June 24, 1958 G. C. SOUTHWORTH 2,840,820

ARTIFICIAL MEDIUM OF VARIABLE DIELECTRIC CONSTANT

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FIG. 1A

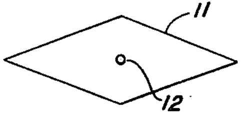

FIG. 1B

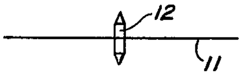

FIG. 3A

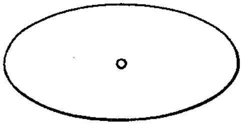

FIG. 3B

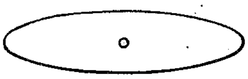

FIG. 3C

FIG. 2A

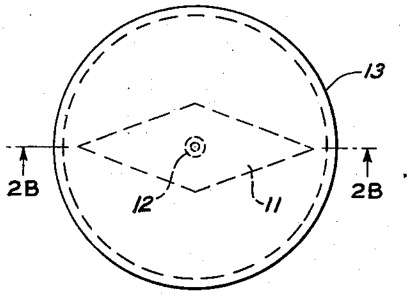

FIG. 2B

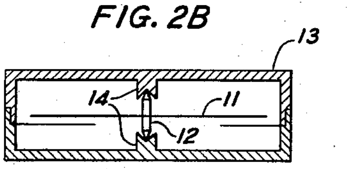

FIG. 4A

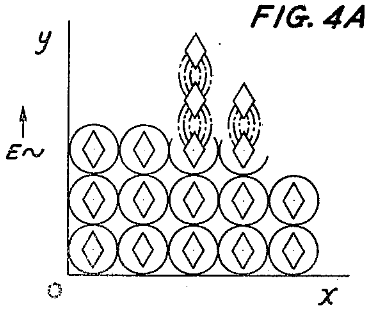

FIG. 4B

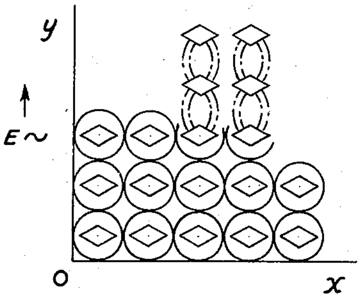

FIG. 5

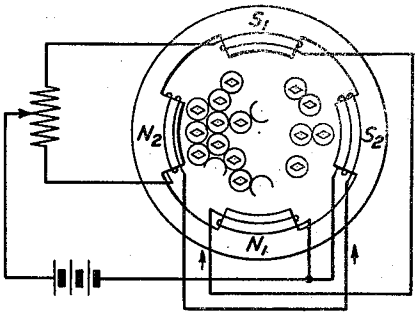

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FIG. 6

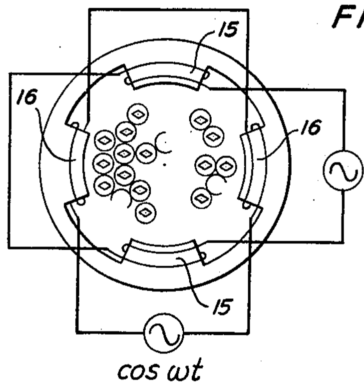


FIG. 8

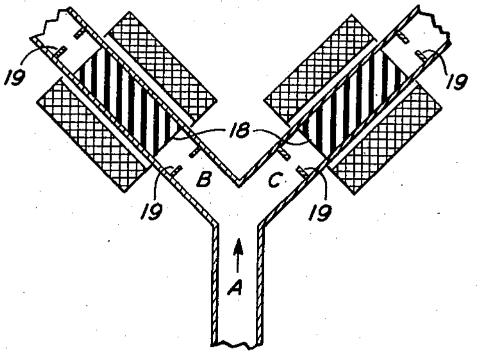


FIG. 7

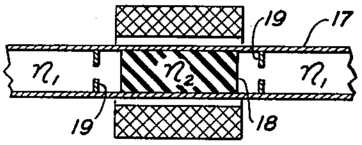


FIG. 9A

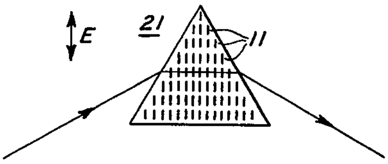


FIG. 9B

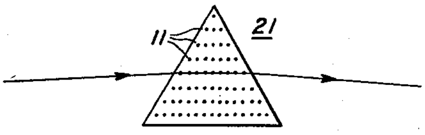


FIG. 10A

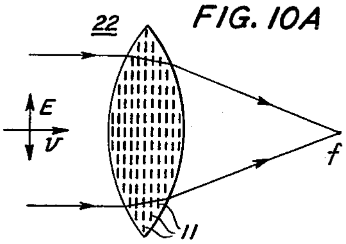
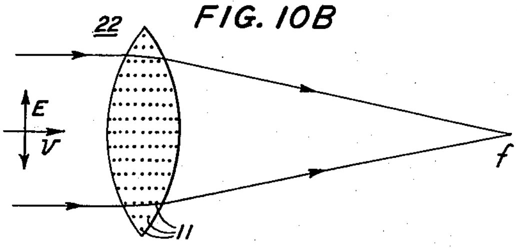


FIG. 10B



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United States Patent Office

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ARTIFICIAL MEDIUM OF VARIABLE DIELECTRIC CONSTANT

George C. Southworth, Chatham, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application April 14, 1954, Serial No. 423,195

15 Claims. (Cl. 343—909)

This invention relates to artificial media suitable for the propogation of electromagnetic waves and more particularly to media in which the dielectric constant and hence both the intrinsic propagation constant and the intrinsic characteristic impedance may be readily varied.

An object of this invention is to provide dielectric media in which the dielectric constant can be varied by the application of an external force thereby making possible (1) a change in the velocity of propagation inside the medium and (2) a change in the reflection and transmission coefficients at its interfaces.

One of the favored theories of dielectric media assumes that there are present in the medium resonators so constituted that they are able to pick up and re-radiate a portion of any wave power that may be passing. The process of pick up and subsequent re-radiation entails a redistribution of the relative energy residing in the electric and magnetic components