United States Patent

[11] 3,631,501

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Berkeley, Calif.
[21] Appl. No. 11,712
[22] Filed Feb. 16, 1970
[45] Patented Dec. 28, 1971
[73] Assignee General Dynamics Corporation

[54] **MICROWAVE PHASE SHIFTER WITH LIQUID DIELECTRIC HAVING METALLIC PARTICLES IN SUSPENSION**
31 Claims, 13 Drawing Figs.

[52] U.S. Cl. .... 343/754, 343/854, 343/872, 343/909, 333/31 A, 333/98 P
[51] Int. Cl. H01q 19/06
[50] Field of Search .... 343/753, 754, 755, 909, 910, 911, 854, 872; 333/31, 31 A, 778, 98 P

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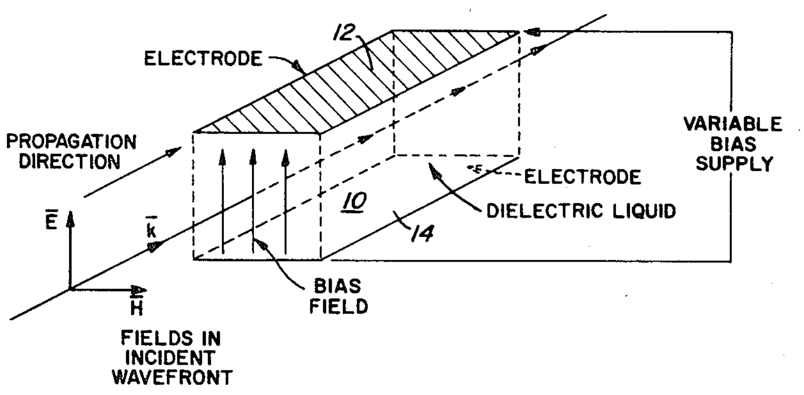
ABSTRACT: Microwave phase shifters and electronic beam steering antennas are described which use an electrically controllable anisotropy dielectric medium in the microwave beam path.



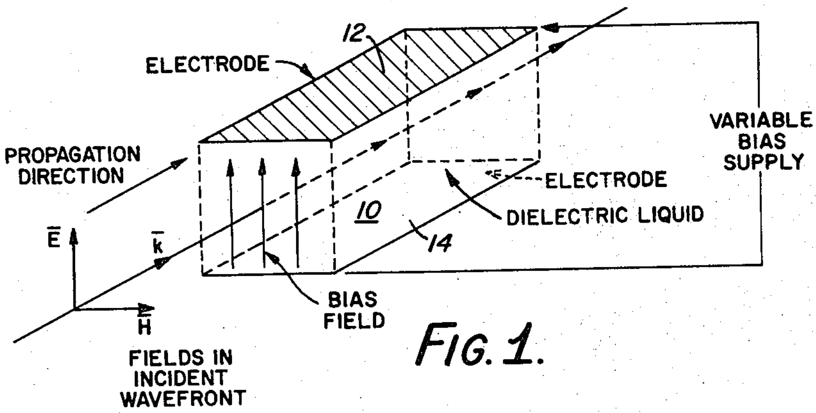


FIG. 1.

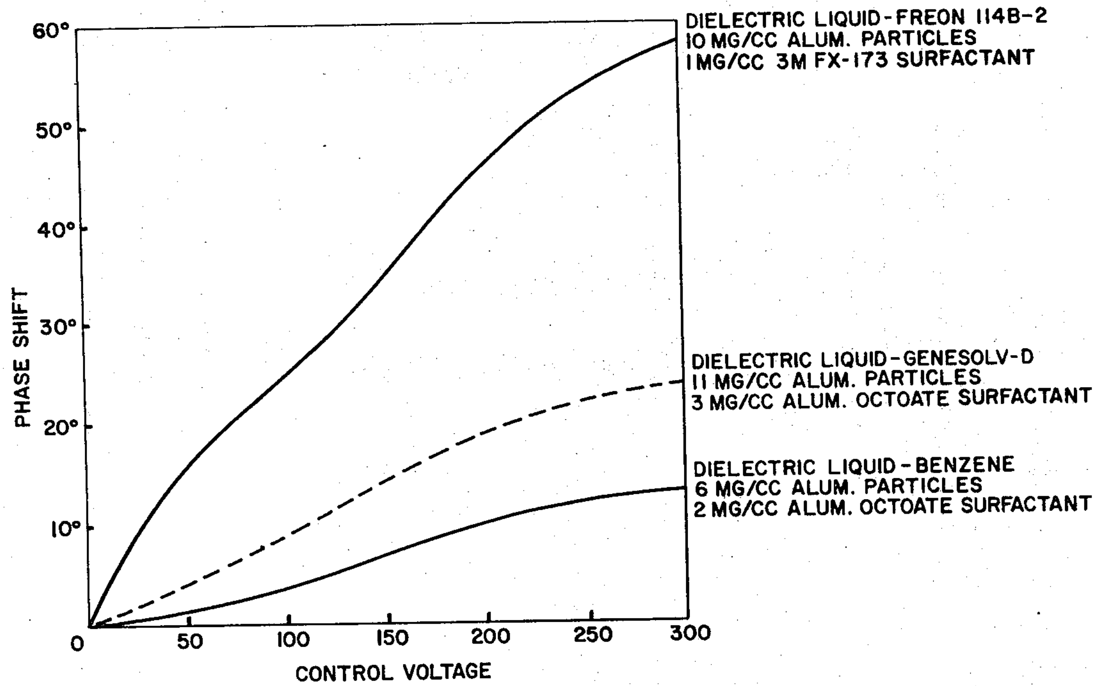


FIG. 2.

