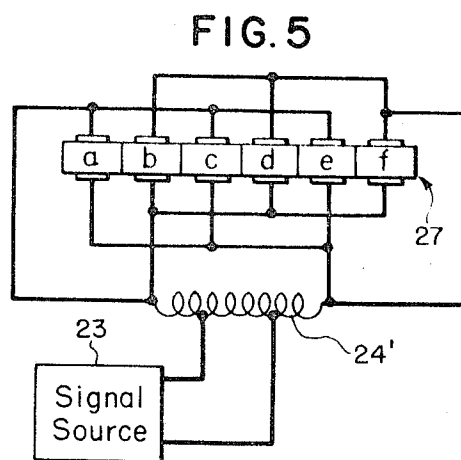
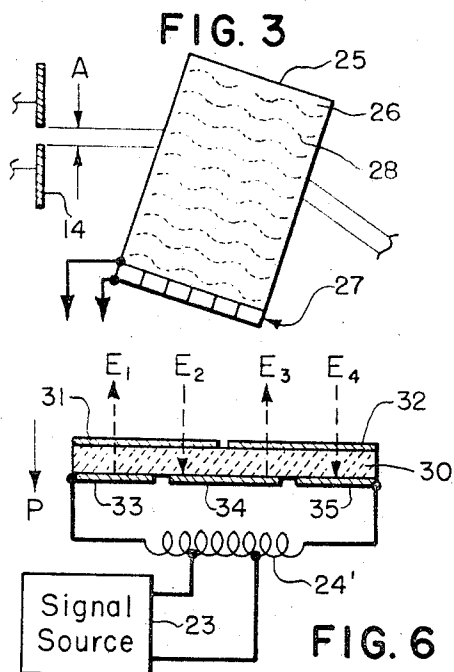
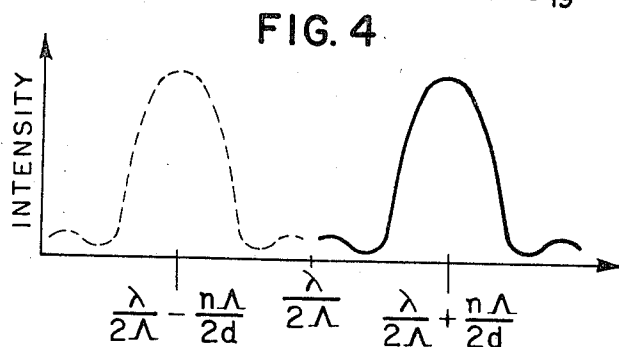
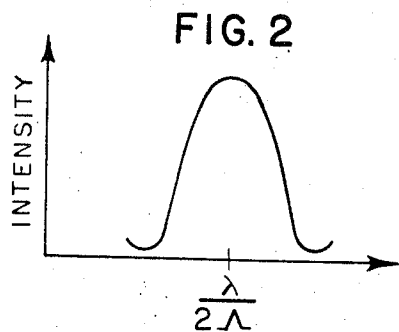
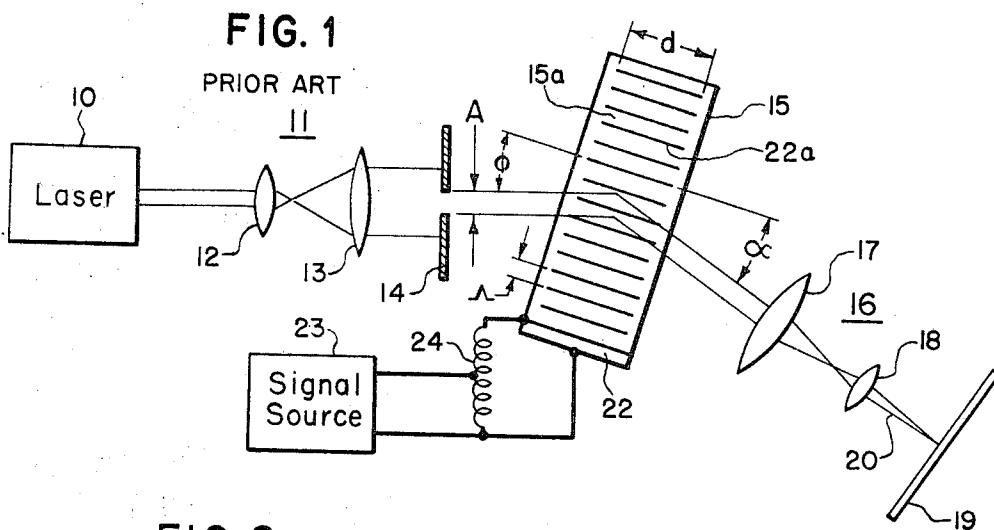


