

[54] **DIFFERENTIAL PHASE-SHIFTER FOR PROVIDING A SUBSTANTIALLY CONSTANT DIFFERENTIAL PHASE-SHIFT**

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[22] Filed: **Oct. 6, 1972**

[21] Appl. No.: **295,610**

[52] U.S. Cl. **333/31 A, 333/95 R, 333/98 R**

[51] Int. Cl. **H03h 7/30, H01p 1/18**

[58] Field of Search..... **333/31 A, 21 A, 95 R, 333/98 R**

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[57] ABSTRACT

A differential phase-shifter which provides a substantially constant differential phase-shift to two orthogonally polarized waves having the same frequency band by causing one of the waves to see two phase-constant characteristics having rates of change over the band which are greater than and less than, respectively, the rate of change of the phase-constant seen by the other wave.

6 Claims, 2 Drawing Figures

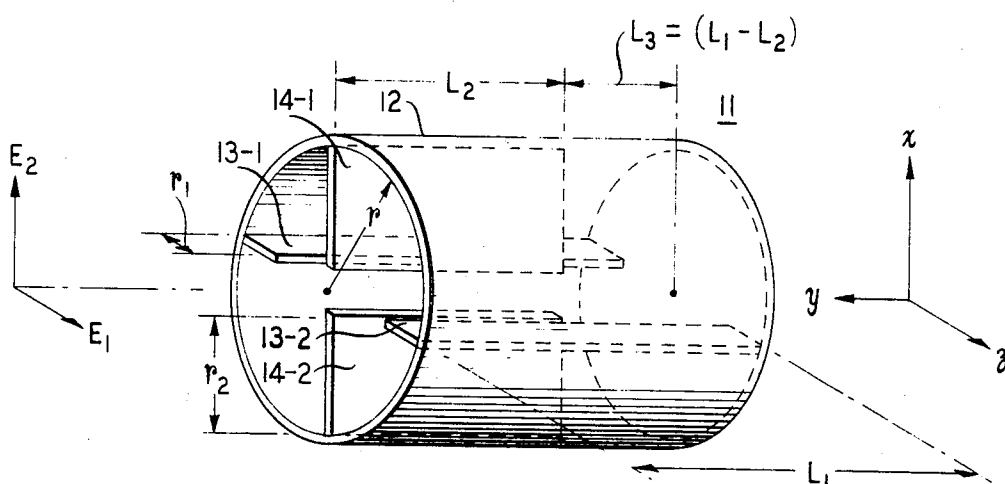


FIG. 1

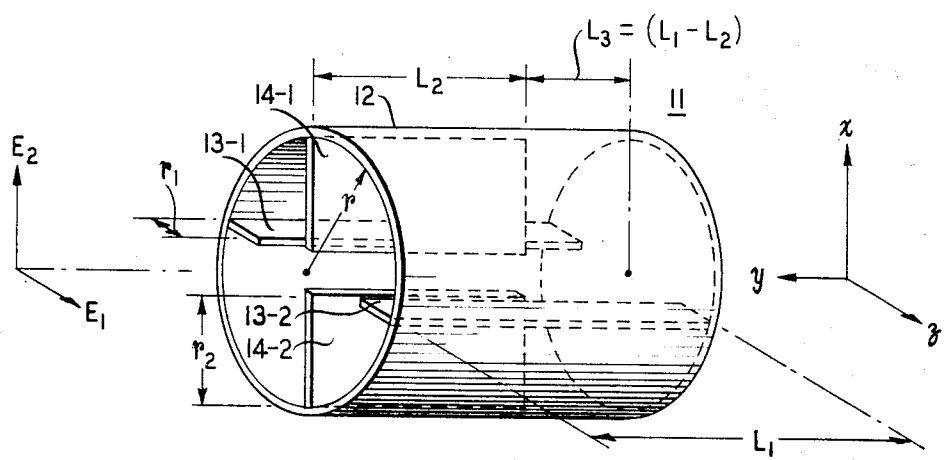
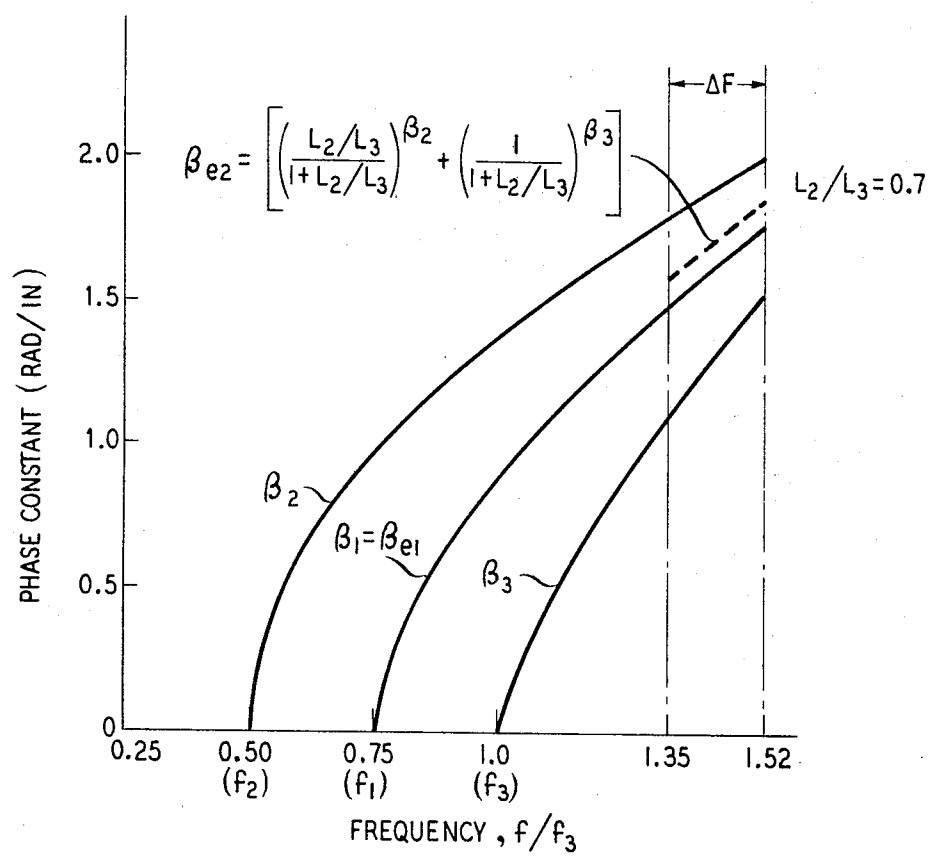


FIG. 2



DIFFERENTIAL PHASE-SHIFTER FOR PROVIDING A SUBSTANTIALLY CONSTANT DIFFERENTIAL PHASE-SHIFT

BACKGROUND OF THE INVENTION

This invention relates to microwave waveguide phase-shifters and, more particularly, to waveguide phase-shifters having a constant differential phase-shift over a broad frequency band.

In dual polarization waveguide systems, it is often required that one of the propagating orthogonal polarizations be shifted in phase relative to the other polarization. Differential phase-shifters for providing such a difference in phase-shift to the two orthogonal polarizations are well known in the art.

A typical prior art differential phase-shifter might comprise a circular waveguide which is loaded by symmetrically disposing therein in a plane parallel to one of the polarizations a pair of thin elongated fins. As a result of the presence of such fins, the cutoff frequency seen by the one polarization in traversing the guide will be less than the cutoff frequency seen by other polarization. This, in turn, causes the phase constant (i.e., phase-shift per unit length) versus frequency characteristic of the guide corresponding to the former polarization to have a greater magnitude and lesser rate of increase over any given frequency band than the respective magnitude and rate of increase of the phase-constant characteristic of the guide corresponding to the latter polarization. The two characteristics will thus have differing magnitudes at any given frequency within the frequency band of the two polarizations. As a result, the two polarizations will experience different amounts of phase-shift at such frequencies.