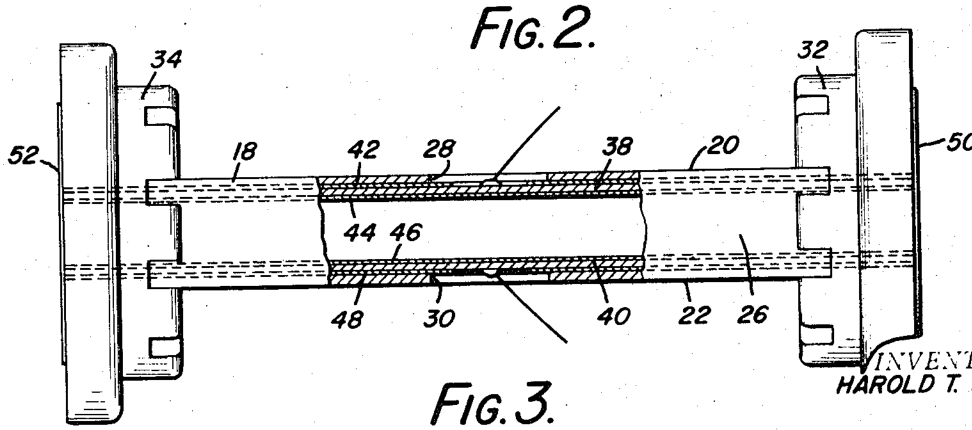


FIG. 3.

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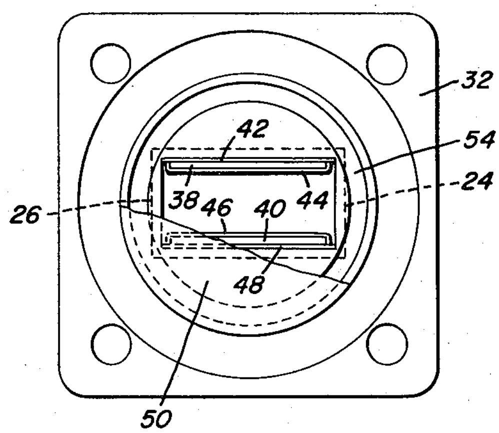

FIG. 4.

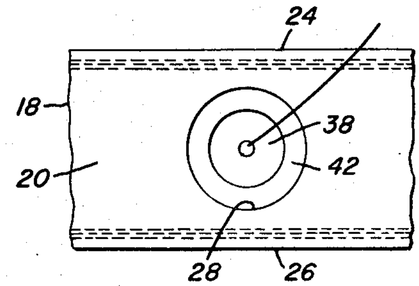

FIG. 5.

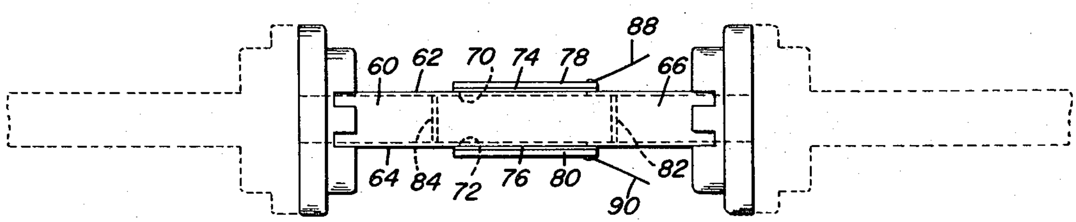

FIG. 6.

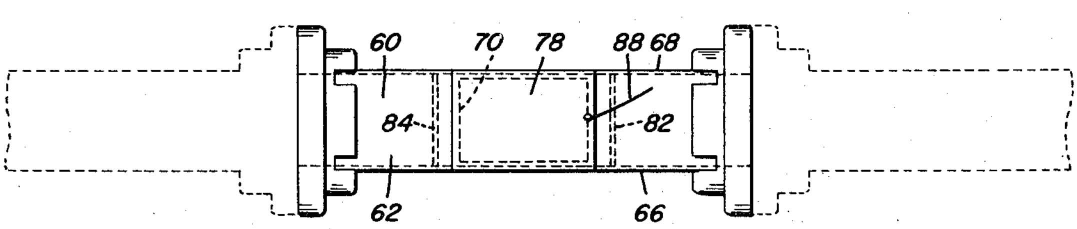

FIG. 7.

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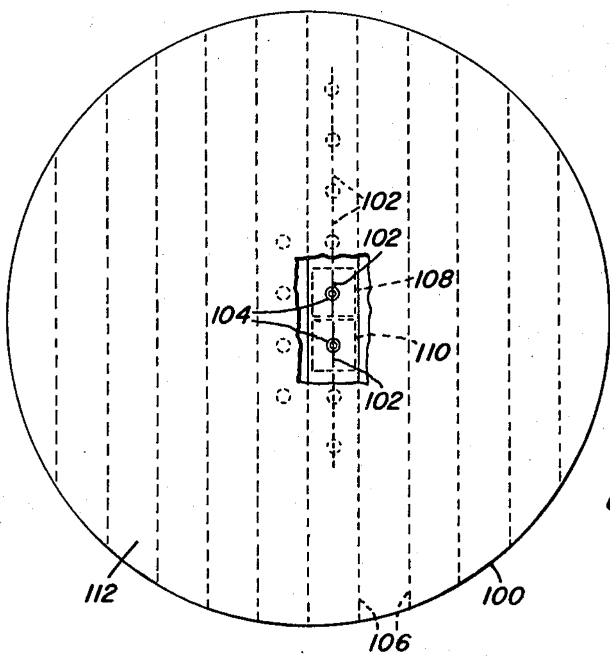

FIG. 10.