in any wave power that may be passing. From one point of view it is permissible to say that re-radiation entails a loss in time and accordingly wave power transmitted through the medium appears to have traveled more slowly than if no resonators were present. More especially, the velocity has been reduced and accordingly the apparent index of refraction, that is, the ratio of the velocity in free space to the velocity in the medium, has been increased by the presence of the resonators. From an alternate point of view it is permissible to regard the presence of the resonators as having altered the ratio of the electric and magnetic components in wave power that may be passing through the medium. This is equivalent to saying that the presence of resonators has altered the intrinsic characteristic impedance of the medium and hence waves incident upon an interface of such a medium will be reflected accordingly. This invention relates to a method whereby either the velocity of propagation may be altered or the reflection and transmission coefficients at an incident interface may be altered.

The velocity of propagation for free space is given by

$$v_o=\frac{1}{\sqrt{\epsilon_o\mu_o}} \qquad (1)$$

The velocity in any particular insulator is

$$v_m=\frac{1}{\sqrt{\epsilon_o\mu_o\epsilon_r}} \qquad (2)$$

Hence the index of refraction is

$$n=\frac{v_o}{v_m}=\sqrt{\epsilon_r} \qquad (3)$$

The intrinsic impedance for free space is given by

$$\eta_o=\sqrt{\frac{\mu_o}{\epsilon_o}}=377 \text{ ohms} \qquad (4)$$

For a particular insulating medium

$$\eta_m\sqrt{\frac{\mu_o}{\epsilon_o\epsilon_r}}=\frac{377}{\sqrt{\epsilon_r}} \qquad (5)$$

The reflection coefficient at the interface between η_o and η_m but looking into η_m is

$$q_E=-q_H=\frac{1-\sqrt{\epsilon_r}}{1+\sqrt{\epsilon_r}} \qquad (6)$$

The transmission coefficient at the interface between η_o and η_m but looking into η_m is

$$p_E=\frac{2}{1+\sqrt{\epsilon_r}} \qquad (7)$$

$$p_H=p_E\sqrt{\epsilon_r} \qquad (8)$$

Numerous artificial dielectric media have already been proposed. One was suggested by Lindeman in Ann. D. Phys., volume 63, No. 7, pages 621 through 644, December 1, 1921. Other more recent media were described by W. E. Kock in the Bell System Technical Journal, volume 27, No. 1, pages 58 through 82, January 1948.