While, however, the differing magnitude between aforesaid phase-constant characteristics does result in a difference in phase-shift between the two polarizations, it is found that the differing rates of change of the characteristics causes such difference to change from frequency to frequency. As a result, the differential phase-shift provided by the phase-shifter does not remain constant over the frequency band of the polarizations. The failure to maintain a constant differential phase-shift over the frequency band causes the phase-shifter to generate unwanted cross-polarization components, thereby introducing loss and signal degradation into the waveguide system.

It is, therefore, a broad object of the present invention to provide a differential phase-shifter having a substantially constant differential phase-shift over a broad frequency band.

SUMMARY OF THE INVENTION

In accordance with the principles of the present invention, the above and other objectives are accomplished by a differential phase-shifter comprising a waveguide which is loaded such that a first wave introduced therein is caused to see a first cutoff frequency over a first length of the waveguide and a second introduced wave polarized orthogonal to the first is caused to see second and third cutoff frequencies which are less than and greater than, respectively, the first cutoff frequency over second and third lengths of the guide which together equal the first length of guide. As a result of the aforesaid loading, the phase-constant characteristic corresponding to the second wave over the second length of guide will have a greater magnitude

but a lesser rate of change than the respective magnitude and rate of change of the phase-constant characteristic corresponding to the first wave over the first guide length. Conversely, however, the phase-constant characteristic corresponding to the second wave over the third length of guide will have a lesser magnitude but a greater rate of change than the respective magnitude and rate of change of the characteristic corresponding to the first wave. Owing to the aforesaid relationships between the magnitudes and rates of change of the phase-constant characteristics corresponding to the second wave relative to the magnitude and rate of change of the phase-constant characteristic corresponding to the first wave, the second and third waveguide lengths can be so proportioned relative to each other as to cause the former characteristics to tend to produce the same phase-shift of the second wave as would be produced by a composite phase-constant characteristic which tracks or follows the phase-constant characteristic corresponding to the first wave. The composite phase-shift induced by the guide to the second wave will thus also tend to track the phase-shift induced thereby to the first wave.

In one specific embodiment of the present invention, the loading of the guide is accomplished by inserting first and second pairs of appropriately dimensioned thin, elongated plates or fins therein. More specifically, the first pair of fins are symmetrically disposed with their planes parallel to the plane of the first wave, while the second pair of fins are symmetrically disposed with their planes parallel to the plane of the second wave. By selecting the radial and axial dimensions of each of the second pair of fins to be greater than and less than, respectively, the radial and axial extent of each of the first pair of fins, the two pairs of fins will produce the required type of loading of the guide described hereinabove.

BRIEF DESCRIPTION OF THE DRAWING

A clearer understanding of the above-mentioned objects and features of the present invention can be obtained by reference to the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 shows a broadband differential phase-shifter in accordance with the principles of the present invention;

FIG. 2 shows the phase-constant versus frequency characteristics of the phase-shifter of FIG. 1 which contribute to the phase-shifts experienced by the two orthogonally polarized waves introduced therein.

DETAILED DESCRIPTION

Prior to beginning a discussion of the present invention, a brief review of some of the basic waveguide principles which have been referred to hereinabove and which will be referred to again hereinbelow will now be given. As is well known, the phase-shift versus frequency characteristic θ_g of a waveguide corresponding to a particular electromagnetic wave is given as

$$\theta_g = \beta_g L_g \quad (1)$$

where β_g is the phase-shift versus frequency characteristic of a unit length of the guide and is referred to as the phase constant characteristic and L_g is the length of

the guide. The phase-constant characteristic β_g , in turn, is uniquely defined in terms of the cutoff frequency f_c of the guide pertaining to the particular wave being phase-shifted. More specifically, β_g can be written as

$$\beta_g = 2\pi/c f \sqrt{1 - (f_c/f)^2} \quad (2)$$

where f is the wave frequency and c is the speed of light in a vacuum.

As is apparent from Eq. (2), the magnitude and rate of increase of the phase-constant characteristic of a guide over a given frequency band of a wave depends upon the degree to which the frequency band is above the cutoff frequency seen by the wave. Two waves having the same frequency band but seeing different cutoff frequencies will thus have corresponding phase-constant characteristics having different rates of increase and different magnitudes over their frequency band, since the wave seeing the lower cutoff frequency will have the frequency band farther above its cutoff frequency than the wave seeing the higher cutoff frequency. More particularly, the phase-constant characteristic corresponding to the former wave will have a greater magnitude but a lesser rate of change over the frequency band than the respective magnitude and rate of change of the characteristic corresponding to the latter wave, since the farther the frequency band is above a cutoff frequency the lesser will be the rate of change of the corresponding characteristic over the band and the greater will be its magnitude.

