequencies increases as the mode of higher frequencies is utilized. For this reason, low frequency modes of vibration are used and, as the third harmonic longitudinal vibration along the length, or Y axis, was found to be free from secondary frequencies when the ratio of the dimensions of the crystal are kept within limits the coatings applied to the respective crystal surfaces were each divided into three sections and the alternate sections were connected together as shown in Fig. 3, in order to obtain maximum coupling for the third harmonic vibration.

According to Fig. 3, the electrode coating 12 on one side of the crystal is divided into three sections 12*a*, 12*b*, and 12*c*, and the electrode coating on the other surface of the crystal is divided into three corresponding sections 12*d*, 12*e* and 12*f*, the sections 12*a*, 12*e* and 12*c* being connected together by connectors 21 and 22. The former connector extends across one end and along part of the opposite side of the crystal to 12*e*, while 22 extends from 12*e* along the remainder of this side of the crystal and across its other end to 12*c*. Sections 12*d*, 12*b* and 12*f* are connected together by connectors 23 and 24. The former extends across the same end of the crystal as 21 and along its other side to 12*b*, while 24 extends along the same side of the crystal as 23 and across the same end of the crystal as 22 to the section 12*f*. Electrical contact is made with the three sections 12*a*, 12*e*, 12*c* and 12*d*, 12*b* and 12*f*, respectively, and the crystal is supported, by point or knife edge contacts 25 and 26, which clamp the crystal at a nodal point on the length, or Y axis, of the crystal. Light from source 1 is directed through the crystal as indicated by the arrow A, the coating applied to the surfaces of the crystal in the path of the light beam having been removed.

An apparatus, as shown in Fig. 1, which included a crystal one millimeter thick, 11.28 millimeters wide and 50 millimeters long having a resonant frequency of 162 kilocycles was mounted as illustrated in Fig. 3. This crystal was supplied with alternating current of 162 kilocycles to cause the crystal to vibrate in its third harmonic mode along its length, or Y axis, over a circuit which was not provided with a shunting condenser 17 but included a resistance 15 of 8800 ohms in series with an inductance 16, which was adjustable to vary the selectivity of the complete circuit, including these impedances and the crystal, over the frequency range between 150 kilocycles to approximately 170 kilocycles. As the selectivity of the circuit was varied, the light transmitted through the crystal, as measured by a Macbeth illuminometer, was substantially constant over a frequency range of 9500 cycles, the resonant frequency of the crystal being at substantially the mid-point of this range, whereas when the same crystal was similarly energized over a circuit which did not include the impedances 15 and 16, the light transmitted through it was substantially constant over a range of 42 cycles, the resonant frequency of the crystal being approximately the mid-frequency of this range.

Similar results were obtained with other crystals having somewhat different anti-resonant frequencies, respectively, than that supplied to the crystal referred to above. In general, it was found necessary to adjust the value of the inductance so that the upper limiting frequency of the band, on which a uniform response was obtained, was closer to the anti-resonant frequency of the crystal than the lower limiting frequency of this band. However, by tuning the input of the amplifier toward the upper frequency of the voltage supplied to the crystal circuit, the voltages applied to the crystal in the upper portion of the frequency range were increased with respect to those in the lower portion of this range. In this manner the band over which uniform response occurred was adjusted so that the anti-resonant frequency was approximately equal to the mean of the limiting frequencies. Under different operating conditions, it may be that the anti-resonant frequency is closer to the lower limiting frequency of the uniform response band than to the upper limiting frequency, in which event, the tuning of the amplifier input circuit would be adjusted toward the lower limiting frequency of the voltage supplied to the crystal circuit.

In certain cases it may not be necessary to obtain a uniform response band as wide as that provided by the circuit described above. In this case, the sensitivity of the light valve can be increased by reducing the band width. This may be accomplished by adjusting the condenser 17.

