

[54] **BROADBAND QUARTER-WAVE PLATE ASSEMBLY**

[75] Inventor: **James J. Epis**, Sunnyvale, Calif.

[73] Assignee: **GTE Sylvania Incorporated**, Mountain View, Calif.

[22] Filed: **Nov. 2, 1973**

[21] Appl. No.: **412,297**

[52] U.S. Cl. **333/21 A, 333/31 A, 333/98 R**

[51] Int. Cl. **H01p 1/18**

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

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Primary Examiner—James W. Lawrence

Assistant Examiner—Wm. H. Punter

Attorney, Agent, or Firm—John F. Lawler; Norman J. O'Malley; Elmer J. Nealon

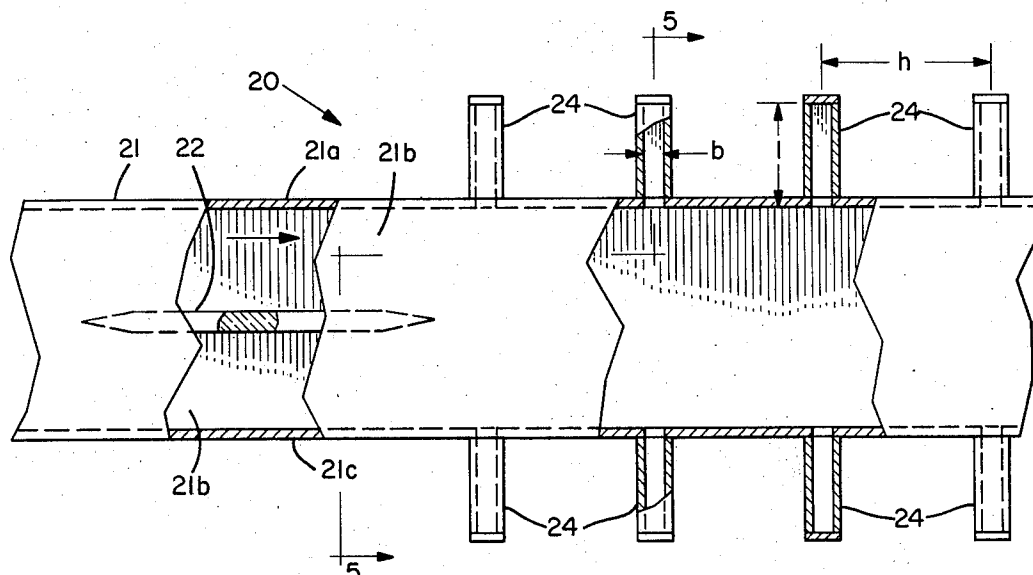
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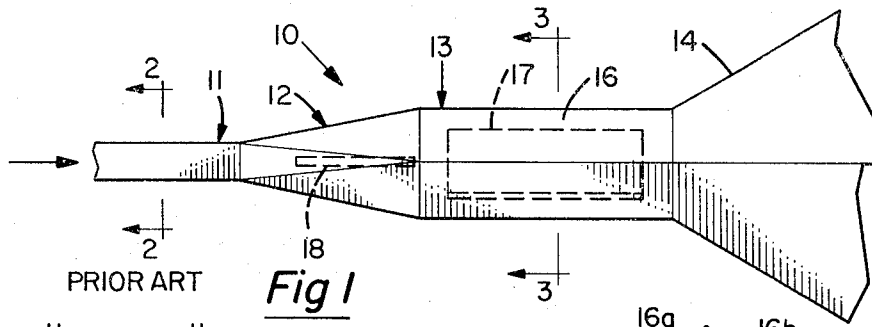
ABSTRACT

A broadband quarter-wave plate having a minimum axial ratio over an octave bandwidth comprises a waveguide transmission line having a tapered dielectric slab and a plurality of longitudinally spaced pairs of rectangular waveguide stubs connected to the line in alignment with the undelayed component (E_N) of the spatially orthogonal linearly polarized waves comprising the principal electromagnetic wave propagating in the transmission line. Each stub is oriented with the longer of its cross-sectional dimensions extending transversely of the direction of propagation of the wave in the main line and the stubs comprising each pair are diametrically opposed to each other. The transmission line to which the waveguide stubs are connected preferably is square waveguide although circular waveguide may also be used with advantage. The stubs are perpendicular to the axis of the line or alternatively may be folded to conserve space. The primary phase changing element, preferably a linearly tapered or step-tapered dielectric slab, is mounted in the line adjacent to the stubs for longitudinal compactness of the assembly.