As is apparent from the above, in determining the magnitude and rate of change of the phase-constant characteristic of one wave relative to that of another wave having the same frequency band, it is necessary that the cutoff frequency f_c of the guide pertaining to each of the waves be determined. In general, the latter frequency is a unique function of the inverse of the largest apparent guide dimension d which lies in the plane which is orthogonal to the plane of polarization of the wave. Thus, typically, f_c can be written as

$$f_c = k/d \quad (3)$$

where k is a constant determined by the type of guide cross-section.

In portions of a guide which are empty (i.e., unloaded), the apparent dimension d seen by a wave is the actual physical dimension of the guide. However, if the guide is appropriately loaded, the dimension d seen by the wave appears larger than the aforesaid physical dimension. Such loading can take the form of a symmetrically disposed pair of fins, each fine having a radial and axial extent which is substantially greater than its thickness. By disposing the fins within the guide with their planes (i.e., plane defined by their axial and radial dimensions) parallel to the plane of polarization of the wave, the fins cause a capacitive loading which results in making the dimension of the guide in the plane orthogonal to the fins and thus orthogonal to the plane of polarization of the wave appear larger. The degree of apparent increase in the guide dimension, moreover, is dependent upon the radial extent of the fins. In general, the larger such extent, the larger will be the apparent increase.

A portion of guide loaded with fins in the above-indicated fashion thus has a cutoff frequency which is

less than the cutoff frequency of the empty portions of the guide. Additionally, in portions of the guide in which different degrees of the latter type fin loading are present, those portions having fins with a larger radial extent have smaller cutoff frequencies than those portions having fins with a smaller radial extent.

A wave passing through the guide polarized parallel to a pair of fins will thus have a corresponding phase-constant characteristic in the aforesaid fin loaded portion of the guide whose magnitude and rate of change over the frequency band of the wave are greater than and less than, respectively, the magnitude and rate of change of the phase-constant characteristic corresponding to the wave in the unloaded portions of the guide. Moreover, the magnitude and rate of change of the phase-constant characteristics corresponding to fin loaded guide portions including fins having a larger radial extent will likewise be greater than and lesser than, respectively, the magnitude and rate of change of the phase-constant characteristics corresponding to fin loaded guide portions comprising fins of a smaller radial extent.

Since a single waveguide can have some portions which are unloaded and other portions which are fin loaded, it is apparent that a wave traversing such a guide will see different cutoff frequencies and thus have phase-constant characteristics having different magnitudes and rates of change in the differently loaded guide portions. The effective phase-constant versus frequency characteristic of such a guide will thus be a composite sum of the different phase-constant characteristics multiplied by the proportionate lengths of the guide over which they govern. The net phase-shift versus frequency characteristic of the guide, in turn, is merely the product of the latter effective phase-constant characteristic and the total guide length.

Having discussed some of the waveguide principles which will be referred to in the description hereinbelow, attention is now directed to FIG. 1 which shows a phase-shifter 11, in accordance with the principles of the present invention. Phase-shifter 11 provides a differential phase-shift $\Delta\theta$ to two electromagnetic waves E_1 and E_2 which are polarized in the orthogonal y , z and x , y planes, respectively, of a mutually orthogonal reference coordinate system x , y , z . Each of the waves E_1 and E_2 is assumed to propagate parallel to the y direction. Furthermore, each of the waves is assumed to have the same broad frequency band Δf . It is over the latter band that the differential phase-shift $\Delta\theta$ provided by phase-shifter 11 is to have a substantially constant value.

As shown in FIG. 1, phase-shifter 11 comprises a waveguide 12 having a length L_1 and a circular cross section of radius r . The latter waveguide is arranged with its axis along the propagation direction of the waves E_1 and E_2 . Disposed within waveguide 12 are a first pair of symmetrically arranged, thin, elongated members or fins 13-1 and 13-2.