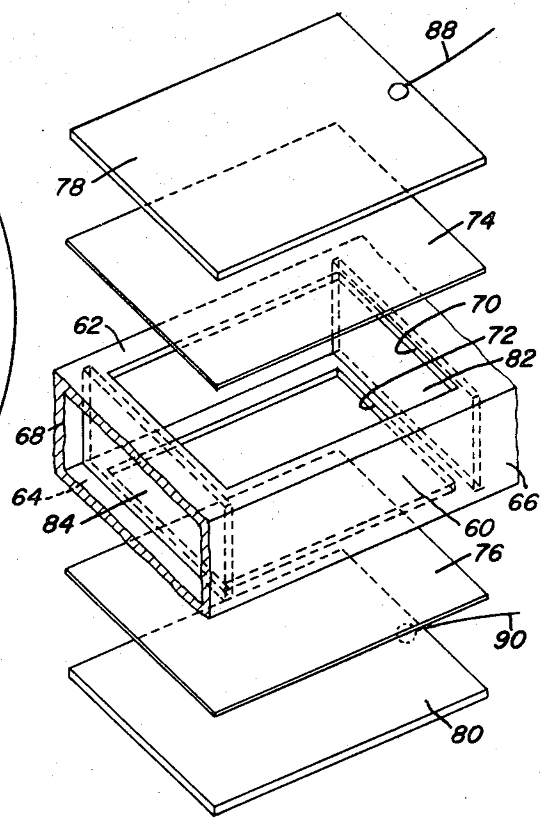

FIG. 8.

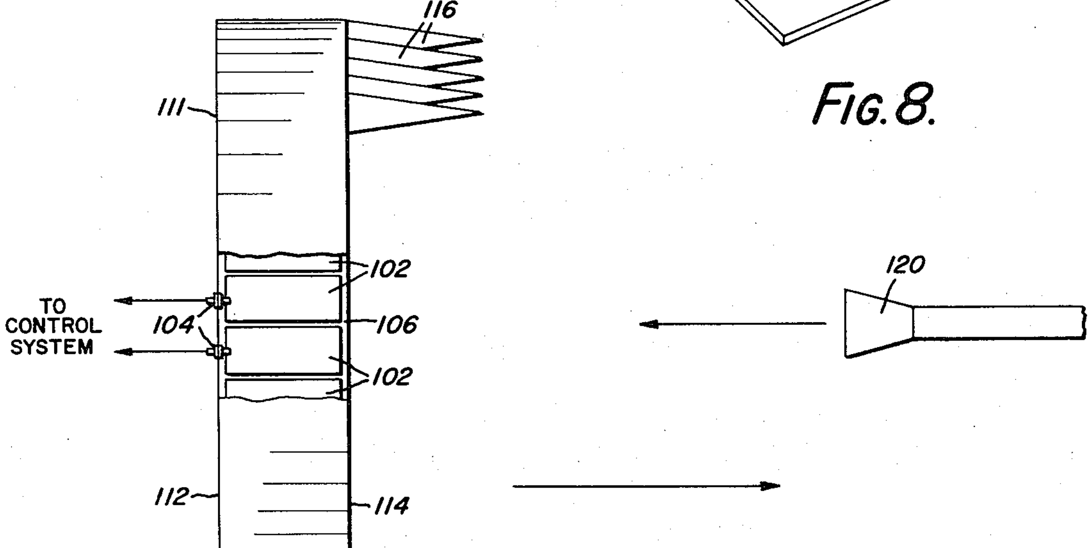

FIG. 9.

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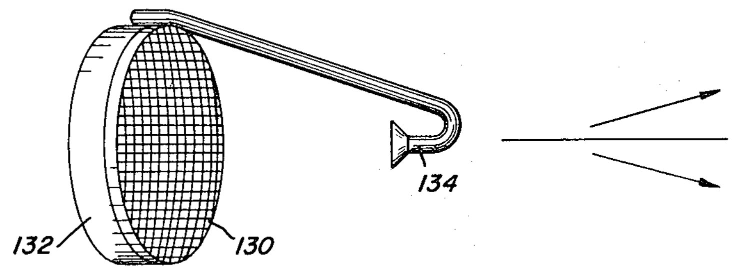

FIG. 11.

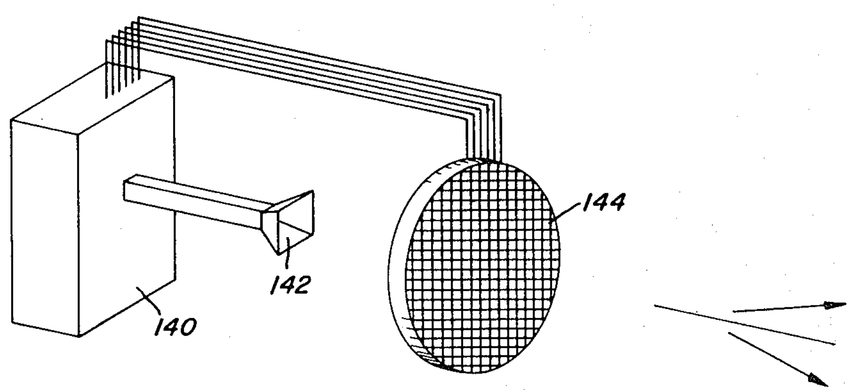

FIG. 12.