One form of artificial medium comprises a number of resonators suspended in space. These resonators may be spheres of appropriate diameter or they may be discs or rectangles or simply wires of the proper length. In the latter case, the apparent dielectric constant is greatest when lines of electric force of the incident wave power lie parallel to the axis of the wire and least when they are perpendicular thereto. The apparent dielectric constant of the artificial medium depends on the number of resonators per unit volume and also on their proximity to resonance. Specifically, the dielectric constant ϵ_r is given by

$$\epsilon_r=\epsilon_o+N\alpha\frac{f_o^2}{f_o^2-f^2} \qquad (9)$$

where ϵ_o is the dielectric constant of the medium in the absence of resonators, N is the number of resonators per unit volume, α is a form factor depending on whether the resonators are spheres, discs, cylinders, or ellipsoids, f_o is the resonant frequency and f is the operating frequency. Normal operating frequencies are usually below the resonant frequency, a figure of

$$f=\frac{f_o}{2}$$

being representative. In this region, the apparent index of refraction does not vary rapidly with frequency.

It is of interest that in the vicinity of resonance, the effective dielectric constant passes rather quickly from very high values to very low values. Theoretically, at least, it may approach zero or may even assume a negative value. The possibility of using unusual values of dielectric constant in connection with this invention is fully recognized, and it is obvious that such uses will be within the spirit and scope of this invention.

The invention herewith rests not primarily in the use of suspended resonators, but rather in the use of resonators that are asymmetrical in shape and which may be rotated to a prescribed angle by any convenient means such as, for example, the superposition of an external field, either magnetic or electric. By this means it becomes possible not only to vary ϵ_r, but also to set up arrangements to vary the velocity of propagation (Equation 2), the intrinsic impedance (Equation 5), and also the reflection and transmission coefficients at any interface (Equations 6, 7 and 8).

An elemental resonator suitable for use in this special artificial medium may consist of an equilateral parallelogram cut from sheet metal and suspended on an axis perpendicular to the principal plane. Alternatively, the resonant element may be an ellipse. The ratio of the lengths of the major and minor axes of the rectangular or elliptical figure determines the degree of asymmetry. By "asymmetry" is meant a lack of symmetry about an axis perpendicular to the plane of the element resulting in a configuration having axes of unequal length in the plane of the element. A representative ratio is two, but the ratio may be as much as four or more. A better understanding of the invention will best be gained, however, from a consideration of the following description given in connection with the accompanying drawings, in which

Figs. 1A and 1B show plan and side views of a resonator forming a part of the invention;

Figs. 2A and 2B show plan and side views of a housing for the resonator of Fig. 1;

Figs. 3A, 3B and 3C show alternative shapes for the resonator shown in Fig. 1;

Figs. 4A and 4B show two states of the same medium utilizing a number of individual resonators;

Fig. 5 shows an illustrative means for orienting the resonator of Fig. 1;

Fig. 6 refers to means for rotating elemental resonators;

Fig. 7 shows a structure by which the coefficients of reflection and transmission may be varied;

Fig. 8 shows schematically how Fig. 7 may be used to switch wave power;

Figs. 9A and 9B show an application of my invention to prism refractors; and

Figs. 10A and 10B show an application of my invention to wave lenses for varying the focal length of the lens.