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A. KORPEL  
LIGHT-SOUND INTERACTION SYSTEM  
WITH ACOUSTIC BEAM STEERING  
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3,424,906



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**FIG. 6**

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**LIGHT-SOUND INTERACTION SYSTEM WITH ACOUSTIC BEAM STEERING****Adrianus Korpel, Prospect Heights, Ill., assignor to Zenith Radio Corporation, Chicago, Ill., a corporation of Delaware**

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7 Claims

**ABSTRACT OF THE DISCLOSURE**

Light-sound interaction signal-translating apparatus of the Bragg diffraction type is modified to provide an improvement in modulation bandwidth. This is accomplished by causing the sound waves to have composite wave fronts of non-uniform phase throughout their width in a direction longitudinally related to the path of the light beam. The exemplary transducer means of the light-sound interaction device comprises a plurality of differently energizable longitudinally spaced electromechanically active sections, and adjacent sections are energized in phase opposition. The result is to provide acoustic waves with wave fronts whose angular relationship to the light path automatically changes as a function of the sound wave frequency to maintain the light-sound interaction angle at substantially one-half the Bragg angle over a substantial sound frequency range, a type of action which has become known as acoustic beam steering. Bandwidths of up to 60% are obtained, as compared with typical bandwidths of 20% or less in prior systems.

This device pertains to a signal translating apparatus. More specifically, it relates to systems and apparatus in which light and sound are caused to interact. As used herein, the terms light and sound are most general. That is, the term light refers to both visible and invisible electromagnetic radiation, and the term sound includes both audible and super-audible compressional wave energy of any frequency including, for example, microwave frequencies.

A spatially-coherent substantially monochromatic light beam impinging upon a sound wave at a particular angle in accordance with the Bragg relationship, which depends upon the wavelengths of the light and sound, is diffracted by the sound wave at that same angle. That is, when light and sound interact at the Bragg angle, the travelling sound waves act as if they were moving mirrors for the light. With plane sound and light wave fronts, usable Bragg angle reflection is attainable only over a limited range of sound frequencies without readjustment of the angle between the sound and light fronts. Certain previous systems seek to overcome this limitation by embodying means for physically changing the relative orientation of the elements with change in sound frequency.

It is, therefore, a general object of the present invention to provide light-sound interaction signal translating apparatus which maintains usable Bragg angle diffraction over an increased range of sound frequencies in a manner either reducing or eliminating the need for physical repositioning of any of the elements in the apparatus.

Application Ser. No. 476,873, filed Aug. 3, 1965 now Patent Number 3,373,380 by Robert Adler and assigned to the same assignee, describes the use of curved wave fronts to maintain a portion of a sound wave front incident to a light wave front in accordance with the Bragg angle over a wide range of sound frequencies. However, since the light and sound only interact along a small portion of the curved wave front, much of the power in the curved wave front is wasted. Accordingly, another object of the present invention is to provide a signal translating

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apparatus of the aforementioned type in which the sound frequency may be scanned over a substantial frequency range without undue loss of efficiency.

