MICROWAVE ANTENNA ARRAY

Filed June 3, 1950 2 Sheets-Sheet 1

FIG-1

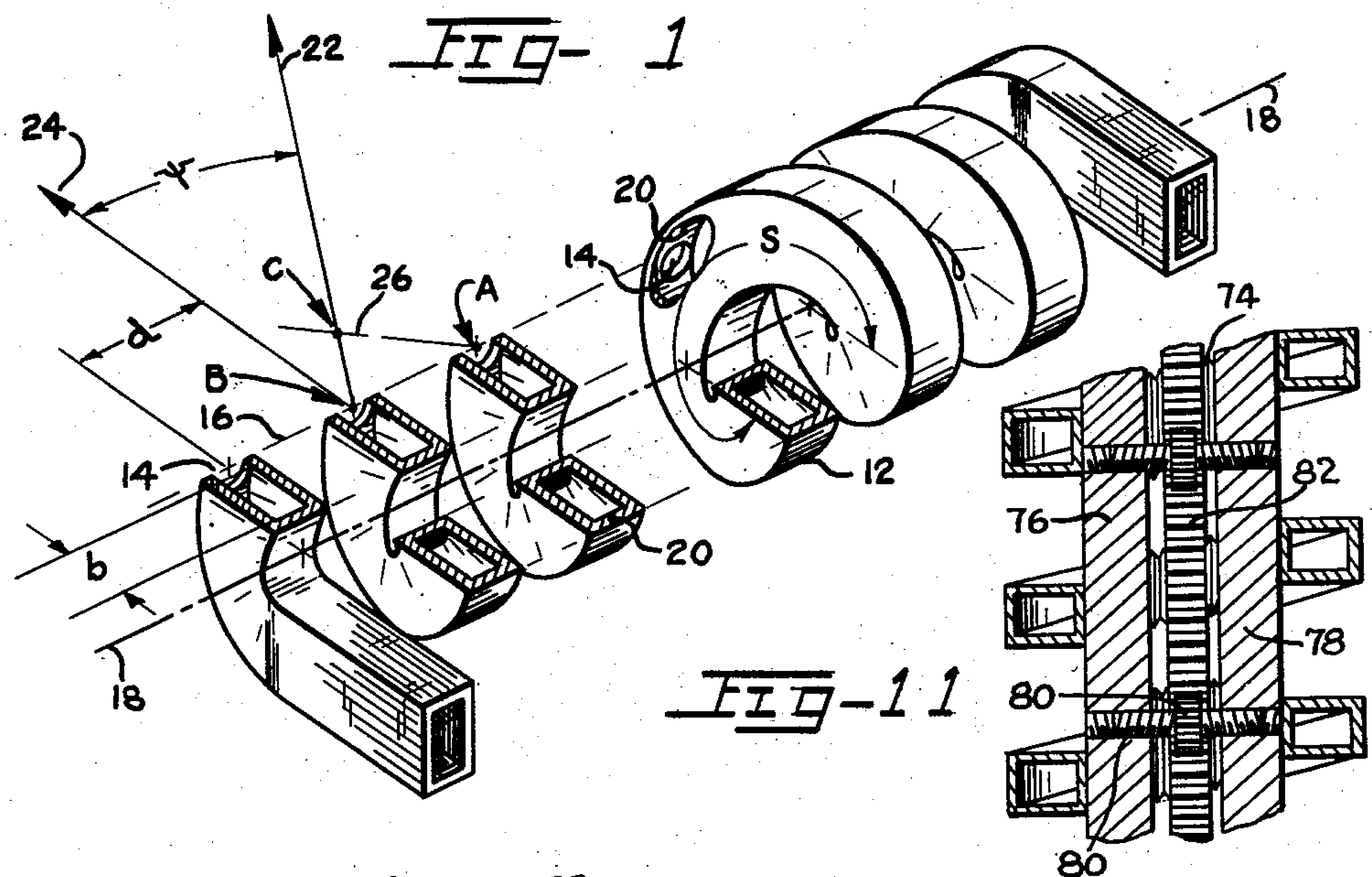

FIG-11

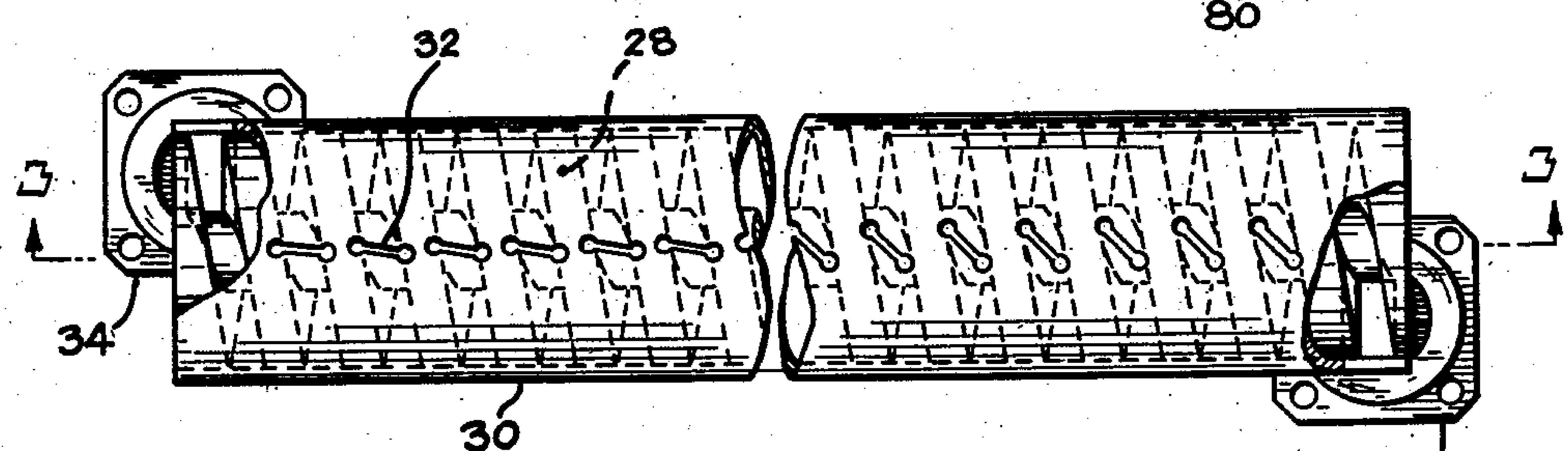

FIG-2

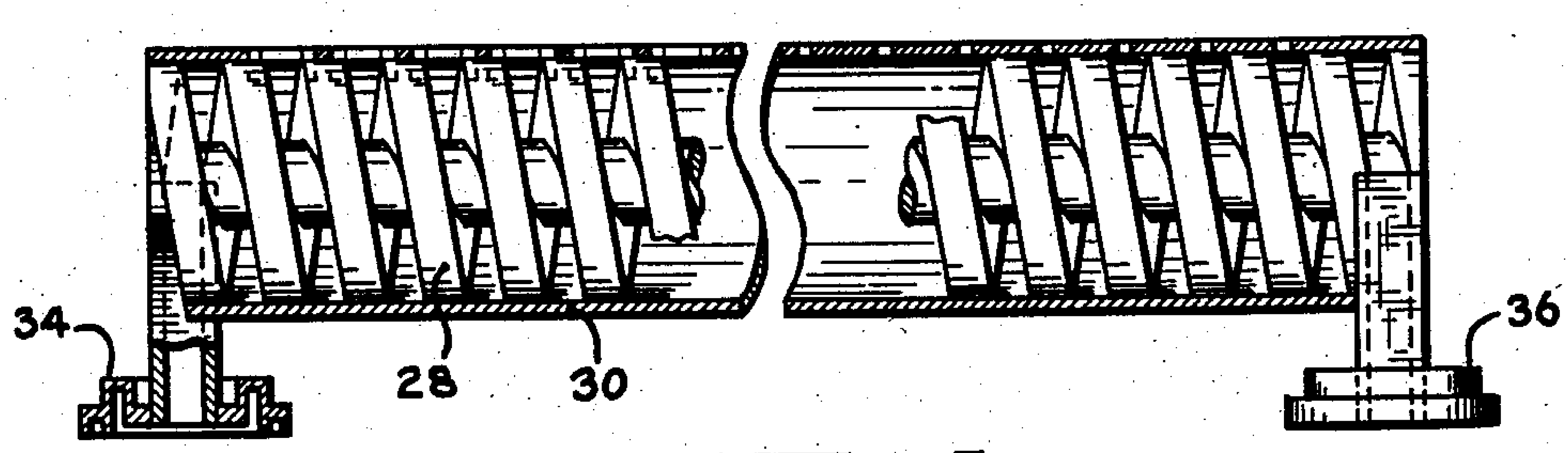

FIG-3

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April 20, 1954 W. B. HEBENSTREIT 2,676,257