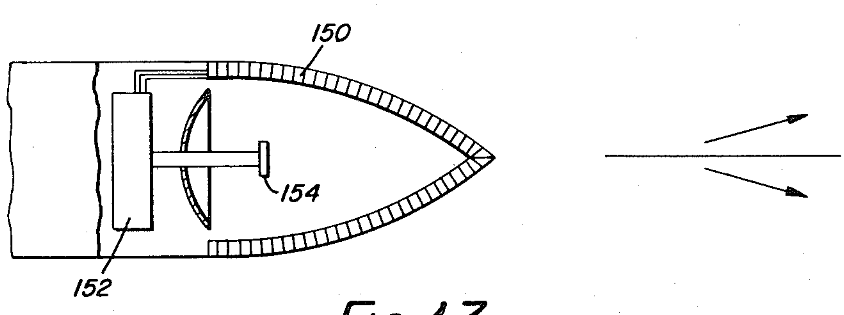

FIG. 13.

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MICROWAVE PHASE SHIFTER WITH LIQUID DIELECTRIC HAVING METALLIC PARTICLES IN SUSPENSION

The present invention relates to microwave components and particularly to an electro-optical control system for microwaves.

The present invention is especially suitable for use in electronic beam steering antennas such as may be used in airborne radar systems. The invention is also suitable for providing microwave phase shift components. Aspects of the invention will be generally applicable for other microwave control purposes.

Conventional means for the control of microwave energy to provide phase shift and electronic beam steering are subject to several limitations. Devices which use ferrite phase shift elements as exemplified by the beam steering array described in U.S. Pat. No. 3,305,867, issued Feb. 21, 1967, to A. R. Miccioli and Donald H. Archer, are heavy and there are limitations upon power handling capacity, as well as accuracy of angular control over beam direction. The cost of such conventional equipment is also high.

Attempts to use other means have also not been entirely successful. Ionizable gases are suggested in U.S. Pat. No. 3,404,401, issued Oct. 1, 1968, to M. Arditi. Such devices require a high amount of power to maintain the gas discharge. Heating of the device proscribes its use in many applications. In addition, the electron discharge absorbs much of the microwave energy which it is intended to control.

A mechanical device using movable resonators is described in U.S. Pat. No. 2,840,820, issued to G. C. Southworth on June 24, 1958. Devices which use mechanical resonance have a limited frequency range, and usually require bearings and the like, which are difficult, if not impossible to fabricate in production.

Accordingly, it is an object of the present invention to provide improved apparatus for electro-optical control of microwave energy.

It is a further object of the present invention to provide improved electro-optical apparatus for the control of microwave energy which is readily adaptable to provide beam steering of radar beams.

It is a still further object of the present invention to provide an improved electro-optical phase shifter for microwave energy.

It is a still further object of the present invention to provide improved apparatus for electro-optical control of microwave energy which is not affected by the microwave energy which it is intended to control.

It is a still further object of the present invention to provide an improved electro-optical beam steering antenna which has fast response and therefore provides a rapid scan of the microwave beam.

It is a still further object of the present invention to provide an improved electro-optical beam steering antenna and phase shifting devices which are capable of handling high microwave power.

It is a still further object of the present invention to provide improved electro-optical apparatus for microwave control purposes which is lighter in weight and may be fabricated at lower cost than conventional apparatus which has been provided for the purpose.

It is a still further object of the present invention to provide an improved electro-optical microwave control system which does not use mechanically movable parts.

It is a still further object of the present invention to provide improved electro-optical microwave control apparatus which has low power consumption and does not absorb significant amounts of the microwave power which it controls.

It is a still further object of the present invention to provide a reciprocal electro-optical microwave control apparatus.

Briefly described, a microwave energy control component provided in accordance with the invention makes use of a dielectric medium having electronically variable anisotropic permittivity. This medium is inserted in the microwave signal path and is electronically controlled to vary the propagation velocity of the microwave energy. Thus, it produces a phase shift or delay. An array of cells including the dielectric medium which is disposed in the path of a microwave beam may be controlled to steer the beam on transmit or to steer the directional response on receive so that an electronic scanning antenna is provided. More particularly, the dielectric medium may contain conductive particles having a normally random orientation which normally renders the medium isotropic. When an electric field is applied to the medium, the particles polarize and align their long axis with the control field, thus changing the path permittivity of the medium in the control field direction (viz the medium is made anisotropic). The degree of statistical alignment and therefore the change in permittivity is related to the strength of the control field. The microwave energy itself does not disturb the particle alignment because the inertia of the particles and the viscosity of the medium in which they are suspended is such that the particles can not respond to the high-frequency microwave energy, especially when that energy is in pulse form (viz, pulses of less than 500 microsecond duration).

