June 10, 1952 A. G. FOX 2,599,753

WAVE GUIDE PHASE SHIFTER

Filed Jan. 11, 1946

FIG. 1

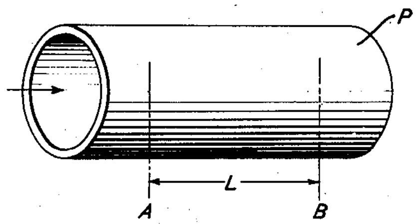


FIG. 1A

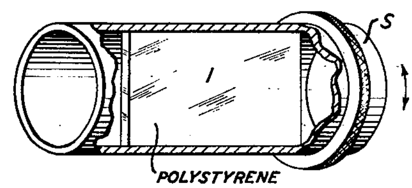


FIG. 2

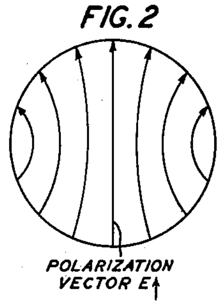


FIG. 2A

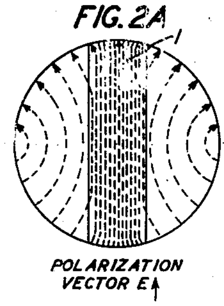


FIG. 2B

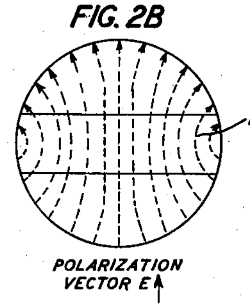


FIG. 3

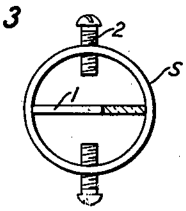


FIG. 3A

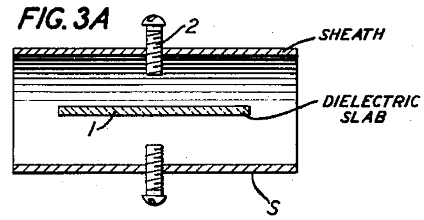


FIG. 4

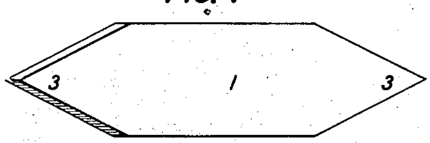


FIG. 4A

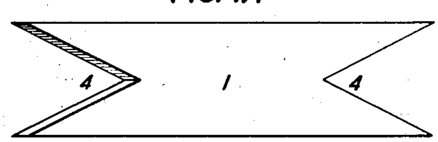


FIG. 5

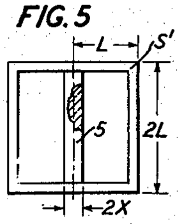
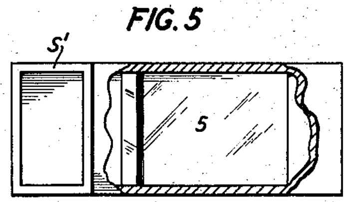


FIG. 5



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UNITED STATES PATENT OFFICE

2,599,753

WAVE GUIDE PHASE SHIFTER

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Application January 11, 1946, Serial No. 640,498

1 Claim. (Cl. 178—44)

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This invention relates to the transmission of electro-magnetic waves and more particularly to phase shifters for use in connection with wave guides.

An object of the invention is to simplify and improve the construction and operation of phase shifters including, especially, adjustable phase shifters.

A feature of the invention is a section of wave guide comprising a conductive boundary, an enclosed dielectric medium and longitudinally disposed therein a plate of dielectric material having a dielectric constant substantially different from that of said medium.

A feature of the invention is a microwave phase shifter comprising a section of wave guide loaded by a plate of high dielectric constant disposed longitudinally in the guide section. The wave transmission characteristics will differ for mutually perpendicular orientations of linearly polarized waves referred to the dielectric plate as a reference axis.

Another feature of the invention is a wave guide phase shifter having a dielectric plate therein adapted to provide a predetermined phase shift over a broad band of frequencies.

A further feature of the invention is a wave guide phase shifter that alters the phase velocity of the waves having a certain polarization by a substantially greater amount than waves polarized perpendicular thereto.

Still another feature of the invention is a reflectionless wave guide phase shifter having a low loss dielectric plate therein proportioned to transform a linearly polarized wave into a circularly polarized wave.

Other objects, features and advantages will be apparent from the detailed specification taken in connection with the accompanying drawings wherein:

Fig. 1 shows a cylindrical wave guide;

Fig. 1A shows a wave guide phase shifter having an internal dielectric plate in accordance with the invention;

Figs. 2, 2A, 2B show explanatory electric force diagrams;

Figs. 3, 3A show a modification of the wave guide phase shifter;

Figs. 4, 4A show modifications of the dielectric plate element; and

Figs. 5, 5A show a modified wave guide phase shifter for square pipes.