MICROWAVE ANTENNA ARRAY

Filed June 3, 1950 2 Sheets-Sheet 2

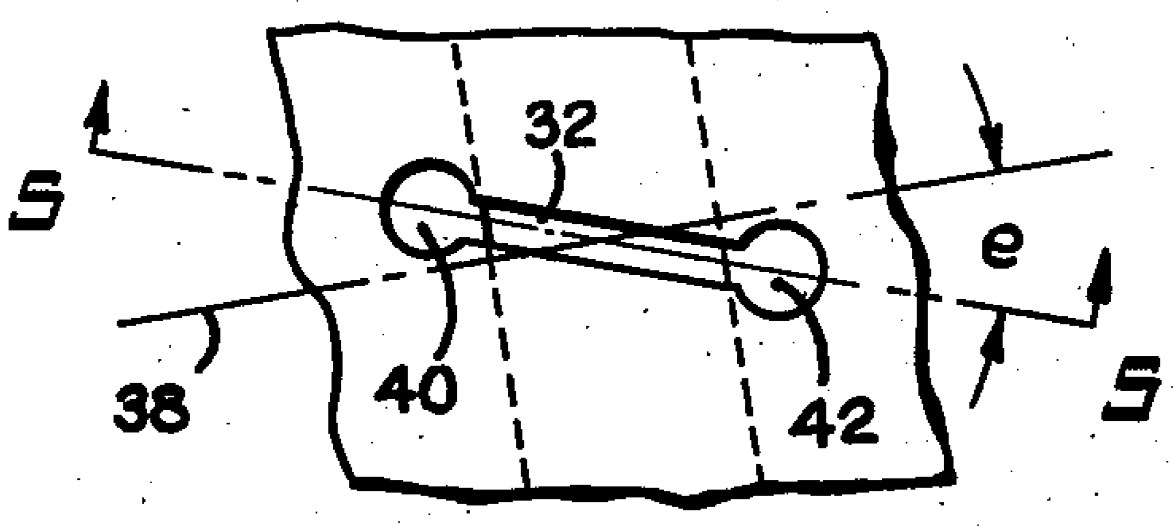

FIG-4

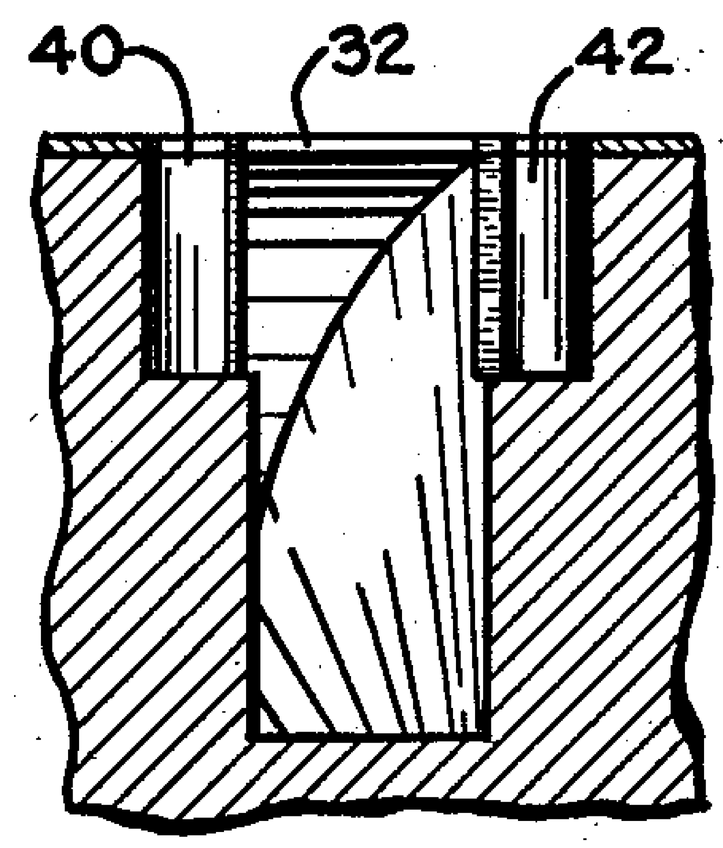

FIG-5

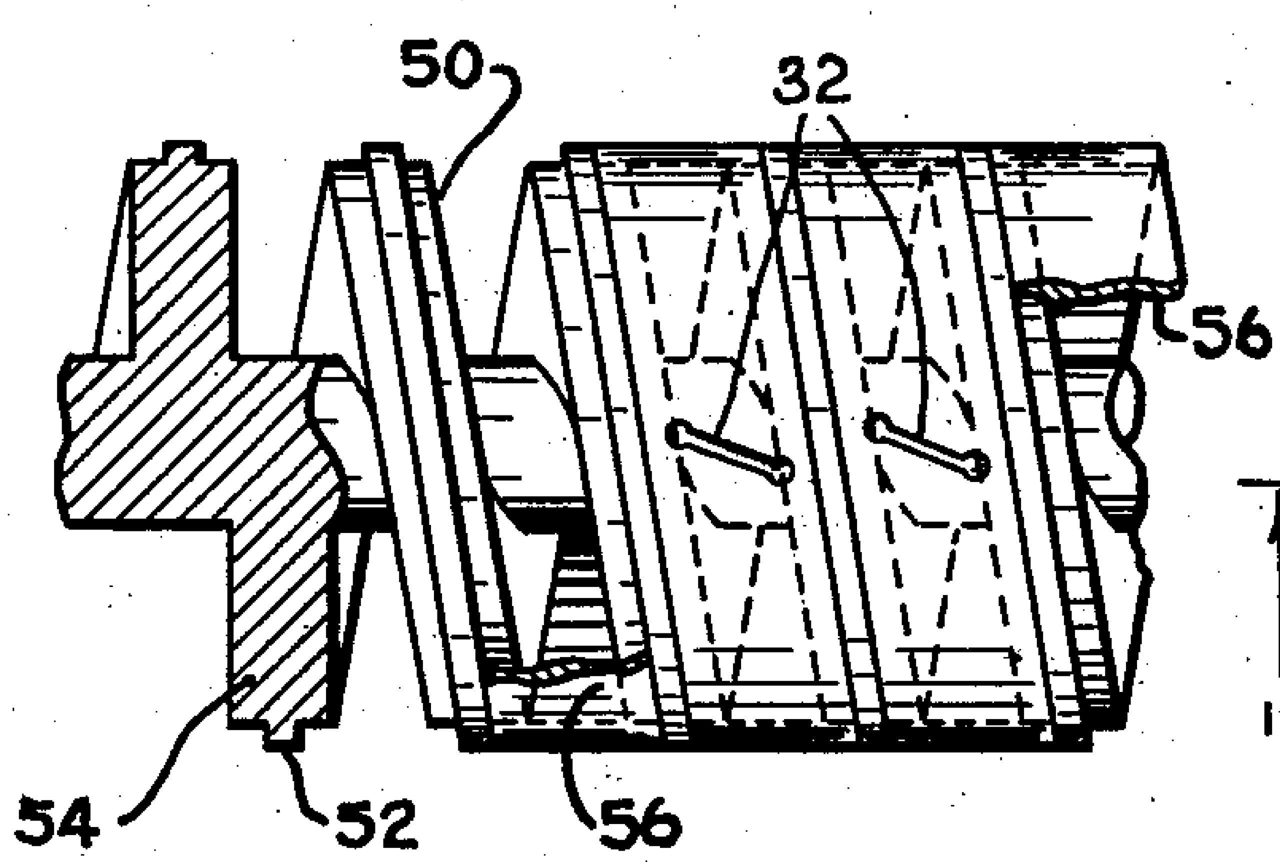

FIG-6

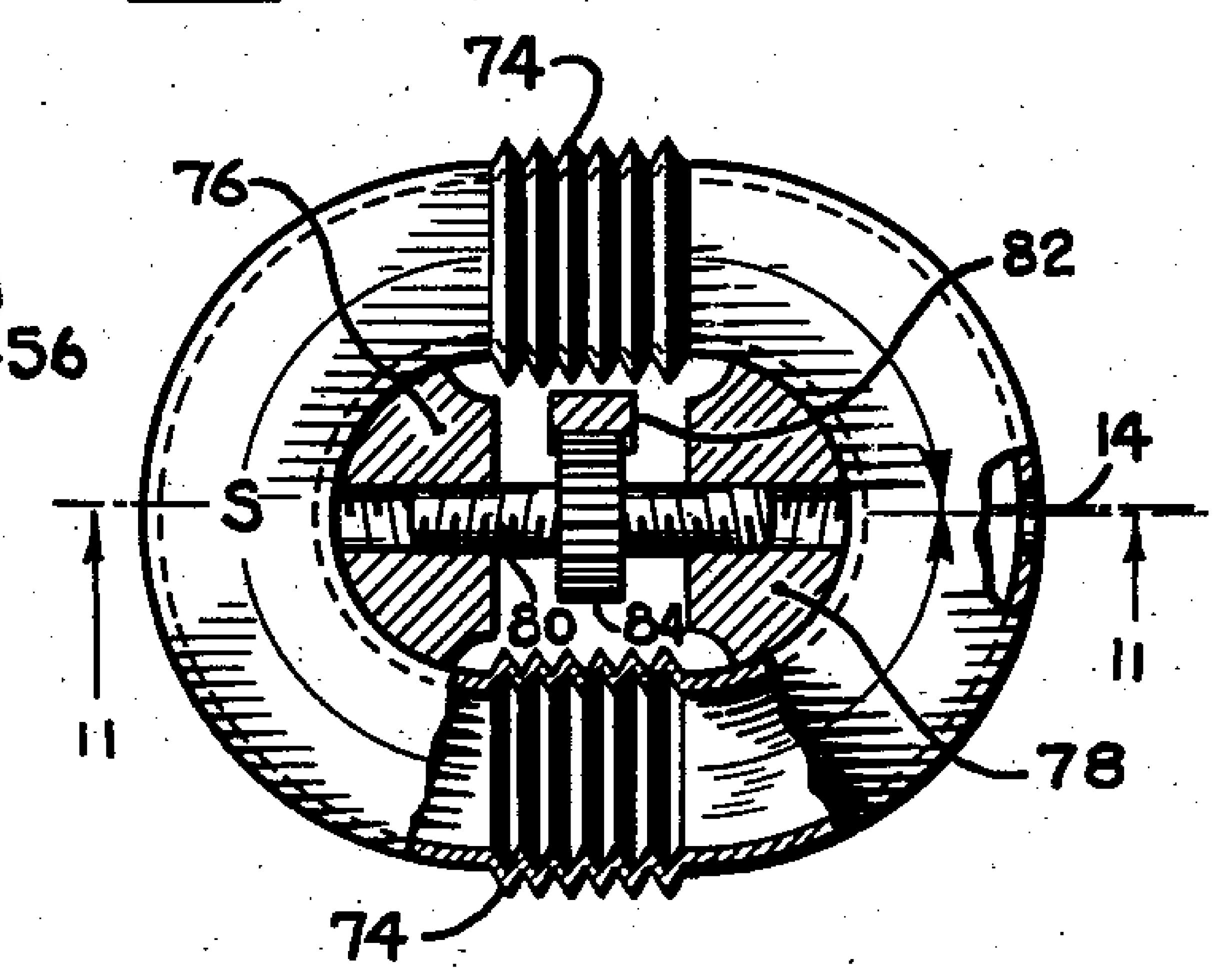

FIG-10

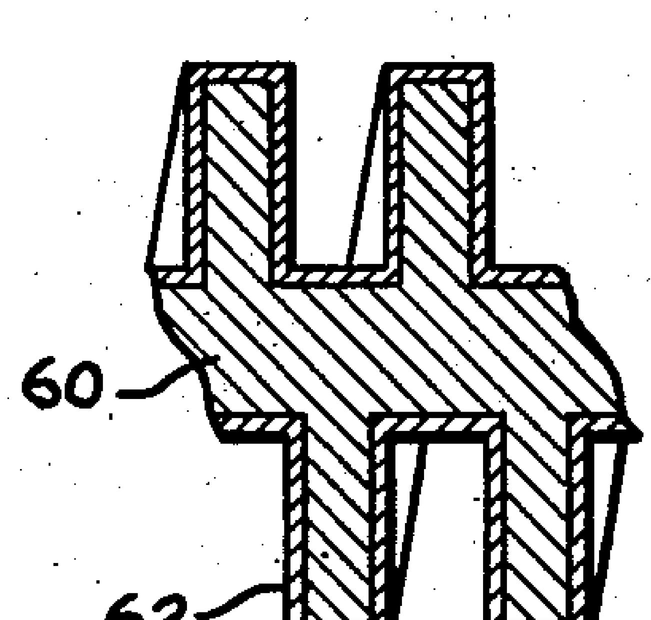

FIG-7

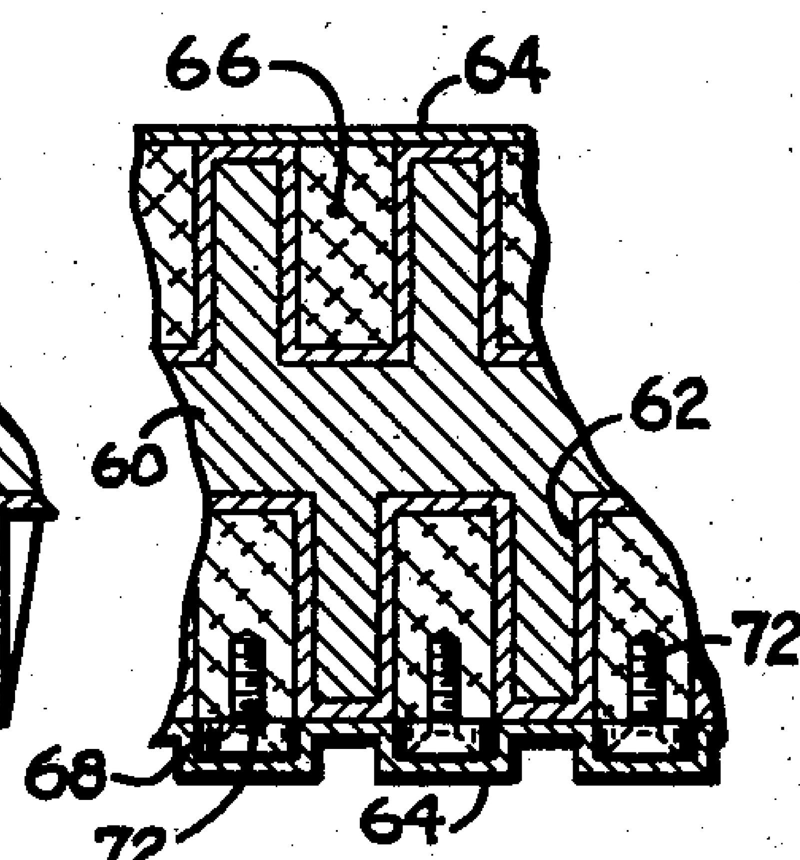

FIG-8

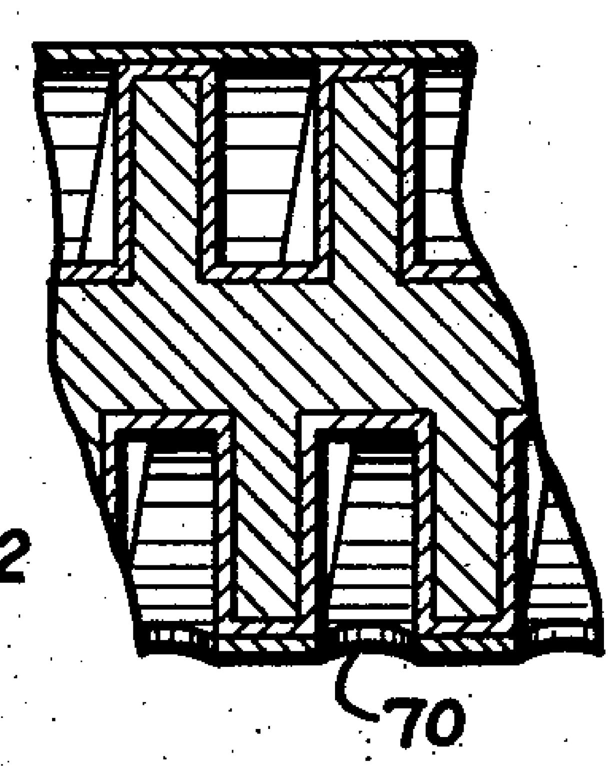

FIG-9

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MICROWAVE ANTENNA ARRAY

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5 Claims. (Cl. 250—33.63)

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This invention relates to antenna systems, and more particularly to antenna systems employing waveguides of helical configurations.

The antenna system of the type here contemplated comprises a number of radiator elements which are spaced along and coupled to a transmission line, the transmission line being most conveniently provided in the form of a waveguide. Microwave energy applied to the transmission line is coupled to the array of radiator elements and radiated therefrom in a directional pattern, the particular shape and characteristics of the pattern being dependent upon the physical spacing and electrical phasing of radiator elements, and upon the configuration of the array formed by said radiator elements. A scanning action of this pattern through a spatial angle may be obtained by varying the electrical phasing of the radiator elements.

In order to provide a better understanding of the invention, and of the manner in which its advantages and improved characteristics are achieved, certain basic considerations of importance in waveguides and waveguide antenna arrays are first described.