Referring now in particular to the drawings where, by way of example, a particular embodiment of the invention is shown in Figs. 1A and 1B, a metal resonator **11** is mounted on a thin rod or axle **12** which serves as an axis of rotation. For resonator **11**, iron is a preferred material but only for the reason that iron elements may easily be rotated to any desired angle merely by impressing a suitable external magnetic field. In order to reduce the high frequency resistivity of the iron it may be plated with copper or silver. Rod **12** should preferably be a low-loss insulator of relatively low dielectric constant. The metal resonator complete with axle is then mounted in a thin pill-box compartment **13** provided with bearings **14** for supporting the axis of the element as illustrated in Figs. 2A and 2B. The two-piece compartment is made of a thin walled moulding compound of low dielectric loss such as polystyrene and is so designed that it can be made very cheaply on a quantity production basis. The finished element, consisting of resonator, axis and support, when assembled, closely resembles an ordinary pocket compass except in this case the needle need not necessarily be permanently magnetized. These elements are mounted in close proximity to one another in a thin layer of polyfoam as suggested by Figs. 4A and 4B. A number of these layers stacked together constitute the artificial dielectric medium.

Alternate designs for the resonator include conductors other than iron and also insulators. If insulators are used the dielectric constant should preferably be very high, in which case the elements may be brought to their proper orientation by the superposition of a strong electric field. It is of interest that the above principles apply also to the case where conditions in the artificial medium are reversed. More particularly, my invention applies to an artificial medium in which elements of low dielectric constant are suspended in a medium which would otherwise have a high dielectric constant. Alternate shapes for resonator **11** are shown in Figs. 3A, 3B and 3C.

The length of the resonator **11** suggested above is not critical. For a wavelength of ten centimeters, it may, for example, be of the order of 2.5 centimeters or approximately one inch. For shorter wavelengths, the metal element should be proportionately smaller. If the conducting element is coated with a medium of high dielectric constant the conductor may be made still smaller.

In a suggested embodiment of this invention, the elements **11** are suspended in space with their axes of rotation parallel to the direction of wave propagation. For best effect these elements should be in close proximity to one another. They may be arranged in plane layers, such as the layer shown in Figs. 4A and 4B. These figures show two conditions (*a*) and (*b*) which represent two opposite orientations of the resonators in a layer relative to the electric vector E in the incident wave power.

In the first case (*a*), the electric vector E lies parallel to the major axis of each aligned resonator and in this condition between the tips of the resonators there is a dense concentration of lines of electric force. Though this represents an instantaneous state as the wave passes, it nevertheless corresponds to stored electrostatic energy, or, more accurately, added electric displacement density D relative to the applied electric intensity E. Accordingly, the effective dielectric constant

$$\epsilon_1=\frac{D_1}{E}$$

is greater on the average than that for the space without resonators.

In the second base (*b*), the electric vector E lies perpendicular to the major axis of each aligned resonator and in this case the tips across which lines of electric force reside are now more widely separated. Thus, the stored energy between tips is less than before and accordingly the effective dielectric constant

$$\epsilon_2=\frac{D_2}{E}$$

is now less. The effective dielectric constant of the medium may therefore be altered merely by changing the orientation of the individual resonators by any convenient means. It should be obvious that if the resonators are oriented to an angle intermediate between that shown in condition (*a*) and that in (*b*) the effective dielectric constant will be altered accordingly. This constant may be expected to vary more or less in accordance with the cosine of the angle. It will be seen that the two values of the dielectric constant ϵ_1 and ϵ_2 depend on the ration of the major and minor axes of the parallelogram which comprises the resonator **11**. In the extreme case in which the needle is a slender wire, ϵ_2 may be relatively small and the ratio of ϵ_1 to ϵ_2 may be correspondingly large.

The discussion above centers about a single layer in the medium. As already indicated, the composite medium may consist of a multiplicity of such layers. As should be evident, the over-al medium may be shaped to fit a wide range of conditions. For example, it may be made in the shape of a prism for bending a narrow portion of the wave front. Alternatively, it may be made into a lens for bringing a plane wave to a focus or it may be made cylindrical for use in a wave guide. In the latter case in particular, it becomes possible to taper the dielectric constant on either side so that there will be no abrupt discontinuity and accordingly no serious reflection from either face. A number of uses for this type of an artifical medium suggest themselves. Others, less obvious, will be described below.