Phase shifters involving a section of wave guide provided with internal diametrical rods suitably spaced apart, have been disclosed in the

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United States patent applications, Serial No. 464,333, filed November 3, 1942, by A. G. Fox, now Patent No. 2,438,119, issued March 23, 1948, and Serial No. 469,897, filed December 23, 1942, by D. H. Ring, now Patent No. 2,425,345, issued August 12, 1947. The phase shifting action in these devices is developed essentially from the transmission properties of a single frequency or relatively narrow band wave filter.

Phase shifters involving a section of wave guide provided with an internal metal fin, longitudinally and peripherally connected thereto to provide broad-band characteristics, and also to alter the phase velocity of waves polarized parallel thereto while leaving unchanged the phase velocity of waves polarized perpendicular thereto, have been disclosed in the United States patent application of W. A. Tyrrell, Serial No. 590,365, filed April 26, 1945, now Patent No. 2,546,840, issued March 27, 1951.

The phase shifters in accordance with the present invention overcome the limitations inherent in critical resonance or narrow band phase shifters, and are characterized by the broad-band transmission characteristics of a uniformly loaded wave guide such as is disclosed in the United States Patent 2,199,083 issued April 30, 1940, to S. A. Schelkunoff.

In accordance with an embodiment of the invention a phase shifter comprises a section of wave guide having a dielectric plate or septum therein, such as polystyrene or the like, with a high dielectric constant for providing a predetermined shift in the phase of a wave propagated therethrough. The dielectric plate will alter the phase velocity of all polarizations of waves. However, waves linearly polarized parallel thereto will be retarded to a greater degree than waves polarized perpendicular thereto. In practice it is desirable to so design the plate that the velocities of the waves of these two principle polarizations are as unequal as possible, so that the phase shift differential between them will be as great as possible. The plate may be dimensioned and shaped to provide a predetermined differential phase shift, and more particularly a 90 or 180 degree differential shift.

The phase shifter may be rendered practically reflectionless by capacitive reactance screws, so oriented and adjusted as to provide a compensating and neutralizing reflection.

The term "dominant wave" as used in this specification denotes a wave corresponding to that particular mode having the lowest possible cut-off frequency in a pipe of predetermined cross-section.

The term "linear polarization" as applied to wave guides, denotes a state of the electromagnetic field, wherein the electric force vector at the center of the wave guide cross-section, executes as a function of time, simple harmonic motion on a straight line.

Similarly, the terms "circular and elliptical polarization" are characterized by an electric force vector at the center of the guide executing a circular or elliptical sweep respectively as a function of time variation.

Analytically, an elliptical polarized wave may be compounded from two linearly polarized waves of the same frequency, whose axes of polarization are perpendicular and whose relative amplitudes and phases are different. Accordingly, from this viewpoint circular polarization represents a special case of elliptical polarization wherein the linearly polarized components are equal in amplitude, but differ 90 degrees in time phase.

Wave guides and the phenomena associated with the propagation of electromagnetic waves therein have been fundamentally disclosed in the United States patents to G. C. Southworth Nos. 2,129,711 and 2,129,712 both issued September 13, 1938, to which reference is herewith made.

The phase velocity or propagation of waves in an empty hollow pipe wave guide is given by

$$v=\frac{c}{\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2}} \qquad (1)$$

Where c equals the volocity of light in vacuo, λ equals the wavelength in vacuo and λ_c equals the critical or cut-off wavelength associated with the propagation of a particular wave mode and a particular cross-section of pipe.

From the formula it is apparent that the phase velocity v in a hollow pipe wave guide will always be greater than c and that v approaches c as the wavelength λ is made small relative to λ_c the cut-off wavelength.

Referring to Fig. 1, which shows a cylindrical wave guide pipe P of uniform circular cross-section, assume that input waves of the dominant mode are applied thereto at the left and propagate therethrough in the direction of the indicated arrow.

At any given instant, the waves at any arbitrary cross-section A will have a certain phase Φ_A, with respect to some fixed reference point in the guide. At the same instant, the phase at some other cross-section B will correspondingly be Φ_B.

The phase difference between points A and B will then be expressed by the formula

$$\Phi_B-\Phi_A=\frac{L}{\lambda_g}\times 360°=\frac{Lf}{v}\times 360° \qquad (2)$$

where

λ_g=the wavelength within the guide;
f=the frequency of the wave oscillations; and
L=distance between A, B.

From Equation 2, it is apparent that for a given frequency, the phase difference between two given points is dependent only upon the phase velocity v.