The phase velocity at which energy is propagated in a hollow pipe waveguide is a variable quantity dependent both upon the waveguide cross-sectional dimension and upon the frequency of the energy. Expressed in another manner involving wavelength, it may be said that while the free-space wavelength is dependent only upon frequency, the wavelength of microwave energy as measured within a hollow pipe waveguide is further dependent upon a cross-sectional dimension of the waveguide, and under practical conditions is always much greater than the free-space wavelength. For a rectangular waveguide operating in the dominant mode, the relationship between guide-wavelength λ_g and free-space wavelength λ is given by the equation

$$\lambda_g=\frac{\lambda}{\sqrt{1-(\lambda/2b)^2}} \qquad (1)$$

in which b is the inside dimension of the waveguide's wider wall. In this connection, it should be noted that to accommodate propagation of microwave energy along the waveguide, the dimension b must be greater than one-half of a free-space wavelength, and that to avoid operation in higher modes, the dimension b must be less than a full free-space wavelength. The most favorable waveguide characteristics are obtained when the dimension b is of the order of

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seven-tenths of a free-space wavelength at the nominal operating frequency.

Waveguide antennas must themselves satisfy several major requirements to yield a practical array, those of immediate importance for present consideration being (for broadside or cross-fire directionality) first, that the radiator elements fed from the waveguide should have a spacing along the line of the array not greater than approximately three-fourths of a free-space wavelength; and second, that the waveguide structure must be so proportioned and the array elements so spaced relative thereto as to cause the said elements to radiate in phase agreement, at the nominal operating frequency.