If a cylinder of this artificial dielectric is placed in a cylindrical wave guide carrying the dominant type of wave and the active elements or resonators are randomly oriented relative to the electric vector of the advancing wave, the two equal components into which incident wave power may be regarded as resolved will be slowed up by substantially the same amount and hence the wave will remain plane-polarized. If, however, the active elements are aligned by any suitable means there are produced a variety of effects as follows.

If the elements are aligned along the electric vector of the advancing wave, the wave will travel with a velocity of

$$v_1=\frac{k}{\sqrt{\epsilon_1}}$$

where k is a constant depending on the units chosen. Hence, by properly adjusting the length of the medium, any desired phase difference may be introduced relative to that that would have prevailed had no medium been introduced.

If the elements are aligned in a direction perpendicular to the electric vector, the wave will travel with a velocity

$$v_2=\frac{k}{\sqrt{\epsilon_2}}$$

Hence for the same length as above there will be a different phase delay.

If the elements are aligned 45 degrees relative to the electric vector the two components will travel with different velocities v_1 and v_2 and by a suitable choice of lengths, any degree of ellipticity in polarization may be achieved including linear and circular polarization. It is particularly significant that having established a given state of polarization, say circular, it is possible to rotate the individual resonators to produce other degrees of ellipticity including horizontally plane-polarized waves and vertically plane-polarized waves.

If instead of a circular guide a rectangular guide is used and the latter is proportioned so as to propagate but one component wave, then the transmitted wave will always be plane-polarized with its electric vector parallel to the short side of the guide. The velocity of this single wave will be varied as the elemental resonators are rotated. Also the longitudinal impedance of the guide may be varied and substantial reflection effects may be produced.

Fig. 5 shows a convenient means for orienting resonators **11** in the event these resonators are made of magnetic material. The means illustrated here consists of two pairs of electromagnets N_1—S_1 and N_2—S_2 aligned with respect to each other so that two steady-state orthogonal magnetic fields can be generated in the region surrounded by the magnets. By varying the strength of these fields any desired orientation of the magnetic resonators can be obtained. It should be understood, however, that in the event resonators **11** are non-magnetic, other suitable means for rotating them shall be used in place of this magnetic means.

Figure 6 shows a waveguide containing a matched section of artificial dielectric of the kind already described. The medium is now surrounded by two orthogonally placed pairs of magnets **15**, **15** and **16**, **16** as before but this time they are energized by a two-phase alternating magnetic field in such a way that the assemblage of elemental resonators rotates in space. The rate of rotation is numerically equal to the frequency of the two-phase energizing current. Alternatively, three-phase alternating fields may be used in accordance with standard engineering practice. Rotation of the resonators may also be accomplished by transmitting through the medium circularly polarized electromagnetic waves, the wave itself causing the rotation. Such a method of rotation lends itself to effecting the transmission of waves other than high frequency electromagnetic waves, thus effects on the transmission of sound waves may be accomplished. It is significant that the rotating configuration of resonators may be used to rotate the plane of polarization of any plane-polarized waves that may be passing through the medium.

It was shown many years ago that a plane-polarized wave is equivalent to two circularly polarized waves, one rotating clockwise and the other counter-clockwise. When these two components pass through the rotating medium described above, one is speeded up in its rotation while the other is retarded. Upon recombination after passing through a given length of such a rotating medium, the resultant appears to have been rotated in space. This method of rotating the plane of polarization is somewhat analogous to the mechanism believed to be operative in the so-called ferrites. Thus the rotation effects observed are nonreciprocal in their behavior and like the ferrites they make possible a large variety of useful circuit elements.

Thus far the above methods have been described as though they were applicable only to transverse electromagnetic waves. In most practical cases it is difficult in artificial dielectric media to spin the elemental resonators sufficiently fast to produce an appreciable rotation in the plane of polarization. It seems reasonable, however, to expect that with improvement this difficulty may be corrected.