Each of the latter fins has a length which is greater than its width and a width which is substantially greater than its thickness. The length of each fin extends parallel to the guide axis over the entire axial extent L_1 of the guide. The width of each fin 13, on the other hand, has an extent r_1 and runs parallel to the radial direction of the guide which lies in the plane of polarization of the wave E_1 . Each of the fins 13 is thus arranged so that its plane (i.e., the plane defined by its length and width)

is parallel to the plane of polarization of the wave E_1 .

A second set of symmetrically arranged fins 14-1 and 14-2, each having a length which is greater than its width and a width substantially greater than its thickness, are also disposed within waveguide 12. More particularly, each of the fins 14 has a length L_2 which is less than the length L_1 of the fins 13 and a width r_2 which is greater than the width r_1 of the latter fins. Moreover, the length of each fin 14 extends parallel to the guide axis, while the width of each fin extends parallel to the radial direction of the guide which lies in the plane of polarization of the wave E_2 . Hence, the fins 14 are disposed so that their planes are parallel to the plane of polarization of the latter wave and, thus, orthogonal to the plane of fins 13.

It is noted that the fins 13 have been described above as having lengths which extend over the entire axial length L_1 of guide 12. It should be further noted, however, that the fins have been depicted as being of such a length only to simplify the discussion which is to follow. The principles of the invention are thus intended to apply as well to cases where the fins 13 have a shorter length than that of waveguide 12.

As above-indicated, passage of the waves E_1 and E_2 through phase-shifter 11 results in a differential phase-shift $\Delta\theta$ between the two waves. The latter differential phase-shift $\Delta\theta$ will thus be equal to the difference between the phase-shift θ_1 imparted to the wave E_1 and the phase-shift θ_2 imparted to the wave E_2 by the phase-shifter. That is

$$\Delta\theta = \theta_2 - \theta_1 \quad (4)$$

The phase-shifts θ_1 and θ_2 can, in turn, be expressed in terms of the effective phase-constant versus frequency characteristics β_{e1} and β_{e2} of the guide 12 corresponding to the waves E_1 and E_2 , respectively, as follows:

$$\theta_1 = L_1 \beta_{e1} \quad (5)$$

$$\theta_2 = L_1 \beta_{e2} \quad (6)$$

Substitution of Eqs. (5) and (6) into Eq. (4) yields for $\Delta\theta$

$$\Delta\theta = L_1 (\beta_{e2} - \beta_{e1}) \quad (7)$$

As is apparent from Eq. (7), in order for $\Delta\theta$ to remain substantially constant over the frequency band Δf of the waves E_1 and E_2 , the two phase-constants β_{e2} and β_{e1} , must have different magnitudes but the same rate of change over the band, i.e., the two characteristics must track or follow one another thereover. That such a condition is achieved by the phase-shifter 11 of FIG. 1 will become apparent from the discussion hereinbelow.

As discussed above, the effective phase-constant characteristic of a waveguide corresponding to a particular wave is dependent upon the individual phase-constant characteristics of the guide corresponding to the wave and the different proportional lengths or portions of guide over which such phase-constants govern.

Moreover, as also discussed above, guide portions having different degrees of loading will have different cutoff frequencies and, as a result, will likewise have different phase-constant characteristics.

Following the traversal of the wave E_1 through waveguide 12, it is thus noted that the wave sees a guide loaded with fins 13 throughout the entire length of the guide. The wave E_1 thus sees a single cutoff frequency f_1 over the entire guide length and, as a result, a single phase-constant characteristics β_1 . Since the effective phase-constant β_{e1} of guide 12 corresponding to E_1 is the sum of the phase-constants of different portions of the guide corresponding to the wave multiplied by their proportionate governing lengths, β_{e1} is merely given as