The introduction of a longitudinal dielectric plate 1 into the circular guide, as shown in Figs. 1A and 3A, results in an altered cut-off wavelength λ_c' and phase velocity v', respectively.

Whereas the dielectric plate definitely alters the phase velocity and critical cut-off frequency for polarizations or orientations of electric field parallel thereto, it has practically a much smaller effect on the corresponding perpendicular polarizations. For such perpendicular polarizations the plate may be considered to produce a second altered cut-off wavelength λ_c'' and phase velocity v''.

Therefore, a guide section with a longitudinal dielectric plate may be considered to have two separate phase velocities, corresponding to waves polarized parallel and perpendicular to the plane of the plate, respectively, as illustrated in Figs. 2A and 2B, respectively.

The phase difference between points A and B for waves polarized parallel to the plate is

$$\Phi_B'-\Phi_A'=\frac{Lf}{v'}\times 360° \qquad (3)$$

whereas for the perpendicular polarization

$$\Phi_B''-\Phi_A''=\frac{Lf}{v''}\times 360° \qquad (4)$$

The differential phase shift, that is, the difference in phase between transmitted waves in the two orientations is given by

$$\Phi=(\Phi_B'-\Phi_A')-(\Phi_B''-\Phi_A'')=Lf\,360°\left(\frac{1}{v'}-\frac{1}{v''}\right) \qquad (5)$$

The term "differential phase shift" as used herein, denotes a difference in the electrical length of two transmission paths. In the wave guide phase shifter disclosed, these two paths are present within the same section of wave guide and result from the introduction of the dielectric plate therein, which may be considered the analog of a transmission line with uniformly distributed capacitive loading. The distributed capacitive loading affects differently the transmission of the two sets of linearly polarized waves, whose axes of polarization are mutually perpendicular. Having chosen a particular dielectric for the material of the plate and a particular shape therefor, both of which factors determine a specific difference in phase velocities, then any desired phase shift may be achieved by a suitable choice of the longitudinal dimension or length L.

Such a differential phase shift section may then be employed for any of the purposes described in the United States application of A. G. Fox, Serial No. 464,333, filed November 3, 1942, now Patent No. 2,438,119, issued March 23, 1948, such as converters from linear to circular polarization, polarization rotators, variable phase changers, etc.

A particular type of structure conforming with the present invention comprises a low loss dielectric plate 1 of polystyrene, attached within the guide section so as to possess both radial and longitudinal extent as illustrated in Fig. 1A. The plate 1 may extend only part way across the guide section like a fin or completely in a diametral plate as shown, and more preferably should possess a high dielectric constant.

Thereby a pair of geometrical axes, mutually perpendicular is set up within the wave guide or wave guide section, to which will correspond the aforementioned different propagation and transmission characteristics. The effect of the diametral plate 1 on wave transmission will accordingly depend upon its orientation with respect to the polarization of the waves. For simplicity hereinafter, the discussion will be limited to the dominant mode of wave propagation.

Fig. 2 shows the approximate configuration of the electric lines of force in a uniform circular wave guide as set up by a linear polarized wave. Fig. 2A shows qualitatively the electric force configuration established by the presence of a diametral dielectric plate in the wave guide, wherein the plane of the plate coincides with the direction of polarization as indicated; while Fig. 2B represents the lines of force, when the plate is perpendicular to the direction of polarization. These indicate that the field pattern and hence the transmission characteristics are more profoundly altered when the plate is parallel to the electric field.

In some practical applications, the phase shifter may form an integral part of a main wave guide or may be inserted therein or connected thereto as a rotatable joint in the manner more fully disclosed in the United States application of A. G. Fox, Serial No. 464,333, filed November 3, 1942, now Patent No. 2,438,119, issued March 23, 1948.

The manner of operation of these wave guide phase shifters may be inferred from the general discussion above, and will now be described with more particularity.

The projection of the plate into the wave guide section along a diametral plane thereof acts to increase the cut-off wave-length for the parallel polarization case shown in Fig. 2A, and according to Equation 1, decreases the phase velocity relative to the values appropriate for Figs. 2 or 2B.

Let it be assumed that a linearly polarized, dominant wave is incident upon a phase shifter and let the angle between the axis of polarization and the plane of the dielectric plate be denoted by β. The incident wave may be regarded as the resultant of two linearly polarized components in phase, whose axes of polarization are parallel and perpendicular, respectively, to the plane of the plate. The relative amplitudes of the orthogonal components will be related as cosine β to sine β. The components will propagate through the wave guide phase shifter with differing phase velocities, the component parallel to the dielectric plate traveling slower. In their progress therethrough the components acquire a phase difference, which increases with the distance of wave penetration into the phase shifter. The total phase shift developed between the two components will depend essentially upon the length of the plate, its thickness and the dielectric constant of the material of which it is made and by proper proportioning of these dimensions and factors, any desired phase shift may be secured. When the components emerge from the phase shifter, therefore, the resultant will in general have been transformed from the input linearly polarized wave to an output elliptically polarized wave.