It can readily be shown, that, up to the time that dissipation plays a controlling part, the sensitivity of the crystal will be inversely as the square of the band width. Hence, if the band width is decreased by one-half by using a paralleling condenser, the sensitivity will be increased four times and the amount of power to obtain the same sensitivity will be decreased sixteen times. However, as the band width is decreased, the effect of dissipation becomes more prominent and the gain in sensitivity obtained, by decreasing the band width, becomes less.

A crystal valve of the type described above may be used in a sound recording system or a picture transmission system, and by utilizing a crystal having an anti-resonant frequency of the order of a million cycles, a light valve may be provided for use in a television system designed to generate an image current extending over a limited frequency range, for example, of the order of 50 kilocycles.

For high quality television systems in which the image band may extend to upwards of a million or more cycles, a light valve of the type disclosed in Fig. 2 may be used.

The valve of Fig. 2 includes a series of crystals 31, 32, 33 and 34, each included in a respective filter circuit 35, 36, 37 and 38. By designing the crystal circuits as described above and so that they are respectively effective to select contiguous portions of a continuous frequency band and by connecting a plurality of these circuits in parallel with respect to the signal supply source 13, there is provided a light valve assembly having a substantially uniform response over a wide band of frequencies.

No loss of sensitivity results from this method of widening the frequency band, because practically all of the energy in a given frequency range is selected and applied to the proper crystal by the impedance relation of the parallel filters. Since filters of this type have a high impedance outside the transmission band which corresponds to the radiation band of the crystal used as a unit of the light valve assembly, they may be connected in parallel and practically all of the energy lying in a given frequency range will be delivered to the filter having a band-pass in that range.

If, for example, eight crystal circuits are used, it is possible to provide a light valve having a substantially uniform response over a frequency range the upper limiting frequency of which is twice that of the lower limiting frequency.

By including an amplifier having an adjustable tuned input circuit, as shown in Fig. 1 in each of circuits 35, 36, 37 and 38, it is possible to adjust the position of the frequency band over which the response of each circuit is uniform with respect to the anti-resonant frequency of the crystal included in the circuit.

While in the preceding description certain details and numerical examples are set forth for the purpose of disclosing the principles of the invention, it will be apparent that the dimensions of the crystals and hence the value of the carrier frequency used may be varied over wide limits, any crystals having piezoelectric properties may be used, substantially any number of crystal circuits may be connected in parallel to provide an assembly of the type herein described, any well-known type of distortionless amplifier and suitable type of modulating device may be used, that by increasing the coupling coefficient the uniform response band width for a given crystal may be increased, and by placing the crystal in a vacuum, the effect of arcing can be eliminated and hence a large percentage of the available light can be usefully employed.

While the use of monochromatic light appears preferable, various optical arrangements using white light have been tested with some measure of success, from which it appears that, with some refinements, it is possible to provide a light valve of the type herein disclosed to control white light.

What is claimed is:

1. A light molulating apparatus comprising a piezoelectric element included in a circuit supplied with signals extending over a frequency band corresponding to at least one per cent of the resonant frequency of said element, and a plurality of impedances included in said circuit for causing the response of said element to be substantially uniform over said band.

2. A light modulating apparatus comprising a piezoelectric element which responds uniformly to a frequency band definitely related to its resonant frequency, and means for extending the limits of said uniform response band comprising a plurality of impedances connected in series with said element.

3. A light modulating apparatus comprising a piezoelectric element which responds substantially uniformly to signal potentials extending over a frequency band definitely related to its resonant frequency, a plurality of impedances connected in series with said element for widening the band to which its response is uniform, and an impedance in shunt to said element for controlling the extent of said band.

4. An electro-optical system including a source supplying light of constant intensity, a plurality of parallel connected circuits respectively selective of a different frequency range, each circuit comprising a piezoelectric crystal in the path of said light and a plurality of impedances in series with said crystal.

5. A light valve comprising a piezoelectric crystal, means for causing its response to be substantially uniform over a wide frequency band of driving potentials, and means for adjusting the position of said frequency band with respect to the resonant frequency of the crystal.