It might at first appear to be impossible to design a waveguide antenna satisfying the practical requirements mentioned above, for in-phase excitation of the radiator elements normally requires that the spacing of these elements relative to the waveguide shall be a full guide-wavelength, generally obtainable only at the expense of a physical spacing along the guide of very considerably greater than the recommended maximum (three-fourths free-space wavelength) mentioned above. As one solution to this problem, however, and now familiar to those versed in this art, in-phase radiation can be achieved with a one-half guide-wavelength spacing of radiator elements, with a concurrent reduction of their free-space interval to a practical value, by reversing the coupling of alternate elements. For example, in the instance where the radiator elements are provided as apertures in the narrower wall of the waveguide, this reversal of coupling can be accomplished by making the apertures of elongated configuration, and having them extend in directions generally crosswise to the axis of the waveguide in such manner that adjacent apertures are oppositely inclined relative to the said axis.

In accordance with the above-mentioned expedient of coupling reversal, an advanced but otherwise now conventional design of a cross-fire microwave antenna, here mentioned for comparison purposes, calls for a length of hollow pipe waveguide having a series of elongated apertures or slots formed in a wall of the guide and consecutively spaced therealong at substantially one-half guide-wavelength intervals. The dimension b of the waveguide is so chosen that, at nominal or cross-fire operating frequency f_o, the guide-wavelength λ_{go} (corresponding to the cross-fire frequency) is approximately 1.5 times the free-space wavelength; this occurs for a value of b which is approximately two-thirds of the free-space wavelength. The resultant physical spacing of the slots along the waveguide is approximately three-fourths of a free-space wavelength, a value in agreement with that already indicated as satisfactory from a practical standpoint. It may be noted at this point