It is a still further object of the present invention to achieve the foregoing with apparatus which features simplicity of construction and of operational requirements.

Signal-translating apparatus according to the present invention comprises means for projecting a substantially collimated monochromatic light beam along a predetermined path. The apparatus further comprises a light-sound interaction device comprising an acoustic-wave transmitting medium and transducer means coupled to the medium for propagating therein, across the predetermined path of the light beam, sound waves with corrugated wave fronts of nonuniform phase throughout their width in a direction longitudinally related to the path.

In accordance with another feature of the invention, signal-translating apparatus comprises means for projecting a substantially collimated monochromatic light beam along a predetermined path, in combination with a light-sound interaction device comprising an acoustic-wave transmitting medium and transducer means coupled to the medium for propagating therein, across the path of the light beam, sound waves having wave fronts whose orientation relative to the light beam path effectively varies with their frequency to provide Bragg diffraction of the light beam at all sound wave frequencies within a predetermined frequency range.

As used therein, a "finite plane wave front" defines a plane surface of finite width along which every element has the same phase. A "corrugated wave front," however, refers to a plane surface composed of individual finite plane wave fronts of varied phase.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in the several figures of which like reference numerals identify like elements, and in which:

FIGURE 1 is a partly schematic diagram of a known light-sound signal translating apparatus;

FIGURE 2 is a diffracted light intensity response curve in such a known light-sound signal translating apparatus;

FIGURE 3 is a partly schematic side elevational view of a light-sound signal translating apparatus constituting one embodiment of the present invention;

FIGURE 4 is the diffracted light intensity response curve useful in explaining the FIGURE 3 embodiment;

FIGURE 5 is a schematic representation of a transducer used in the apparatus of FIGURE 3; and

FIGURE 6 is a schematic representation of an alternative transducer.

In order to facilitate understanding, apparatus effecting known light-sound interaction of plane wave fronts is depicted in FIGURE 1. The apparatus includes a source 10, such as a laser, of spatially coherent substantially monochromatic light, a magnifying telescope 11 having an eye piece 12 and an object lens 13, a beam-limiting aperture plate 14 having an aperture width A, a light-sound interaction cell 15, a reverse telescope 16 having an object lens 17 and an eye piece 18, and, in this illustration, a light responsive screen 19 across which a light beam 20 is scanned. Cell 15 is a container the walls of which are transmissive to the light waves and which is filled with water that serves as a propagating medium 15a. At one end of cell 15, coupled to the water, is a transducer 22 driven by electrical signals from a signal generator or source 23 suitably matched to transducer 22 by a transformer 24. Transducer 22 develops finite plane wave fronts in water 15a.

Operationally, signal source 23 impresses signals across transducer 22 which launches sound waves 22a of period  $\Lambda$  and width  $d$  into the water. The direction of sound propagation is selected relative to the direction of light propagation to achieve that which is known as Bragg diffraction. For small angles of incidence, the collimated light beam of wavelength  $\lambda$  from source 10 is incident at an angle  $\phi$  of  $\pm\lambda/2\Lambda$  with respect to the sound wave fronts; for larger angles, the latter value is equated to  $\sin \phi$ . The sound wave causes a travelling-wave type density fluctuation in the water which acts upon the light as a three dimensional moving phase grating, causing a portion of the original beam to be diffracted at an angle  $\alpha$  relative to the sound wave fronts. In this case, exit angle  $\alpha$  is equal to incident angle  $\phi$ , as if part of the original beam were reflected off the sound wave fronts. For sufficiently high sound frequencies, at 50 mc. for example, and with a sufficient interaction length  $d$  for which a value of 20 mm. is typical, there is only one diffraction order and only two angles of incidence for which this phenomenon occurs. These angles,  $\pm\lambda/2\Lambda$  are one-half the value of those which are defined as the positive and negative Bragg angles; the Bragg angle by this definition is the angle between the diffracted and undiffracted light beams.