It is of interest that by substituting for the very fast-moving electromagnetic waves the much slower moving waves of sound the plane of polarization may be rotated even with the above-described apparatus in its present state of development. Ordinarily, sound waves in fluids have no transverse components either of pressure or particle-velocity but when confined to pipes there may be set up, as the resultants of multireflections of zig-zag compression waves, very substantial transverse components. It is these waves that are utilized in the method here described. It is of interest that we may transmit through the medium circularly polarized electromagnetic waves and use these to rotate the resonators thereby rotating the plane of polarization of any transverse sound waves that may be present. An alternate method of rotating the plane of polarization of a transverse sound wave was described by W. E. Kock, application Serial No. 323,175, filed November 29, 1952.

The foregoing disclosure illustrates how variations in the effective dielectric constant of the medium may be varied to modify the velocity of propagation. In this case it was recognized that reflections may take place at the incident interface but suitable tapering was invoked as a means of keeping this to a minimum. Techniques for accomplishing this result are well known and need not be reviewed at this time. We now consider cases where we make a virtue of reflection losses. More particularly we use the change in effective dielectric constant as described above as a means of varying the intrinsic impedance of the medium and hence the reflection coefficient at its interfaces.

I show as Fig. 7 a section of waveguide **17** containing a plug **18** of artificial dielectric of the kind described above. It is assumed that the reflecting interfaces corresponding to the two ends of the plug are each plane surfaces perpendicular to the axis of the guide. It is further assumed that the unit resonators may be oriented as desired by a mechanism like that already shown in Fig. 5. If the resonators are oriented to give an effective dielectric constant ϵ_2 corresponding to the lower of the two limits available, it may be expected to produce an appreciable reflection coefficient at the two interfaces. If this is undesirable, it may be cancelled by introducing near each end an iris diaphragm **19**, **19** of suitable diameter and spacing. Under this condition the coefficient of transmission will be substantially unity.

If next we reorient the elementary resonators to produce the higher dielectric constant ϵ_1, then a very substantial reflection coefficient will appear, and the coefficient of transmission will be reduced accordingly. Since reflections take place from both ends of the plug we should preferably adjust the length of the plug so that the two reflected components appear on the incident side in the same phase. This favorable condition will obtain when the length of the plug is equal to an odd number of quarter waves.

It will be evident that circuit components like that just described are, in effect, wave switches and they may be used in a variety of ways. One simple example is illustrated in Fig. 8 where wave power from a guide A is transferred in any desired proportion to either guide B or guide C. To effect this transfer, units like that just described are placed in arms B and C with their control circuits so wired that one unit opens as the other closes.

Figures 9A and 9B are illustrative of an application of this invention to a refracting prism 21, whereby the refractive effects of the prism may be varied. In Fig. 9A, the elements 11 are shown oriented with respect to the electric vector of the incident wave in such a manner as to have a large index of refraction. That is, the dielectric constant of the medium, i. e., prism, is a maximum and the incident wave will undergo a change in direction as shown. If it is desired to decrease the refractive effect, the elements 11 may be rotated in any suitable manner to vary the dielectric constant in the manner hereinbefore described. Fig. 9B shows the elements 11 rotated to the position where the dielectric constant of the prism, and hence the index of refraction, is at a minimum.

The same principles of operation may be utilized in the case of a lens or focusing element 22 to vary the focal length thereof. Fig. 10A shows the elements 11 in the short focal length position for a converging lens, that is, the refractive index is greatest. The focal length may be increased to a maximum as shown in Fig. 10B by rotation of the elements 11, in the same manner as discussed in connection with Figs. 9A and 9B. An interesting fact to be noted with respect to Figs. 10A and 10B is that a continuously variable focal length lens may be had by application of a rotating magnetic field.

The above description is given in illustration and not in limitation of the invention. It should be understood in particular that the shapes and spacings of the individual resonators are not limited to those shown but may include others as well. It should be understood also that while described in connection with transverse electromagnetic waves, this method applies quite generally to all types of wave motion including particularly sound waves propagated through fluids enclosed in pipes having rigid walls. Various changes and modifications in the invention and in the ways of utilizing it will occur to those skilled in the art and these changes or modifications may be made without departing from the spirit or scope of the invention as set forth in the appended claims.