that in order to overcome certain excitation difficulties that often arise in cross-fire operation, an in-phase radiation condition may be slightly departed from, causing the antenna's directivity axis to extend just a bit askew to the cross-fire direction. Further, the waveguide parameters and operational frequency may also for other reasons be so chosen as to increase the angle between the directivity axis and the cross-fire direction to any desired value within certain limits dictated by waveguide transmission characteristics.

A conventional slotted waveguide antenna array as just described is quite satisfactory for radiating microwave energy in a fixed direction, relative to the line of the array, but many practical applications call for a scanning action of the energy. One of the possible methods of providing this scanning action is to frequency-modulate the excitation energy, which causes variation in phase velocity and guide-wavelength and correspondingly produces variable phasing of adjacent elements. Such a method has been little used, however, principally for the reason that with waveguide antenna structures of conventional type such as that above referred to, the frequency excursion required to scan over a sector of, say, sixty degrees, is considerably larger than can be conveniently obtained from present day high-level microwave energy sources. Further, even if the problems imposed by this inadequacy can be overcome by improvements in microwave sources, the scanning action of a conventional antenna would have to be limited to sectors of considerably less than sixty degrees, in order to keep the effective spacing of radiating elements within satisfactory limits. This frequency modulation method of scanning nevertheless would otherwise offer distinct advantages, such as avoiding mechanical complexities presented by other types of scanning antenna systems, or reducing the space requirements needed for their mounting.