FIGURE 2 depicts the diffracted light intensity as a function of angle of incidence with respect to the value  $\lambda/2\Lambda$  for the known light-sound interaction of planar wave fronts as in FIGURE 1. The response or relative intensity  $R$  of the diffracted light, normalized to unity at maximum, is given by the relationship:

$$R = \left\{ \frac{\sin [(\lambda/2\Lambda - \phi)d\pi/\Lambda]}{[(\lambda/2\Lambda - \phi)d\pi/\Lambda]} \right\}^2 \quad (1)$$

It may be noted that the angle of deflection always equals  $\lambda/\Lambda$  and is independent of the incident angle  $\phi$ . Over a range of sound frequency, with a center frequency  $f_0$  and a change of frequency  $\Delta f$  from that center frequency, the normalized bandwidth  $2\Delta f/f_0$  is definable as twice the separation between the maximum and a point where the argument of the sine in Equation 1 is equal to  $\pi/2$ . This corresponds to a response at the band edge of  $4/\pi^2$  or about 3 decibels. When incident angle  $\Delta$  equals  $\lambda/2\Lambda_0$ , where  $\Lambda_0$  is the wavelength at the center frequency,  $\Lambda = \Lambda_0$ ,  $R=1$  and the relative bandwidth becomes:

$$\frac{2\Delta f}{f_0} \cong \frac{2\Lambda^2}{\lambda d} \quad (2)$$

In order to extend the bandwidth, the system of FIGURE 3 embodies apparatus similar to that of FIGURE 1 but enables operation over a wider frequency range. The optical elements for the FIGURE 3 apparatus are the same as in FIGURE 1. As before, the cell walls are transmissive to the light waves and the cell is filled with water 26 which serves as a sound propagating medium. At one end of cell 25, coupled to the water, is a transducer 27 driven by electrical signals from signal source 23. In accordance with the invention, transducer 27 generates corrugated wave fronts 28, not plane wave fronts as in FIGURE 1. Each corrugated wave front is composed of a plurality of adjacent finite plane sound wave fronts of individually different phase.

Transducer 27, actually or effectively, is a split piezoelectric transducer system. That is, it is composed of a number  $n$  of individual sections each of which produces an acoustic wave front corresponding to the input signal. The individual sections, within the concept implemented, are a plurality of individual transducers spaced side-by-side, a segmented single transducer structure or a unitary structure in which the individuality is afforded by electrical, instead of physical, separation. As illustrated in FIGURES 3 and 5, transducer 27 is divided into a plurality of contiguous segments 27a-f each of which produces its own plane wave fronts in water 26. Barium titanate is a typical piezoelectric material.

In operation, the signal from source 23 is impressed in adjacent alternate polarity across the individual segments of transducer 27 and the individual plane wave fronts combine to produce in water 26 corrugated wave fronts corresponding to the signal from source 23. The acoustic waves represented by the corrugated wave fronts interact with the light beam produced by source 10. Because of the relationship between the individual plane wave fronts, the effective acoustic wave propagation direction changes with changes in the sound frequency. This change in direction, in turn, increases the bandwidth of the light-sound interaction process by compensating for the change in required angle of incidence of the light for Bragg diffraction.

FIGURE 4 shows the response curve of the light diffracted by the apparatus of FIGURE 3; the plot again is of the light intensity as a function of the incidence angle with respect to the value  $\lambda/2\Lambda$ . Maximum intensity can be caused to appear at either of two distinct points each with intermediate sidelobes of less intensity; these two points correspond to two primary sound propagation directions. The two maxima correspond to angles that differ symmetrically by an angle  $n\Lambda/2d$  from the angle  $\lambda/2\Lambda$  of the FIGURE 2 plot. That is, the required angle of incidence  $\phi$  of the light is determined by the relationship:

$$\phi = \lambda/2\Lambda \pm n\Lambda/2d \quad (3)$$

where  $n$  is the number of individual wave fronts produced by the individual transducer segments and  $d$  is the width of the aggregate of the wave fronts. This particular response curve is that exhibited when the adjacent individual plane wave fronts have a phase difference of  $180^\circ$ , as for instance when generated by opposite movement of adjacent elements.