The invention itself, both as to its organization and method of operation, as well as additional objects and advantages thereof will become more readily apparent from a reading of the following description in connection with the accompanying drawings in which:

FIG. 1 is a diagrammatic view of a microwave energy control cell provided in accordance with the invention, the view illustrating in perspective the basic geometry of the cell;

FIG. 2 is a graph showing the phase shift characteristics of a cell of the type illustrated in FIG. 1;

FIG. 3 is a side view of a section of microwave waveguide, the guide being broken away to illustrate the apparatus contained within the waveguide which provides a microwave phase shifter in accordance with the invention;

FIG. 4 is a end view of the waveguide shown in FIG. 3, partially broken away to illustrate the phase shifting elements in greater detail;

FIG. 5 is a fragmentary top view of the device shown in FIG. 3;

FIG. 6 is a front view of a microwave phase shifter in accordance with another embodiment of the invention;

FIG. 7 is a top view of the phase shifter shown in FIG. 6;

FIG. 8 is an exploded view, fragmentarily showing the phase shifter shown in FIGS. 6 and 7;

FIG. 9 is a front view of an electronic beam steering antenna provided in accordance with the invention, the view being broken away to better illustrate the internal construction thereof;

FIG. 10 is a left side view of the antenna shown in FIG. 9, also partially broken away to illustrate the internal construction thereof;

FIG. 11 is a perspective view of a beam steering antenna similar to the antenna shown in FIG. 9 which is provided in accordance with another embodiment of the invention;

FIG. 12 is a perspective view of another beam steering antenna which is provided in accordance with another embodiment of the invention; and

FIG. 13 is a left side view partially broken away to illustrate a radome structure which also provides a beam steering antenna in accordance with another embodiment of the invention.

Referring more particularly to FIG. 1, there is shown a cell **10** filled with a dielectric medium and having a pair of control electrodes **12** and **14** on opposite sides thereof. These electrodes define the area of the cell. The cell controls the phase shift of a microwave signal which is illustrated as a TEM-mode signal. The vector $\overline{k}$ is the direction of propagation of the signal. The $\overline{E}$ and $\overline{H}$ vectors of the signal are also illustrated. A variable voltage bias source is connected to the electrodes **12** and **14** so as to produce and establish a bias or control field. Note that the field direction is parallel to the direction of the $\overline{E}$ vector of the microwave signal.

The dielectric medium may be a dielectric liquid which fills the cell. The liquid contains conductive particles which are desirably microscopic in size and are also desirably asymmetrical in shape (e.g., needles or discs). The properties of the suspension (its mass density, viscosity, loss tangent and dielectric constant) determine, together with the strength of the bias field, the phase shift or delay produced by the cell. The bias field may be a DC field; however, an AC field is much more preferable. This field may have a frequency which is very low as compared to the frequency of the microwave energy. Suitable frequency for the AC control field is 20 kHz. Among the features of the device are:

1. Lightweight, both as to the device itself and the circuitry which controls it.
2. Relative simplicity and low cost.
3. Reciprocity for at least one polarization of the microwave signal.
4. Electrostatically controllable with very low control power consumption.
5. Substantially independent of temperature, humidity and stray magnetic fields.
6. High efficiency and low insertion loss, even at high microwave frequencies (e.g., K,u-band frequencies and higher), since a negligible amount of microwave energy is absorbed in the cell.
7. Capability to provide 360° phase shift control.
8. Readily and continuously adjustable throughout its control range.
9. Rapid response time.
10. Capability of handling very high power (e.g., several hundred kilowatts per square centimeter power loading).
11. Inert chemically, so that it is fireproof and does not release toxic gases or liquids.

The characteristics of the dielectric medium in the cell shall now be considered. In a preferred form of the invention, the dielectric medium is a suspension in a base liquid which is nonpolar, has substantially zero conductivity and low permittivity. The suspended particles are conductive material. They may be needles or filaments 2 microns in diameter and 200 microns long (the dimensions being given here solely for purposes of illustration). The particles may also be discs, which configuration is presently preferred. Thus, the particles are small as compared to a wavelength of the microwave energy. Under quiescent conditions, the particles are randomly oriented so that the suspension is statistically isotropic. The apparent permittivity of the suspension may be calculated approximately in accordance with the following equation:

$$\epsilon' = \epsilon_0 + \frac{\epsilon_0 N \alpha_e}{1 - \alpha_e C}$$

where ϵ' is the apparent permittivity

ϵ_o is the permittivity of free space

α_e is the dipole polarizability of each particle, and

N is the particle number density

For highly-conductive particles which are right circular cylinders, 200 microns long and 2 microns in diameter, and for a liquid which has a dielectric constant of 1.85, the value of N required to provide 360° phase control over a 3-cm. path length is 3.3×10^4 per cubic centimeter. For particles, such as silicon carbide whiskers having mass density of 3.12, the number of particles necessary to satisfy the foregoing value of N weighs 0.67 mg. It will therefore be apparent that the cell may be extremely light in weight and yet will provide a large amount of phase control.

The viscosity of the liquid is an important criteria. It is important that the particles not be affected by the microwave energy, while they at the same time have rapid response to the bias field. A 0.8 centistoke liquid viscosity has been found suitable. The rotational viscous drag due to the liquid is essentially negligible for field intensities of the bias field of approximately 1 kilovolt per centimeter. The response time is therefore rapid. Rotation of the particles (in response to the field) to any desired orientation can be accomplished in a matter of milliseconds, even for extremely high particle densities. The viscosity mentioned above is also important since it makes the settling rate (due to gravity) of the particles extremely slow. For example, for a 0.85 centistoke viscosity, the settling rate is about 0.2 centimeters per hour. As will be explained hereinafter, the use of surfactants reduces the settling rate to a degree where it is negligible so far as operation of the system is concerned.

The chemical structure of the suspension is dictated by a need for low insertion loss (viz, low absorption of the microwave energy). It has been found that fluorocarbon liquids and some hydrocarbon liquids, such as benzene, are especially suitable. The filamentary or whisker particles of silicon carbide and boron nitride, as mentioned above, are suitable. It is, however, preferable to use microscopic discs of aluminum (viz, 1 micron diameter).