$$\beta_{e1} = \beta_1 (L_1/L_1) = \beta_1 \quad (8)$$

The wave E_2 , on the other hand, in its traversal of guide 12, sees a first portion of guide of length L_2 loaded with fins 14 and a second portion of guide of length L_3 (i.e., $L_1 - L_2$) which is unloaded. The E_2 wave will thus see two cutoff frequencies f_2 and f_3 and, hence, two phase-constant characteristics β_2 and β_3 corresponding, respectively, to the two lengths of guide L_2 and L_3 . The effective phase-constant β_{e2} corresponding to E_2 will then be the sum of the latter two phase-constants each being multiplied by the proportion of the total length of the guide to which it pertains. Thus,

$$\beta_{e2} = (L_2/L_1) \beta_2 + (L_3/L_1) \beta_3 \quad (9)$$

Substituting $(L_2 + L_3)$ for L_1 in Eq. (10) and rewriting the equation in terms of the ratio L_2/L_3 yields

$$\beta_{e2} = \left[\frac{L_2/L_3}{1 + L_2/L_3} \right] \beta_2 + \left[\frac{1}{1 + L_2/L_3} \right] \beta_3 \quad (10)$$

Insight into the behavior of the characteristic β_{e2} given by Eq. (10) relative to that of the characteristic β_{e1} given by Eq. (8) over the band Δf of the waves E_1 and E_2 can be obtained by examining the relative behavior of three characteristics β_1 , β_2 and β_3 over the band.

As above indicated, the behavior of a phase-constant characteristic over a particular frequency band is dependent upon the cutoff frequency seen by the wave to which the phase-constant corresponds. Over a given frequency band, phase-constants corresponding to waves seeing smaller cutoff frequencies will have magnitudes and rates of change which are greater than and less than, respectively, the magnitudes and rates of change of phase-constants corresponding to waves seeing larger cutoff frequencies. Moreover, in portions of a guide in which there is fin loading, that is, in which fins are symmetrically placed in a plane parallel to the plane of a wave, the cutoff frequency seen by the wave will be smaller than the cutoff frequency seen by the wave in portions of the guide in which no fins are present. Likewise, in portions of a guide having different degrees of the latter type of fin loading, those portions having fins of a larger radial extent will have smaller apparent cutoff frequencies than those portions having smaller radial extent.

Based on the above principles, it is thus apparent that the cutoff frequency f_1 seen by E_1 over the loaded length L_1 will be greater than the cutoff frequency f_2 seen by E_2 over the more heavily loaded length L_2 , but less than the cutoff frequency f_3 seen by E_2 over the unloaded length L_3 . That is

$$f_2 < f_1 < f_3$$

(11).

As a result, the phase constant characteristic β_1 corresponding to f_1 will have a magnitude and rate of change over the band Δf which are greater than and less than, respectively, magnitude and rate of change of the phase constant characteristic β_3 corresponding to f_3 . The phase-constant characteristic β_2 corresponding to f_2 , in turn, will have a magnitude and rate of change over Δf which are, respectively, greater than and less than, respectively, the magnitude and rate of change of β_1 .

It is noted, therefore, that the two phase-constants β_2 and β_3 have magnitudes over the band Δf which are, respectively, greater than and less than the magnitude of the phase-constant β_1 but, more importantly have rates of change over Δf which are, respectively, less than and greater than the rate of change of β_1 . The proportionate addition of β_2 and β_3 to form β_{e2} in Eq. (10) will thus tend to cause β_{e2} to have a rate of change over Δf which more closely approximates the rate of change of β_1 and, hence, β_{e1} than either of the rates of change of the individual phase-constants β_2 or β_3 . Proper selection of the proportionality factor (L_2/L_3) of Eq. (10) will result in the effective phase-constant β_{e2} closely tracking the effective phase-constant β_{e1} over the band Δf of waves E_1 and E_2 . The particular value of the aforesaid proportionality factor which will produce the best tracking in any given case will, of course, depend on the system parameters, i.e., the frequency band Δf and the frequencies f_1 , f_2 and f_3 to name a few. However, once the aforesaid parameters are known or selected, empirical techniques can be used to arrive at the value of (L_2/L_3) which produces the closest track between the effective phase-constants β_{e2} and β_{e1} .