It is therefore an object of the present invention to provide a novel type of apertured waveguide antenna structure having an improved frequency-shift-scanning characteristic, that is, one which requires a relatively small frequency excursion to yield wide angle scanning action.

It is a further object of the present invention to provide an apertured waveguide antenna having a novel structure which offers a greater range of design control as to the effective electrical spacing between adjacent apertures.

The foregoing objects, and other objects, features and advantages of the invention which will appear from the description and from the claims appended hereto, are attained by providing an antenna array in which the transmission line interconnecting and feeding the radiating elements is given a helical conformation to produce an effective phase velocity along the line of the array which is a small fraction of the corresponding free-space velocity of the microwave energy. In such a helical structure, the electrical phasing of adjacent radiating elements is no longer limited by the ordinarily compromising effect of their required physical spacing, but may be made

to have any desired value by suitable choice of helical transmission line parameters. One of the important advantages stemming from this improved structure is that, while providing any desired element spacing as expressed in terms of free-space wavelength, the electrical spacing may be increased to several transmission line wavelengths. Thus, in frequency-shift scanning the frequency excursion required to effect scanning action over a sector of specified angle is substantially reduced.

The invention will be more fully understood by reference to the following detailed description accompanied by the drawing in which:

Fig. 1 is a perspective view, partly in section, of a simplified helical waveguide structure illustrative of the present invention;

Fig. 2 shows another helical waveguide antenna structure embodying the invention;

Fig. 3 is a partial section of the above embodiment taken along the line 3—3 of Fig. 2;

Fig. 4 is an enlarged view of a portion of the Fig. 2 waveguide structure encompassing a slot radiator;

Fig. 5 is a sectional view taken through the helical waveguide structure along the line 5—5 of Fig. 4;

Fig. 6 shows another practical embodiment of a helical waveguide antenna;

Figs. 7, 8, and 9 illustrate a helical waveguide structure in several phases of its production by an electroforming process;

Fig. 10 represents a helical waveguide antenna embodiment including mechanical means for producing a scanning action of the directivity characteristic; and

Fig. 11 is a sectional view taken on line 11—11 of Fig. 10.

Referring first to the perspective view of a simplified embodiment of the invention as illustrated in Fig. 1, there is shown at 12 a hollow rectangular waveguide having a helical conformation. A series of apertures 14 are formed in the outer wall of the coiled waveguide, and are positioned to lie in a straight line 16 paralleling axis 18 of the helix. As illustrated, it is preferably the narrow wall 20 of the waveguide which is faced outwardly to form the outermost surface of the helix. By constructing the helix in this manner, the center-to-center distance d between adjacent apertures, corresponding to the pitch of the helix as measured along aperture line 16, may be made equal to or somewhat less than three-fourths of a free-space wavelength as is desirable for optimum pattern characteristics in cross-fire or near cross-fire operation. It may also be here noted with respect to Fig. 1 that the effective length of waveguide which interconnects a pair of adjacent apertures, best determined empirically, may be taken as equal to the length S between adjacent apertures along the center line of the waveguide. This length S is a sufficiently close approximation to the effective wave-guide length for present purposes.

As already indicated in the preceding general observations of waveguide antenna considerations, the antenna's directivity axis extends at a right angle to the aperture line 16 when there is in-phase radiation from apertures 14. Using circular apertures centered in the narrow wall of the waveguide as shown, or using any other equivalent type of apertures or radiator elements, this condition is obtained when the effective length S of the waveguide portion interconnecting a pair of adjacent apertures is an integral multiple of a full guide-wavelength at cross-fire frequency. A departure from this cross-fire frequency results in a change of relative phasing between apertures and causes the directivity axis 22 to extend at an angle ψ relative to the cross-fire direction 24, as measured in the plane defined by aperture line 16 and helix axis 18.

The manner in which the angle ψ is dependent upon operational frequency may be further explained and specifically derived as follows:

A uniphase front of energy radiated by the antenna is, in Fig. 1, indicated by line 26 extending from an aperture A, at a right angle to the directivity line 22 which extends from an adjoining aperture B, and intersecting directivity line 22 at point C. The phase shift as measured from B to C is given by the equation

$$\phi_{BC}=2\pi\frac{d}{\lambda}\sin\psi \qquad (2)$$

where λ is the free-space wavelength at the operating frequency f. The phase shift ϕ_{BA} in the waveguide between the points B and A is given by the equation

$$\phi_{BA}=2\pi\frac{S}{\lambda_g} \qquad (3)$$

where λ_g is the guide wavelength corresponding to operating frequency f. Since points A and C are in phase,

$$\phi_{BC}=\phi_{BA}-2n\pi \qquad (4)$$

The quantity n is an integer, defined by the equation

$$n=\frac{S}{\lambda_{go}} \qquad (5)$$

where λ_{go} is the guide-wavelength at the cross-fire frequency f_o. Combining Equations 2, 3, 4, and 5,

$$\text{Sin }\psi=\frac{S}{d}\left(\frac{\lambda}{\lambda_g}-\frac{\lambda}{\lambda_{go}}\right) \qquad (6)$$