In order that the particles be extremely miscible in the liquids, a surfactant (surface-active-agent) to wet and stabilize the particles in the liquid is desirable. The liquid should be nonionic. Accordingly, the choice of surfactants is limited to those which do not release any significant quantity of ions into the liquid. Aluminum octoate has been found to be a suitable surfactant when aluminum discs are used as particles. The following table lists examples of suspensions which may be used in practicing the invention. It will be appreciated, of course, that other suspensions and dielectric mediums may be provided in accordance with the invention.

Base liquid material (mass density)	Particle material (mass density)	Surfactant (chemical name)
Genesolv-D trichlorotrifluoroethane (1.57)	200μ needles of silicon carbide (3.12)	Span 60 (sorbiton mono-stearate)
		Triton CF-10 (alkyl aryl ether)
		Triton X-405
		Naccolene "A" (modified petroleum sulfonate)
		Quaternary "O" (quaternized amine, 0)
		Cerasynt SE (glycerol and glycol stearate)
	1μ diameter aluminum discs (2.7)	Aluminum octoate
Benzine (0.88)		Aluminum octoate
		PN-430 (alkyl polyoxyethylene-amine)
		Tergitol NP-27 (alkyl phenyl polyethylene glycol ether)
FC-43 Fluorocarbon (1.88)	1μ diameter aluminum discs (2.7)	Stearic acid
Tetrabromoethane (2.96)	200μ needles of silicon carbide (3.12)	Cerasynt M (glycol stearate)
Tetrabromoethane (2.96)	200μ needles of silicon carbide (3.12)	C.P. Hall No. 123
FC-78 Fluorocarbon (1.7)	200μ needles of silicon carbide (3.12)	FC-134 (3-M Co. proprietary)

FIG. 2 demonstrates the amount of phase shift which is obtained with different dielectric media. Three curves are illustrated. The greatest amount of phase shift being obtained from the dielectric medium which is a liquid suspension of aluminum particles in a fluorocarbon (Freon 114B-2 having 10 milligrams per cubic centimeter of aluminum particles which are made miscible by the addition of 1 milligram per cubic centimeter of the 3M Company FX-173 surfactant).

Another advantage of the AC control field over DC control fields is the avoidance of net sweeping effects and convection of the particles due to the slight, nearly unavoidable traces of free ions in the liquid. The use of the low-frequency AC control fields greatly reduces such sweeping and prolongs the suspension lifetime (viz, reduces settling rate). The surfactants have an additional effect in improving the phase shift characteristics. It is believed, and this belief is expressed solely for purposes of explaining the invention and without implying any restriction to any particular theory of operation, that the surfactant produces a chemical charge micelle surrounding each particle. The higher the micelle charged density, the larger will be the achievable phase shift. Certain liquids, such as Freon 114B-2 and Genesolv-D appear to enhance the chemical charge micelle effect.

Sources of the various liquids and surfactants are as follows:

Genesolv-D is manufactured by the Allied Chemical Corp. of Los Angeles, California.

Span-60 is manufactured by the Atlas Chemical Industries of Wilmington, Delaware.

Triton is manufactured by the Atlas Chemical and Manufacturing Company of San Diego, California.

Naccolene is manufactured by the Allied Chemical Corporation of Los Angeles, California.

Freon is manufactured by the Dupont Company of Wilmington, Delaware.

FC-43 and FC-78 and FC-138 are manufactured by the 3M Company of St. Paul, Minnesota.

Katapol PN-430 is manufactured by the General Aniline & Film Corporation of New York, New York.

Cerasyant is manufactured by the Van Dyk & Company of Belleville, New Jersey.

Tergitol is manufactured by the Union Carbide Corporation of New York, New York.

Referring to FIGS. 3, 4 and 5, there is shown a waveguide microwave phase shifter in accordance with the invention. A rectangular guide section **18** is a top wall **20** and a bottom wall **22**, as well as sidewalls **24** and **26**. The wide top and bottom walls have circular openings **28** and **30** therein in alignment with each other.

Flanges **32** and **34** are connected to the guide **18** at the opposite ends thereof. These flanges afford means for connections to other sections of waveguides, as is shown in phantom in FIGS. 6 and 7. A pair of plates **38** and **40** extend the length of the guide **18**, as well as into the flanges **32** and **34**. These plates provide the control electrodes of the phase shifter and may be connected to a variable voltage source for creating the bias field. The plates are surrounded by sheets of dielectric material, **42**, **44**, **46** and **48**. The sheets **42** and **48** insulate the electrodes from the walls of the guide **18**. The sheets **44** and **46** prevent any contamination of or conduction current through the dielectric liquid which fills the guide by the metal plates **38** and **40**. Discs **50** and **52** of dielectric material which are fitted into the choke groove **54** and over the end surfaces of the flanges **32** and **34** secure the liquid in place. These discs **50** and **52** also provide windows through which the electromagnetic waves may enter the phase shifter. The sheets **40** to **48** and the windows **50** and **52** are desirably of polytetrafluoroethylene material such as of the type which is commonly known as "Teflon" sold by the E. I. DuPont DeNemours Company. The plates **38** and **40** and the waveguide walls **20** and **22** which are separated by the Teflon sheets **42** and **48** provide capacitors. These capacitors have substantially no reactance at microwave energy frequency. Accordingly, the plates **38** and **40** will be essentially at the same potential as the waveguide walls for microwave frequencies. However, at the alternating current frequencies which are used to develop the bias field, the Teflon sheets **42** and **48** provide good insulators.