In FIG. 2, the phase-constant characteristics β_1 , β_2 and β_3 and the effective phase-constant characteristics β_{e1} and β_{e2} are plotted for the case of (L_2/L_3) = 0.7, f_1/f_3 = 0.75, f_2/f_3 = 0.5 and a Δf from $1.35f_3$ to $1.53f_3$. As is readily apparent from the figure, the proportionate addition of β_2 and β_3 results in a β_{e2} over Δf having a magnitude greater than the magnitude of β_{e1} and a rate of change substantially equal to that of β_{e1} .

It should be noted, moreover, that in one particular illustrative case, tracking of β_{e2} and β_{e1} over a frequency band from 3.7 GHz to 4.2 GHz (i.e., the 4 GHz common carrier band) so as to result in a differential phase-shift of $\Delta\theta = 90^\circ$ over the band was realized by a differential phase-shifter having the parameter ratios as given above and, in addition, the following parameter values:

$$L_1 = 11.41''$$

$$L_2 = 8.14''$$

$$r = 1''$$

$$r_1 = 0.548''$$

$$r_2 = 0.881''$$

In all cases, it is understood that the above-described arrangement is merely illustrative of some of the possible embodiments which represent applications of the

present invention. Numerous and varied other arrangements can be readily devised in accordance with these principles without departing from the spirit and scope of the invention. For example, while the present invention has been described in terms of loading waveguide 12 with pairs of fins, other types of equivalent loading might also be used. In particular, the loading effect on guide 12 produced by anyone of the pair of fins (e.g., the pairs of fins 13) disposed therein could be similarly produced by replacing the pair of fins with two sets of closing spaced tuning screws. In such a case, each set of tuning screws would replace one fin of the pair and would be so arranged as to be equivalent to that fin. More specifically, each set of the tuning screws would be distributed along the guide axis over a length equivalent to the length of the fin they are replacing and would extend through the guide wall and into the guide in a radial direction parallel to the radial dimension (i.e., width) of the latter fin.

What is claimed is:

1. A differential phase-shifter for providing a substantially constant differential phase-shift to first and second orthogonally polarized waves each having the same frequency band comprising:

a conductively bounded waveguide capable of supporting said first and second waves;

first means for loading a first portion of said waveguide having a first length to cause said first wave to see a first cutoff frequency in said first portion;

and second means for loading a second portion of said waveguide to cause said second wave to see a second cutoff frequency which is less than said first cutoff frequency over a second length of said second portion and to see a third cutoff frequency which is greater than said first cutoff frequency over a third length of said second portion, said second and third lengths having a sum which is equal to said first length and being so proportioned as to cause the phase-shift characteristic of said second portion corresponding to said second wave to track the phase-shift characteristic of said first portion corresponding to said first wave over said frequency band.

2. A differential phase-shifter in accordance with claim 1 in which

said first means results in the phase-constant characteristic of said first portion having a first magnitude and a first rate of change over said band;

and in which said second means results in the phase-constant characteristic of the second length of said second portion having a second magnitude which is greater than said first magnitude and a second rate of change which is less than said first rate of change and in the phase-constant characteristic of the third length of said second portion having a third magnitude which is less than said first magnitude and a third rate of change which is greater than said first rate of change.

3. A differential phase-shifter in accordance with claim 1 in which said waveguide has a circular cross-section.

4. A differential phase-shifter in accordance with claim 1 in which said second portion is included within said first portion.

5. A differential phase-shifter in accordance with claim 1 in which:

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said first means includes a first pair of fins symmetrically disposed within said first portion, each of said first pair of fins having a length which is equal to said first length and which is greater than its width and a width which is greater than its thickness and each being arranged with its length parallel to the axis of said waveguide and its width in plane which is parallel to the plane of polarization of said first wave;

and said second means includes a second pair of fins symmetrically disposed within the second length of said second portion, each of said first pair of fins having a length which is equal to said second length

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and which is greater than its width and a width which is greater than its thickness and each being arranged with its length parallel to the axis of said guide and its width in a plane which is parallel to the plane of polarization of said second wave, said width of each of said second pair of fins being greater than said width of each of said first pair of fins.

6. A differential phase-shifter in accordance with claim 5 in which each of said first pair of fins has the same width and in which each of said second pair of fins has the same width.

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