An inspection of Equation 6 makes readily apparent certain of the improved capabilities achieved by the present invention. For a waveguide of given cross-sectional dimensions, the magnitude of the expression

$$\frac{\lambda}{\lambda_g}-\frac{\lambda}{\lambda_{go}}$$

is controlled by the frequency excursion. For a fixed frequency excursion, then, the magnitude of scan angle ψ is a direct function of the ratio

$$\frac{S}{d}$$

For scanning action over a given large angle of say sixty degrees, the frequency excursion required is reduced by approximately the multiplying factor

$$\frac{d}{S}$$

and by very closely that factor for small scan angles. This may be made more evident by placing Equation 6 in a form using frequency terms, in the following manner. The factor $2b$ in Equation 1 given above is equal to the cut-off wavelength λ_c, and the ratio

$$\frac{\lambda}{\lambda_c}$$

is exactly equal to the ratio

$$\frac{f_c}{f}$$

where f_c represents the cut-off frequency. Equation 1 may thus be equivalently expressed as

$$\lambda_g=\frac{f\lambda}{\sqrt{f^2-f_c^2}} \qquad (7)$$

Substituting (7) into (6),

$$\text{Sin }\psi=\frac{S}{df}\left(\sqrt{f^2-f_c^2}-\sqrt{f_o^2-f_c^2}\right) \qquad (8)$$

where f_o represents the cross-fire frequency. Defining K as the ratio of the frequency excursion to the cross-fire frequency, so that $f=f_o(1+K)$; substituting in Equation 1; and expanding in powers of K:

$$\text{Sin }\psi=K\frac{S}{d}\,\frac{f_o}{\sqrt{f_o^2-f_c^2}}\left[1-\frac{K}{2}\left(1+\frac{f_o^2}{f_o^2-f_c^2}\right)+\frac{K^2}{2}\left(1+\frac{f_o^4}{[f_o^2-f_c^2]^2}\right)-\ \cdots\right] \qquad (9)$$

For small angles, then, it is sufficiently accurate to take into account only the first term to the right of the equality sign in Equation 9, so that, where ψ is expressed in degrees,

$$K=\frac{d}{S}(\psi)\left(\frac{\pi\sqrt{f_o^2-f_c^2}}{180f_o}\right) \qquad (10)$$

Again, Equations 9 and 10 hold true for all arrays of the general type here under consideration, so that, relative to the conventional antenna structure earlier described, the multiplying factor

$$\frac{d}{S}$$

is equal to the reduction in frequency excursion ratio.

While the preceding description of certain basic principles of the invention has been given with reference to the essentially diagrammatic illustration in Fig. 1, it is to be understood that various techniques and expedients which are conventional in the antenna art may be employed therewith. For example, the frequency shift system of scanning requires that the standing wave ratio in the feed transmission line be small. This may be accomplished by providing a proper termination of the helical transmission line. As another example, in a relatively long array as must be used to produce a very sharply directional characteristic, the coupling of consecutive radiator elements must generally be of progressively greater magnitude, in going along the array toward the termination, in order to provide a uniformly illuminated array. Again, where a minimum side lobe level is desired for a given width of the major lobe, certain non-uniform illuminations are provided in a manner familiar to those versed in the art.

Figs. 2 and 3 illustrate another practical embodiment of the present invention, in which there is also provided a progressive variation in radiator element coupling by employing suitably oriented elongated apertures in the narrow wall of the waveguide. The waveguide is here formed by machining, from a metal cylinder, a rectangular thread screw 28 of suitable pitch, and shrinking a metal tube 30 over the machined screw to produce a waveguide having a helical axis and providing a helical transmission path. The waveguide thus produced has a uniform rectangular cross-section in all planes perpendicular to its helical axis. This structure may be fabricated of aluminum, for example, and where a long array is desired, the screw may be made by a centerless grinding method. A shrink fit is obtained by reaming or honing the tube 30 to an inside diameter slightly less than the outside diameter of the machined screw 28. Thus, when tube 30 is heated, its diameter will be increased sufficiently to permit insertion of the machined screw 28 therein. Dumbbell shaped slots 32 are cut through the outer wall of the helical waveguide to serve as the radiator elements, it being understood that dipole or other types of radiators may be alternatively utilized. Conventional coupling structures 34 and 36 are provided at the ends of the helical waveguide antenna, to serve as means for connecting to a source of microwave energy, and to an absorptive load for providing a reflectionless termination.

The dumbbell shaped slots 32 are so proportioned that their perimeters are each substantially equal to a full waveguide wavelength. Positioned in the rectangular waveguide's narrower wall in a manner as here illustrated, the slots interrupt and are excited by the flow of surface currents in the waveguide which are associated with the dominant mode of wave transmission, and radiate quite effectively because of their resonant dimensioning. Referring to the Fig. 4 enlarged view of a typical slot region in the disclosed waveguide structure, the coupling of a slot radiator 32 is dependent upon the magnitude of its inclination e relative to the cross-wise direction 38 in the waveguide passage at that point. Thus, any desired illumination distribution along the array may be obtained by a progressive variation of slot inclinations in some suitable manner, as generally indicated in Fig. 2.

In a design of an antenna array utilizing slot radiators in the narrow wall, the length of a resonant slot radiator may be greater than the narrow wall dimension, as illustrated in Fig. 5. In order to accommodate such a slot and still have it match properly to the waveguide and radiate effectively, the ends of the slot are given access to the interior of the waveguide by removing wall material adjacent thereto, as indicated at 40 and 42, to a depth of substantially one-fourth wavelength at nominal frequency. where it is desired to make length S a multiple of half a guide-wavelength, rather than a multiple of a full guide-wavelength as thus far described, the inclinations of adjacent slots must be in opposite directions relative to the cross-wise direction in the waveguide, in order to provide coupling reversal as already described.

Another method of fabricating the helical waveguide is illustrated in Fig. 6. Here again a rectangularly threaded screw 50 is machined from a metal cylinder, but in this instance a shoulder 52 is provided on the projecting helical rib 54 of the screw. The fourth wall enclosing the waveguide is formed by an elongated metal strip 56 which is wrapped around the threaded core, strip 56 having a width suitable to fit snugly into the shallow passage defined by the configuration of the shouldered rib. Outer wrapping 56 may be bonded to core 50 by soldering, brazing, welding or any other method suitable to the materials employed and capable of providing good electrical continuity. For this purpose, the core and strip may be made of a material inherently suitable to accept such banding treatment, or may be plated or otherwise prepared to accept such treatment. For example, the core and strip may be fabricated of an aluminum alloy, in the interests of both strength and lightness, then

plated with copper or additionally with silver, rendering the core and wrapping suitable for bonding by one of the soldering processes.