As the period  $\Lambda$  of the sound wave varies, the angle at which the intensity maximum occurs changes in a compensatory manner so that Bragg-type diffraction is obtained over a wide frequency range. This can be observed from Equation 3. Since a change in the sound wave period  $\Lambda$  changes a factor in the numerator of one of the terms on the right side of the equation and changes the same factor in the denominator of the other term, the change in one term tends to compensate the change in the other. In a pseudo-physical sense, the upper (+ sign) peak in FIGURE 4 moves in the compensatory direction to maintain Bragg diffraction. The lower peak is not used since the sound period change is such as to exaggerate the error in relative orientation of the light and sound beams. Viewed another way, the change in the factor  $n\Lambda/2d$  substantially compensates, over a finite range, for the change in period of the sound wave which otherwise would require a corresponding change of incidence angle  $\phi$ .

In this compensating case, the relative intensity  $R$  is given by the relationship:

$$R = \left\{ \frac{\sin [(\lambda/2\Lambda + n\Lambda/2d - \phi)d\pi/\Lambda]}{[(\lambda/2\Lambda + n\Lambda/2d - \phi)d\pi/\Lambda]} \right\}^2 \quad (4)$$

The angle of incidence  $\phi$  is chosen so that maximum response,  $R=1$ , is obtained at  $\Lambda = \Lambda_0$ . Therefore,

$$\lambda/2\Lambda_0 + n\Lambda_0/2d = \phi \quad (5)$$

Still more optimum compensation, over a range of sound frequencies around  $f_0$  with a sound propagation velocity  $v$ , is obtained, for small angles, when  $\lambda/2v = nv/2df_0^2$ . Therefore:

$$R = \left\{ \frac{\sin \lambda d/2\Lambda_0^2 \pi (f/f_0 + f_0/f - 2)}{\lambda d/2\Lambda_0^2 \pi (f/f_0 + f_0/f - 2)} \right\}^2 \quad (6)$$

With the relative bandwidth defined as before, it is given, in this case, by the equation:

$$\frac{2\Delta f}{f_0} \cong 2\sqrt{\frac{\Lambda^2}{2d}} \quad (7)$$

To illustrate the difference between the bandwidth available with the apparatus of FIGURES 1 and 3, representative values may be substituted in Equations 2 and 7. With

a value of  $d$  of twenty millimeters in water, a sound frequency of fifty megacycles per second and using visible light ( $\approx 4500$  Å.), the value of  $\Lambda^2/\lambda d$  is 0.1. From Equation 2, the normalized bandwidth in the uncompensated case then is 0.2; this signifies a total bandwidth of about 20%. For Equation 7, the normalized bandwidth for the compensated case is 0.6; this represents a total of about 60%, or a three-fold increase.

The additional bandwidth is obtained at the expense of effective utilization of the available sound power. Since intensity maxima of the sound occur in two directions symmetrically about the non-compensatory sound propagating direction in the FIGURE 1 apparatus, representing an effective splitting of the sound wave pattern into two main beams, the light only interacts with one of the sound beams. The sound power in the beam propagating in the other direction is lost. In addition, the power in the lesser-intensity sidelobes is not utilized. In the general case, the degree of effective utilization of the sound power depends upon the configuration of the plane fronts, since that configuration determines how much of the sound power is in the main lobe and how much is in the sidelobes.