The relatively small waveguide stub is the electrical equivalent of a frequency independent lumped inductance having utility in other waveguide circuits such as diplexers and filters employing a series inductance element as part of the waveguide circuit.

18 Claims, 13 Drawing Figures





PRIOR ART

Fig 1

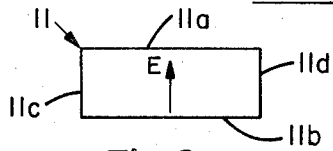


Fig 2

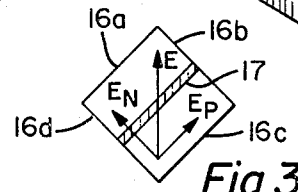


Fig 3

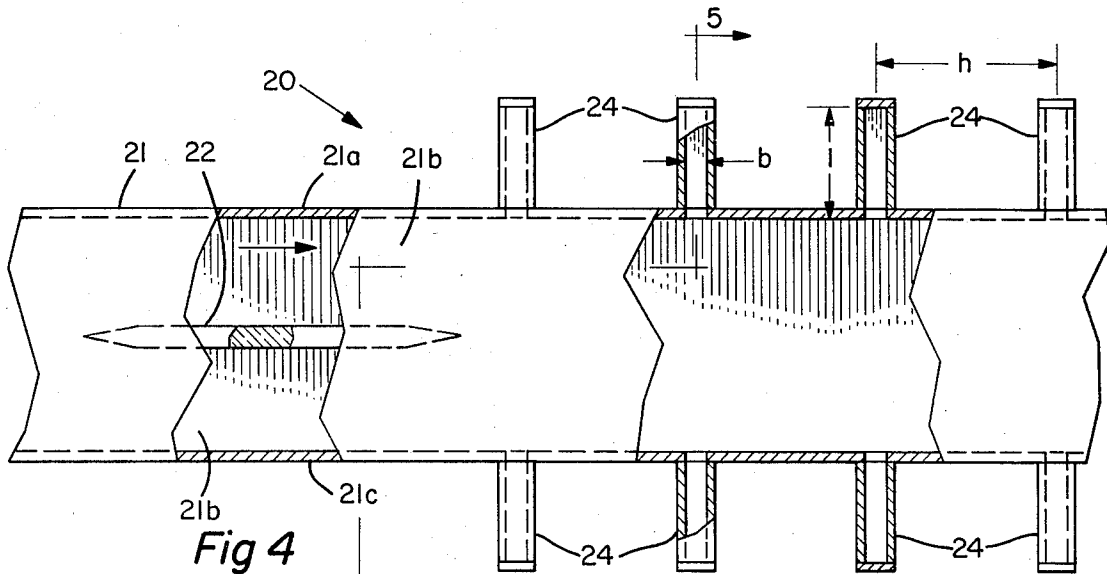


Fig 4

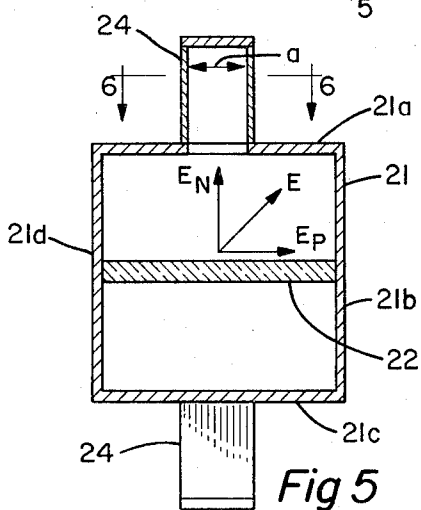


Fig 5

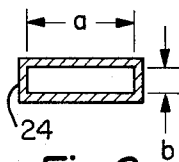


Fig 6