What is claimed is:

1. An electromagnetic wave transmission medium comprising one or more layers of composite material and having a dielectric constant, each of said layers including a number of individual rotatable elements lying substantially in a plane and spaced apart therein, each element having an axis of rotation perpendicular to said plane, each element formed by a piece of material having an asymmetrically shaped surface perpendicular to the direction of wave propagation through said medium, and means for orienting each of said elements relative to the electric field of a wave propagating through said medium whereby the effective dielectric constant of said medium can be varied in accordance with a signal.

2. An electromagnetic wave transmission medium as claimed in claim 1 in which at least some of said elements are thin diamond shaped pieces of magnetic metal.

3. An electromagnetic wave transmission medium as claimed in claim 1 in which at least some of said elements are thin pieces of high dielectric constant insulating material.

4. An electromagnetic wave transmission medium as claimed in claim 1 in which the individual elements in each layer are uniformly spaced apart.

5. An electromagnetic wave transmission medium as claimed in claim 1 in which the ratio of length to width of at least some of said elements is greater than one.

6. An electromagnetic wave transmission medium as claimed in claim 1 in which at least some of said elements are elliptically shaped.

7. An electromagnetic wave transmission medium as claimed in claim 1 in which each of said layers of composite material is spaced from an adjacent layer of said material in the direction of wave propagation.

8. An electromagnetic wave transmission medium comprising one or more layers of composite material and having a dielectric constant, each of said layers including a number of rotatable elements lying substantially in a plane and spaced apart therein, each element having an axis of rotation perpendicular to said plane, each element formed by a piece of material having an asymmetrically shaped surface perpendicular to the direction of wave propagation through said medium, and means comprising a magnetic field for orienting each of said elements relative to the electric field of a wave propagating through said medium whereby the effective dielectric constant of said medium can be varied in accordance with a signal.

9. An electromagnetic wave transmission medium as claimed in claim 8 in which the magnetic field is a continuously rotating field.

10. An electromagnetic wave transmission medium for altering the direction of propagation of wave energy incident thereupon comprising a prism shaped member of composite material having a dielectric constant, said material comprising a plurality of asymmetrically shaped rotatable elements having axes of rotation parallel to the direction of wave propagation through said prism, and means for variably orienting said elements relative to the wave energy whereby the index of refraction of said prism is varied.

11. An electromagnetic wave transmission medium for focusing wave energy incident thereupon comprising a convex lens shaped member of composite material having a dielectric constant, said material comprising a plurality of asymmetrically shaped rotatable elements having axes of rotation parallel to the direction of wave propagation therethrough, and means for variably orienting said elements relative to the wave energy whereby the focal length of the lens shaped member is varied.

12. An electromagnetic wave transmission medium according to claim 11 wherein the means for variably orienting said elements comprises a continuously rotating magnetic field whereby the focal length of the lens shaped member is continuously varied.

13. A composite dielectric member including a plurality of asymmetrically shaped resonators of the order of one-quarter wavelength long spaced apart from one another and oriented in such a manner as to produce in said member an effective dielectric constant greater than one, and means for varying the orientation of said resonators whereby the dielectric constant of said member may be varied.

14. A wave propagation medium comprising one or more layers of composite material and having a propagation constant, each of said layers including a number of individual rotatable elements lying substantially in a plane and spaced apart therein, each element having an axis of rotation perpendicular to said plane, each element formed by a piece of material having an asymmetrically shaped surface perpendicular to the direction of wave propagation through said medium, and means for orienting each of said elements whereby the effective propagation constant of said medium can be varied.

15. A wave propagation medium comprising one or more layers of composite material and having a propagation constant, each of said layers including a number of individual rotatable elements lying substantially in a plane and spaced apart therein, each element having an axis of rotation perpendicular to said plane, each element formed by a piece of material having an asymmetrically shaped surface perpendicular to the direction of wave propagation through said medium, and means comprising

a magnetic field for orienting each of said elements whereby the effective propagation constant of said medium can be varied.

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