The microwave phase shifter operates essentially, as was described in connection with FIG. **1**. Briefly, the particles in the suspension align themselves with the field, thereby making the suspension anisotropic and increasing its permeability, the amount of anisotropy being a function of the field intensity (viz the voltage applied across the plates **38** and **40**).

Another embodiment of the microwave phase shifter is shown in FIGS. **6**, **7** and **8**. Like the phase shifter shown in FIGS. **3-5**, this phase shifter has a flanged waveguide section **60** with a top wall **62**, a bottom wall **64** and sidewalls **66** and **68**. The top and bottom walls **62** and **64** have aligned rectangular openings **70** and **72** therein. The sheets of insulating material **74** and **76** cover these openings, but extend somewhat beyond the edges thereof. Control electrodes in the form of plates **78** and **80** of substantially the same size as the dielectric sheets **74** and **76** are placed over these sheets and secured by suitable fastening means, such as clamps (not shown), onto the guide **60**. The guide section covered by the plates **78** and **80** is sealed by windows **82** and **84** of dielectric material (e.g., Teflon), so as to define the cell which is filled with a dielectric liquid suspension containing particles, as was described in connection with FIG. **1**.

A capacitor is defined around the rim area of the plates **78** and **80**, by the rim area of the sheets **74** and **76** and the top and bottom walls the guides **62** and **64**. This capacitor has a low reactance to microwave energy; thus placing the plates **78** and **80** at essentially the same potential as the walls of the guide for microwave energy.

A bias field may be applied to the plates by way of leads **88** and **90**. The operation of the phase shifter in response to the bias field is as was described in connection with FIG. **1**.

Referring to FIGS. **9** and **10**, there is shown an electronically steerable antenna which utilizes a plurality (an array) of cells of the type shown in FIG. **1**. A container **100** which may be a Teflon shell contains these cells. The cells are formed by columns of individual control electrode plates **102** which are separated from each other and aligned in columns. The plates are thin strips of a highly conductive material, such as aluminum. Connections are made to each of the plates through feedthrough capacitors **104**.

Between the columns of plates **102** are disposed thin strips **106** of conductive material such as aluminum. Each plate and the conductive strips adjacent thereto defines a cell. Two of these cells **108** and **110** are depicted by the dash line squares in FIG. **9**.

The backwall **112** of the container **100** has a sheet of conductive material, such as a reflecting backing of copper or aluminum foil thereon. The front wall **114** of the container **100** is desirably provided with an impedance matching device **116** made up of conical dielectric rods which interface between the air and the dielectric of the phase shifters. The container is filled with a dielectric medium, such as the suspension, as described in connection with FIG. **1**.

In operation, a feed such as the horn **120** projects a beam of microwave energy toward the container **100**. This energy is matched impedance-wise to the beam scanning structure by means of the cones **116**. The beam passes into the container and the cells therein and is reflected by the foil backing **111**. The control system which is connected to the control electrode plates **102** applies different voltages to these plates, depending upon the direction in which the beam is to be steered. If necessary, a varying control potential may be applied to the plates in order to cause the beam to sweep or scan, either conically or linearly. The reflected beam, as shown by the line **122** is therefore steered in the desired direction. A computer may be used to control the voltage levels applied to various control electrode plates **102**. This computer may be similar to that described in connection with FIGS. **10** and **11** of the Miccioli et al. patent referenced above. The programmer controls voltages rather than currents, inasmuch as the beam steering device is electrostatically operated in the case of the device in FIGS. **9** and **10**.

FIGS. **11**, **12** and **13** illustrate different embodiments of the beam steering antenna in accordance with the invention. The beam steering structure **130**, shown in FIG. **11**, is disposed on a concave parabolic support 132. A feed horn 134 projects a beam of microwave energy onto the beam steering device and the beam is reflected therefrom in the manner described in connection with FIGS. 9 and 10. Inasmuch as the structure 130 is parabolic, the same control potentials as are used in steering the beam in the embodiment of FIGS. 9 and 10 will provide a conically scanned or swept but narrowly focused beam for the parabolic configuration of FIG. 11.

In FIG 12, a source of microwave energy 140 drives a feed horn 142. A beam steering device 144 which is associated with the radar equipment forming part of the source 140 is similar to that shown in connection with FIGS. 9 and 10, except that the reflecting foil backing is omitted. Accordingly, the microwave beam projected by the feed 142 passes directly therethrough. This transmission system also serves to steer the beam.

FIG. 13 shows a radome made up of a substantially conical structure 150 containing an array of cells formed by the electrode plates and strips similar to those shown in FIGS. 9 and 10. The surfaces of the strips and control electrode plates are disposed approximately perpendicular to the inner surface of the radome. A radar set 152 provided with a feed 154, projects a beam through the radome beam steering structure. This beam is steered by varying the control potentials applied to the control electrode plates thereof.

From the foregoing description, it will be apparent that there has been provided improved electro-optical apparatus suitable for microwave phase shifting and beam steering. It will be observed that the radar apparatus shown in FIGS. 9 through 13, while described in connection with a radar transmitter is equally applicable for reception of radar beams. The directivity (viz, directional response of the radar) is adjustable by controlling the beam steering device to provide a predetermined look angle, which angle can be swept across the area of interest by programming the control potentials. Other variations and modifications within the scope of the invention will undoubtedly suggest themselves to those skilled in the art. Accordingly, the foregoing description should be taken merely as illustrative and not in any limiting sense.