In essence, the desired corrugated wave front configuration is obtained by using at least a pair of electromechanical transducers or transducer segments which together direct across the path of the light beam sound waves characterized by corrugated wave fronts each composed of at least a pair of finite plane sound wave fronts of respectively different phase. As seen in FIGURE 5, split transducer 27 has a plurality of segments or sections 27a-f each of which produces a wave of different polarity from, but of similar amplitude to that of the adjacent sections. As explained, the result is the development of a square-wave type of corrugated wave front the diffraction intensity pattern of which is depicted in FIGURE 4. In this case, elementary Fourier analysis reveals that the interaction with the light beam utilizes the fractional portion  $4/\pi^2$  of the total sound power.

In order to eliminate or modify the amplitude of the sidelobes on the response curves, it is necessary to change the configuration of the corrugated wave front. To accomplish this in accordance with one modification of FIGURE 5, the corrugated wave fronts are composed of a plurality of individual finite plane wave fronts having amplitudes mutually related sinusoidally; that is, the effective shape or amplitude pattern of the corrugated wave fronts is of sinusoidal instead of square-wave type. To this end, the individual transducers or segments are excited individually in such a way that the amplitudes of their individual wave fronts yield the sinusoidal pattern of the resulting corrugated wave front. In consequence, the minor sidelobes are eliminated so that fully half of the total sound power is used. Analysis reveals that this sinusoidal configuration produces the highest degree of efficiency if only amplitude detection is used. Where phase selectivity is used, the complication of producing a sinusoidal pattern need not be employed for maximum efficiency.

In practice, a signal phase difference from one transducer or transducer segment is obtainable with a variety of known delay type circuitry. For the simpler square-wave case, the even elements on the water side merely are connected to one pole of source 23 and the odd elements to the other. Alternatively, transmission line segments between each successive pair of elements delay the signal, applied at one side of the assembly, by  $\pi$  radians.

The intensity equations discussed above are based on an assumption that the response curve is maximally flat with a 3 db dropoff tolerated at its ends. However, when the apparatus is not optimally oriented initially, as when the angular relationships are not adjusted for maximum intensity Bragg diffraction at the center frequency  $f_0$ , there is a dip in the response curve at its center. By constraining this dip to represent no more than 3 db attenuation, the

bandwidth in this case is increased by an additional factor of  $\sqrt{2}$ . In explanation, by combining terms in Equation 6 and approximating, the response curve is determined by:

$$R = \frac{[\sin \lambda d / 2 \Delta_0^2 \pi (\Delta f / f_0)^2]}{\lambda d / 2 \Delta_0^2 \pi (\Delta f / f_0)^2} \quad (8)$$

When the incident light interacts at an angle differing from the Bragg angle by the increment  $\Delta\phi$ :

$$R = \frac{[\sin (\lambda d / 2^2 \pi (\Delta f / f_0)^2 - \Delta\phi d / \Lambda \pi)]}{[\lambda d / 2^2 \pi (\Delta f / f_0)^2 - \Delta\phi d / \Lambda \pi]} \quad (9)$$

For this condition, the maximum intensity of the sound response (i.e.,  $R=1$ ) occurs when:

$$\frac{(\Delta f)^2}{f_0} = \left( \frac{2\Lambda}{\lambda} \Delta\phi \right) \quad (10)$$

and (for a 3 db drop at  $\Delta f=0$ , i.e.,  $R=4/\pi^2$ ):

$$\frac{\Delta\phi d}{\Lambda} = \frac{1}{2} \quad (11)$$

Consequently, 3 db dropoff points are in this case determined from the relationship:

$$\frac{2\Delta f}{f_0} = 2\sqrt{\frac{2\Lambda^2}{\lambda d}} \quad (12)$$

By comparison with Equation 7, it is evident that the bandwidth has been increased by the factor of  $\sqrt{2}$ .

FIGURE 6 illustrates a very simple and practical transducer arrangement. The piezoelectric element 30 is polarized in one direction P. On one face are two electrodes 31 and 32 each covering almost a respective one-half of one face of element 30. On the opposing face of element 30 are three electrodes 33-35 with the two side electrodes 33 and 35 each covering almost a respective one-fourth of that face and the other element 34 covering almost the intermediate one-half of the face. The signal from source 23 is applied across electrodes 33 and 35.