There are two special cases, however, which are of special importance, namely, the 90-degree phase shifter and the 180-degree phase shifter. Thus, when a linearly polarized wave is incident upon a 90-degree (differential) phase shifter having the plane of the dielectric plate at an angle β of 45 degrees to the axis of polarization, the emerging wave will come out circularly polarized. For other values of the angle β the waves will, in general, emerge elliptically polarized.

The 180-degree phase shifter possesses the significant property that an incident, linearly polarized wave will emerge linearly polarized for all values of the angle β. However, in general, a change in orientation of the polarization vector will result.

As previously disclosed, a longitudinal dielectric plate causes not only a change in phase velocity but also in characteristic impedance relative to the uniform wave guide section. An abrupt transition in impedance properties between the principal guide and the phase shift section would result in undesirable and disturbing reflections.

To eliminate or to neutralize and minimize such effects, capacitive reactance screws **2** (Fig. 3), as disclosed in United States Patent No. 2,432,093 issued December 9, 1947, to A. G. Fox, are provided to set up counteracting reflections, whereby the overall transmission will be essentially reflectionless.

Alternatively, the phase shifting dielectric plate may be made inherently reflectionless by means of impedance matching terminal portions, disclosed in Figs. 4 and 4A. In Fig. 4, the dielectric plate **1** has tapered terminal portions **3** adapted to provide a smooth transition and match into the impedance of the principal guide. Alternatively, the impedance matching terminals may be in the form of a tapering notch **4** as shown in Fig. 4A.

It has been stated earlier that in general the presence of a dielectric plate affects the phase velocities of waves polarized both parallel with and perpendicular to the plate. If, however, the plate is very thin, then the waves polarized perpendicular to the plate are affected only to a negligible extent. In order for such a plate to be effective, it must have a very high dielectric constant. For dielectrics of moderate dielectric constant such as are in common use, a plate of negligible thickness would have negligible effect on waves of both polarizations. Consequently plates of appreciable thickness must generally be used. On the other hand, if the plate is made so thick that it completely fills the waveguide, then waves of both polarizations will be slowed down equally and there will be no differential phase shift. Consequently there must be a plate of some intermediate thickness which will produce a maximum of differential phase shift.

This optimum thickness of plate can, of course, be determined either theoretically or experimentally. However, the theory of wave guides partially filled with solid dielectric is so complex that it is preferable to determine the optimum plate thickness experimentally. This may readily be done by starting with a thick plate and shaving it down in steps, measuring the differential phase shift at each step, and in this way determining a curve of differential phase shift versus plate thickness from which the optimum plate thickness may be read off. For polystyrene plates in circular or square wave guide the optimum thickness will be of the order of but somewhat less than half the diameter or width of the wave guide.

Whereas the dielectric material referred to in this specification has been primarily polystyrene, it should be understood that other low loss dielectrics preferably of high dielectric constant may be used in lieu thereof such as polystyrene loaded with lead chloride, rutile, metallic titanates, and ceramics of strontium titanate or calcium titanate.

Dielectric plates of increasing thickness may be utilized to shorten the length L of the phase shift section required to provide a predetermined phase shift. Various shapes for the conductive boundaries of the wave guide phase shift section may be utilized such as a square pipe shown in Figs. 5 and 5A, a rectangular pipe, or a highly symmetrical curved pipe.

The circular wave guide shifters described in this specification are particularly adaptable as rotatable elements in wave guide systems, in the various ways disclosed in the aforementioned United States application of A. G. Fox, Serial No. 464,333, filed November 3, 1942.

While the invention has been illustrated in specific forms for the purpose of the disclosure, it will be apparent that modifications thereof or therein may be made by the persons skilled in the art without departing from the purpose and scope of the invention.

What is claimed is:

A reflectionless phase shifter for incident linearly polarized, dominant electromagnetic waves comprising a non-radiating, low loss section of uniform hollow wave guide, a low loss dielectric plate disposed longitudinally between the ends of said section, collinear reactance screws disposed in the wall of said guide transverse to said plate to neutralize reflections set up by said plate, said plate being disposed obliquely with respect to the incident polarization and having a thickness small with respect to length and width, whereby polarization components parallel and perpendicular to said plate respectively are propagated through said section with a predetermined differential phase shift and the output wave is elliptically polarized.

ARTHUR GARDNER FOX.

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