6. A light valve which is uniformly responsive to driving potentials extending over a wide frequency range comprising a plurality of circuits, each of said circuits comprising a piezoelectric crystal and an impedance connected in series with the respective crystal, the respective circuits being selective of contiguous bands within said frequency range.

7. A light valve comprising a plurality of parallel connected crystal filter circuits, and means included therein for rendering the respective crystals substantially uniformly responsive to driving potentials extending over a frequency range corresponding to at least one per cent of the resonant frequency of the crystal and included in adjacent portions of a wide frequency band.

8. A light valve comprising a plurality of circuits, a piezoelectric element and a plurality of impedances included in each said circuit for causing said element to be uniformly responsive to driving potentials in a wide frequency band, and means supplying driving potentials extending over a frequency range including a plurality of said bands in parallel to said circuits.

9. A light valve which is substantially uniformly responsive to a signal extending over a wide frequency range comprising a source of signals, a plurality of filter circuits connected in parallel to said source, said circuits respectively including a piezoelectric crystal and means for causing said crystal to be uniformly responsive to signals included in a wide frequency band, said circuits being selective of contiguous bands within said range.

10. An electro-optical system including a source supplying light of constant intensity, a plurality of parallel connected circuits respectively selective of a different frequency range, each circuit comprising a piezoelectric crystal in the path of said light and a plurality of impedances for controlling a characteristic of said crystal.

11. An electro-optical system including a source supplying light of constant intensity, a plurality of parallel connected circuits respectively selec-

tive of a different frequency range, each circuit comprising a piezoelectric crystal in the path of said light, a plurality of impedances for controlling a characteristic of said crystal, and means for modifying said characteristic.

12. An electro-optical system including a source supplying light of constant intensity, a plurality of parallel connected circuits respectively selective of a different frequency range, each circuit comprising a piezoelectric crystal in the path of said light, means for causing the response of said crystal to be substantially uniform over a wide frequency band of driving potentials, and means for controlling said potentials.

13. A light valve comprising a piezoelectric crystal, means for causing its response to be substantially uniform over a wide frequency band of driving potentials, means for adjusting the position of said frequency band with respect to the resonant frequency of the crystal, and means for controlling the width of said frequency band.

14. A light modulating apparatus comprising a piezoelectric element included in a circuit supplied with signals extending over a frequency band corresponding to at least one per cent of the resonant frequency of said element, and a plurality of impedances included in said circuit, said impedances comprising means for causing the response of said element to be substantially uniform over said band and means for controlling the width of said band.

15. A light modulating apparatus comprising a piezoelectric element included in a circuit supplied with signals extending over a frequency band corresponding to at least one per cent of the resonant frequency of said element, a plurality of impedances included in said circuit for causing the response of said element to be substantially uniform over said band and means for adjusting the position of said band with respect to the resonant frequency of said element.

16. A light modulating apparatus comprising a piezoelectric element included in a circuit supplied with signals extending over a frequency band corresponding to at least one per cent of the resonant frequency of said element, a plurality of impedances included in said circuit, said impedances comprising means for causing the response of said element to be substantially uniform over said band and means for controlling the width of said band, and means for adjusting the position of said band with respect to the resonant frequency of said element.

17. A light modulating apparatus comprising a piezoelectric element which responds uniformly to a frequency band definitely related to its resonant frequency, means for extending the limits of said uniform response band comprising a plurality of impedances connected in series with said element, and means for adjusting the position of said uniform response band with respect to the resonant frequency of said element.

18. A light modulating apparatus comprising a piezoelectric element which responds uniformly to a frequency band definitely related to its resonant frequency, means for extending the limits of said uniform response band comprising a plurality of impedances connected in series with said element, means for adjusting the position of said uniform response band with respect to the resonant frequency of said element, and means for controlling the extent of said uniform response band.

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