In operation, as illustrated, element 30 and its electrodes function as four side-by-side transducers connected in series across the source of signals. The adjacent effective transducers are in phase opposition as indicated by the polarity of respective electric field vectors  $E_1-E_4$ . This arrangement has the special advantage of presenting a very high impedance. Alternatively, the same result is obtained with a single electrode on each face by incorporating respectively alternate zones of opposite adjacent polarity in the piezoelectric material itself. In either case, the deflection system function is the same as described for FIGURES 3 and 5.

In general summary, for the desired compensation or bandwidth extension to occur, it is necessary that the overall sound wave front be formed of a plurality of finite plane sound wave fronts at least a pair of which are of respectively different phase. In the embodiments shown, this overall corrugated wave front is produced by a split transducer system which is made up of a plurality of individual transducer sections which produce a plurality of finite plane sound wave fronts at least a pair of which have respectively different phase. The attainment of the improvement is not limited, however, to sound wave fronts which originate in this manner. It is the achievement of the corrugated wave front configuration which moves to compensate for changes in sound frequency which is of the essence. For example, sound waves characterized by corrugated wave front each composed of a plurality of finite plane sound wave fronts with at least a pair of the sound wave fronts having respectively different phase may be directed across the path of the light beam by a transducer which supports a travelling or standing wave along its length. A standing wave, of course, is merely a travelling wave with zero velocity and is defined herein as a travelling wave. In this case, the variations in amplitude and phase along its length are an inherent feature of such a travelling or standing wave. Even a single transducer supporting a travelling or standing wave

along its length is in effect a split transducer when it induces a corrugated wave front generally parallel to itself in the medium where the sound wave interacts with the beam.

While particular embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

**I claim:**

**1. Signal-translating apparatus comprising:**

means for projecting a substantially collimated monochromatic light beam along a predetermined path; and a light-sound interaction device comprising an acoustic-wave transmitting medium and transducer means coupled to said medium for propagating therein, across said predetermined path, sound waves with corrugated wave fronts of non-uniform phase throughout their width in a direction longitudinally related to said path but inclined thereto at an angle selected to provide Bragg diffraction of said light beam.

**2. Signal-translating apparatus according to claim 1, in which said transducer means comprises a plurality of differently energizable longitudinally spaced electromechanically active sections.**

**3. Signal-translating apparatus comprising:**

means for projecting a substantially collimated monochromatic light beam along a predetermined path; and a stationary light-sound interaction device comprising an acoustic-wave transmitting medium and transducer means coupled to said medium for propagating therein acoustic waves across said predetermined path and for effectively changing direction of propagation of said acoustic waves in accordance with their frequency to provide Bragg diffraction of said light beam at all acoustic wave frequencies within a predetermined frequency range.

**4. Signal-translating apparatus according to claim 3,**

in which said transducer means comprises a plurality of differently energizable longitudinally spaced electromechanically active sections.

**5. Signal-translating apparatus according to claim 4, which further comprises a source of signals having frequency components within said predetermined range coupled to said transducer means for simultaneously energizing adjacent electromechanically active sections in opposite phase.**

**6. Signal-translating apparatus according to claim 5, in which the angle of incidence between said predetermined path and said wave fronts at the center frequency in said predetermined range is substantially**

$$\frac{\lambda}{2\Delta} + \frac{n\Lambda}{2d}$$

where  $\lambda$  is the wavelength of said light beam,  $n$  is the number of said electromechanically active sections,  $d$  is the width of said wave fronts in a direction longitudinally related to said path, and  $\Lambda$  is the wavelength of said sound waves at said center frequency.

**7. Signal-translating apparatus according to claim 2, which further comprises means for concurrently developing differently phased acoustic vibrations in adjacent ones of said sections to produce said corrugated wave fronts of non-uniform phase.**

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