What is claimed is:

1. An electromagnetic wave control apparatus which comprises means containing a suspension comprising a dielectric medium having asymmetric conductive particles freely and isotropically suspended therein, the viscosity of said medium and the moment of inertia of said particles being such that the motion of said particles is substantially unresponsive to said wave when propagated therethrough, and means for changing the permittivity of said suspension for controlling the propagation of said wave therethrough wherein said permittivity charging means includes means for orienting said suspension to become anisotropic for a time which is long with respect to the frequency of said waves.

2. The invention as set forth in claim 1 wherein said time is provided by means which applies an AC field of a frequency which is low with respect to said electromagnetic wave frequency across said suspension.

3. The invention as set forth in claim 1 wherein said permittivity changing means comprises means for applying an electric field across said suspension for orienting said particles so that their longest dimension is aligned in the same direction as a component of the electromagnetic field corresponding to said wave.

4. The invention as set forth in claim 3 wherein said particles are nonmagnetic.

5. The invention as set forth in claim 4 wherein the majority of said particles are elongated in shape.

6. The invention as set forth in claim 3 wherein means are included in said field applying means for varying said field in intensity.

7. The invention as set forth in claim 4 wherein said particles are crystal whiskers.

8. The invention as set forth in claim 7 wherein said whiskers are of silicon carbide.

9. The invention as set forth in claim 4 wherein said particles are filamentary in form.

10. The invention as set forth in claim 1 wherein said medium is a nonionic dielectric liquid.

11. The invention as set forth in claim 10 wherein said liquid is somewhat viscous.

12. The invention as set forth in claim 11 wherein the viscosity of said liquid is on the order of 0.8 centistoke.

13. The invention as set forth in claim 10 wherein said liquid is principally a composition selected from the class of fluorocarbons and hydrocarbons.

14. The invention as set forth in claim 13 wherein said liquid is composed principally of a fluorocarbon.

15. The invention as set forth in claim 13 wherein said liquid is benzene.

16. The invention as set forth in claim 13 wherein said liquid includes also a surfactant.

17. The invention as set forth in claim 17 wherein said surfactant is aluminum octoate.

18. The invention as set forth in claim 10 wherein said particles have a number density of about 3.3×10^4 per cm.^{3}.

19. The invention as set forth in claim 10 wherein said particles are aluminum discs.

20. The invention as set forth in claim 19 wherein said discs are less than 1 micron in diameter.

21. A microwave phase shifter which comprises

a. a waveguide,

b. a pair of control electrodes deposited in spaced relationship opposite to each other to define a gap therebetween, said gap being located within said waveguide, said electrodes also being disposed in insulating relationship with said waveguide,

c. means for confining within said guide and in said gap a suspension of conductive particles of microscopic size in an inert viscous liquid having low permittivity, said suspension being isotropic until said electrodes provide a field across said gap for rendering said suspension anisotropic, the amount of anisotropy being related to the phase shift produced by said phase shifter.

22. The invention as set forth in claim 21 wherein said waveguide is rectangular in shape and has wide top and bottom walls and narrower sidewalls, each of said wide walls have openings therein which are opposite each other, said control electrodes being plates disposed against said wide walls and covering said openings, and sheets of dielectric material separating each said plates from their adjacent wall.

23. The invention as set forth in claim 22 wherein said plates and said sheets extend beyond the edges of said openings to define capacitive elements with the portions of said wide walls adjacent thereto, said elements having a reactance which is negligible at microwave frequencies such that said electrodes and said waveguide are at essentially the same potential at microwave frequencies.

24. The invention as set forth in claim 22 wherein said plates are disposed outside said waveguide.

25. The invention as set forth in claim 22 wherein said plates are substantially the same width as said wide walls of said guide and extend along a section of said guide longer than said guide is wide.

26. The invention as set forth in claim 22 including a pair of windows of dielectric material across the cross section of said guide on opposite sides of said gap for confining said suspension in said guide.

27. Apparatus for electrically steering a microwave beam which comprises

a. means disposed in the path of said beam containing a suspension of microscopic conductive particles in a liquid having low permittivity and predetermined viscosity such that said suspension is isotropic in the presence of said beam,

b. an array of cells in said containing means, said cells being comprised of individual control electrodes which are spaced from each other, and

c. means for applying control potentials separately to said electrodes for providing selectively variable anisotropy in different portions of said containing means whereby to steer said beam.

28. The invention as set forth in claim **27** wherein said containing means has opposite front and back surfaces disposed successively in the path of said beam, said back surface being reflective to said microwave energy and said front surface being transmissive thereto.

29. The invention as set forth in claim **28** further comprising a feed projecting said beam in a first direction into said containing means so as to enter first said front surface and then said back surface so as to be reflected therefrom in a second direction opposite to said first direction, said control means being operative to cause said beam to scan in directions transverse to said first direction whereby to provide a scanning antenna.

30. The invention as set forth in claim **27** wherein said control electrodes are plates of conductive material arranged edgewise to lie along the axis of said beam, said plates being disposed in columns with the plates in each column in alignment with each other, and strips of conductive material also disposed edgewise to lie along the axis of said beam, said strip being disposed between said columns of electrodes so that each plate and the strips on opposite sides thereof form individual ones of said cells.

31. The invention as set forth in claim **30** wherein said containing means has a conicallike form, a feed disposed to project said beam into the area circumscribed by said form along the axis thereof whereby said containing means provides a radome.

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