Still another method of fabricating the helical waveguide structure is shown in Figs. 7, 8, and 9, wherein a screw core 60 is provided as already described with reference to Fig. 2. Core 60 may in this instance be made of any desired material, for it here functions primarily as a base upon which is plated a conductive surface 62, and upon which an outer wall 64 is then provided, as by the "lost wax" process of electroforming. For example, core 60 may be fabricated of steel, and the plating applied thereto may be of nickel. The cavity formed by the helical thread may then be filled with aluminum, as indicated at 66, or with any one of the commercially available alloys or waxes specifically formulated for use in the lost wax process, these materials being characterized by low melting-points but nevertheless machinable at ordinary temperatures. The excess of aluminum, wax, or alloy filling should then, of course, be machined away to present a perfectly true cylindrical surface which is in part formed by the plating 62. Plugs or cores 68 having a desired configuration of radiator apertures 70 are then fastened, as by screws 72, in their proper positions against the composite cylinder, and the resultant assembly is again plated with nickel to form a relatively thick outer wall 64. The salient portions of plugs 68 and their fastening elements are then machined off to again provide a smooth cylindrical surface, and the cavity-filling material is removed in some suitable manner. For example, in the specific structure here described, the aluminum may be removed by treatment with a hydrochloric acid solution which attacks the aluminum without appreciable reaction upon the nickel plating. Where low melting-point fillers are used, their removal may be effected simply by a heating process. Whatever the specific material and filler-removal method used may be, however, the end result is the production of a helical waveguide having essentially continuous walls formed of homogeneous conductive material. Alternatively, the radiator apertures 70 during the electroforming process, may be machined in the desired locations after the outer wall of the cylindrical structure has been formed. Where greater electrical conductivity is desired than is provided by the nickel or other material with which the walls may be surfaced, a final plating of silver or other highly conductive material may be applied.

While the waveguide structures thus far disclosed make use of a single line of radiator elements which yield a radiation pattern narrow in a plane parallel to the line of the array but broad in a plane perpendicular thereto, it is to be understood that the pattern in the latter plane may be modified in any desired manner by using additional radiator elements, or by using the helical waveguide antenna as a source of radiation to be shaped by reflectors or baffles or other such means as are conventional, or by using each of the radiator elements to excite supplementary arrays extending in planes perpendicular to the helix axis. It is also to be understood that the coiled waveguide arrays here disclosed are not limited to scanning by the frequency modulation method. It may in some instances be desirable to provide a waveguide antenna array, of the sinuate type here disclosed, in which scanning action may be effected by mechanical means. Various techniques or modifications employed with other waveguide antennas are available. As examples, the antenna array may be designed for fixed frequency operation and bodily rotated to produce a scanning action, or the helical waveguide structure may be provided with supplementary velocity-changing members penetrating the waveguide to a variable extent, or variably positioned therein, these being merely applications of conventional expedients. Still another method which may be employed is illustrated in Fig. 10. Here the effective length S of the convolutions is itself made variable by the use of corrugated or bellows type of waveguide sections 74 which may be repetitively lengthened and shortened. These sections are provided at opposite sides of each convolution, and by way of example, the necessary mechanical movements may be imparted by a rack and gear arrangement as here shown. Members 76 and 78 are structurally rigid bars which extend along the waveguide structure and interiorly thereof, secured to each convolution. At as many points along the helical structure as may be necessary to lend rigidity thereto and uniformity of incremental changes in the spiral length S therealong, are provided spacing members 80 which engage the bars 76, 78 in such manner that the lengths S may be controlled by threading action of the spacing members. Such threading action may be readily achieved by providing a rack 82 in engagement with gears 84 mounted upon the said spacing members 80. Reciprocative movements of rack 82 thus effect a variation in the length S of convolutions interconnecting adjacent radiator elements, resulting in variably phasing the radiator elements as is necessary to produce scanning action.

The above-described structures are illustrative of principles of the present invention. It should be apparent that modifications and other arrangements will readily occur to those versed in the art without departing from the scope or spirit of the invention defined in the appended claims.

It is also to be understood that, in addition to their major applications as transmitting devices, the helical transmission line antenna arrays forming the subject matter of the present invention may also be useful in certain applications as receiving devices, their characteristics in such cases being exactly analogous to those pertaining to transmission.

What is claimed is:

1. An antenna array for radiating microwave electromagnetic energy comprising: a tubular element, a cylindrical member, said cylindrical member being provided with external substantially rectangular threads and being concentric with said tubular element, said tubular element being in contact with the threads of said cylindrical member to define a duct of helical configuration and of substantially rectangular cross section, and said tubular element having a plurality of openings spaced apart to communicate with said duct whereby said duct operates as a waveguide for microwave electromagnetic energy supplied thereto and radiated from said openings.

2. An antenna array for radiating microwave electromagnetic energy comprising: a conductive tube, a rectangular thread screw, said screw being concentric with said tube and in contact therewith to provide a duct having a substantially rectangular cross section to define a waveguide of helical configuration, and said tube being provided with a plurality of slots communicating with said waveguide for radiating microwave electromagnetic energy therefrom.

3. An antenna array for radiating microwave electromagnetic energy of a predetermined frequency comprising: a metallic tube having a plurality of uniformly spaced slots which are axially aligned relative to each other, a metallic screw having a rectangular thread, said screw being concentric with and in contact with said tube, whereby said screw and said tube cooperate to define a duct of substantially rectangular cross section and extending axially in the form of a helix, said slots being spaced apart so that alternate ones of said slots communicate with alternate turns of said helical duct, said duct constituting a waveguide for microwave electromagnetic energy, and said slots radiating said energy from said waveguide in a direction determined by said predetermined frequency.

4. An antenna array according to claim 3 3 wherein said slots have a spacing not greater than three-quarter wavelengths in free space, and approximately equal to an integral number of wavelengths in said waveguide, at said predetermined frequency.

5. An antenna array for radiating microwave electromagnetic energy comprising a hollow cylinder having an inner surface, a cylindrical member in concentric relationship with said element, said member having external substantially rectangular threads in contact with said inner surface, whereby said threads and said inner surface form a hollow duct of helical configuration and of substantially rectangular cross section, and a plurality of openings in said hollow cylinder positioned to communicate with the respective portions of said duct.

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