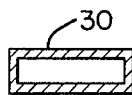


Fig 8

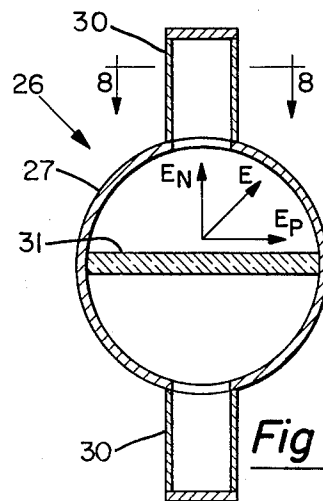


Fig 7

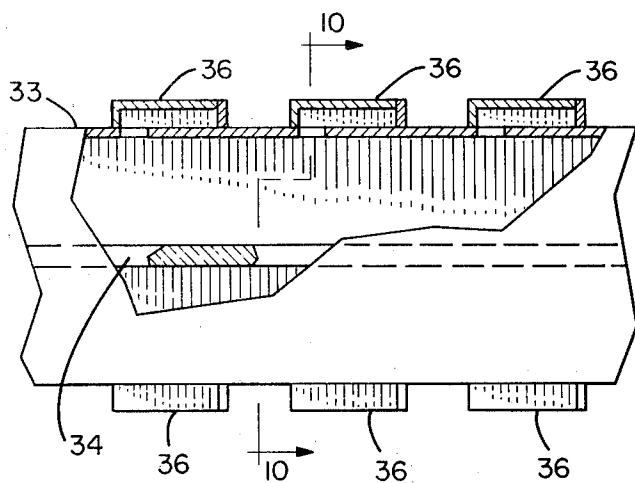


Fig 9

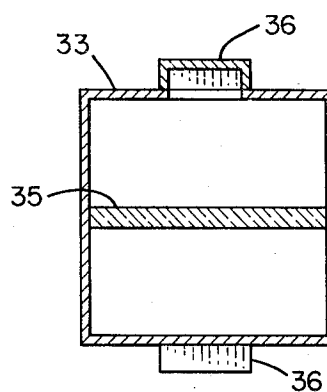


Fig 10

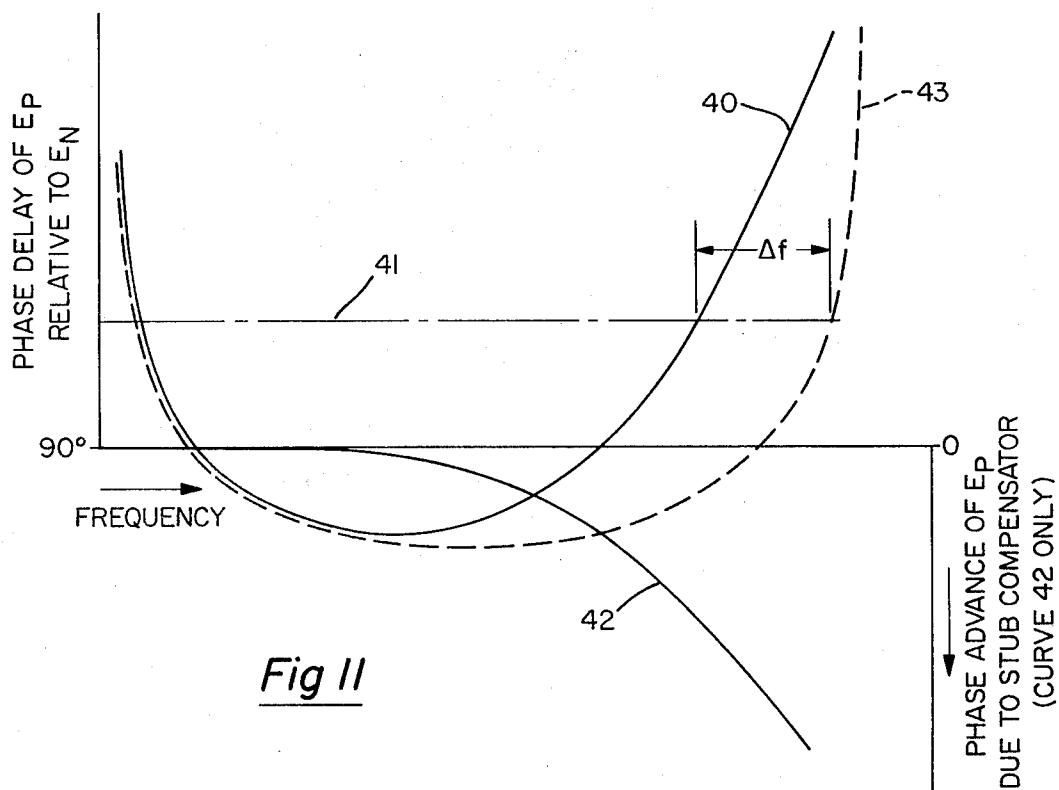
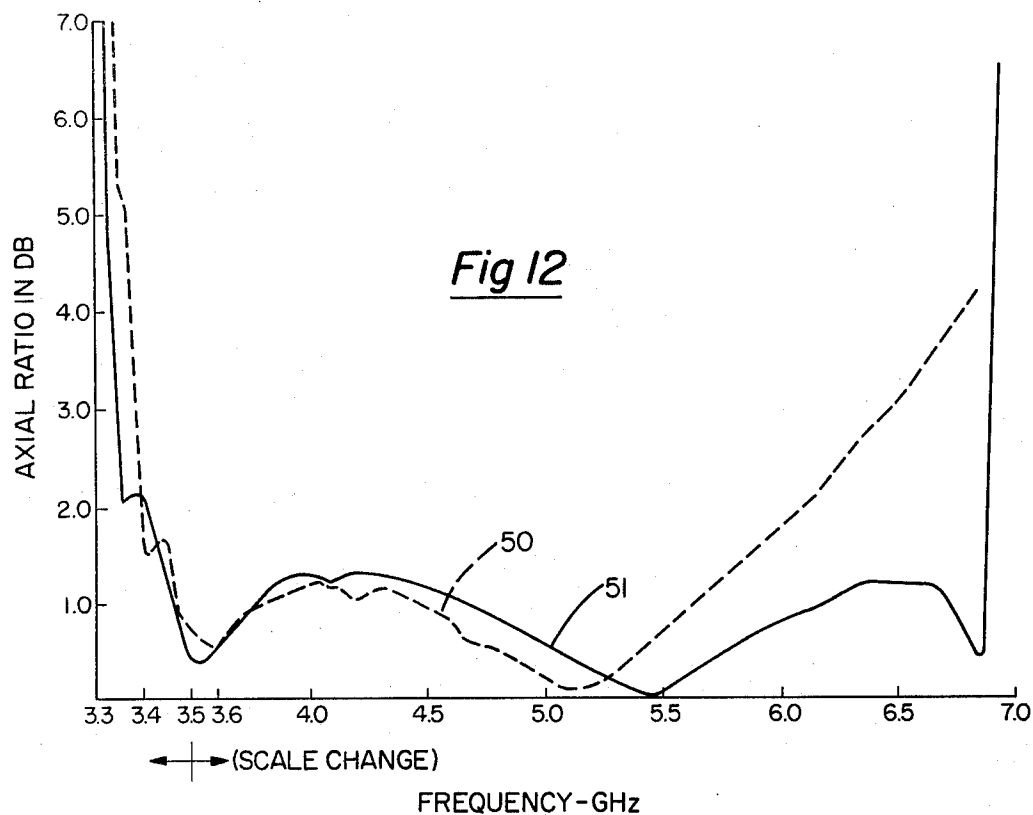
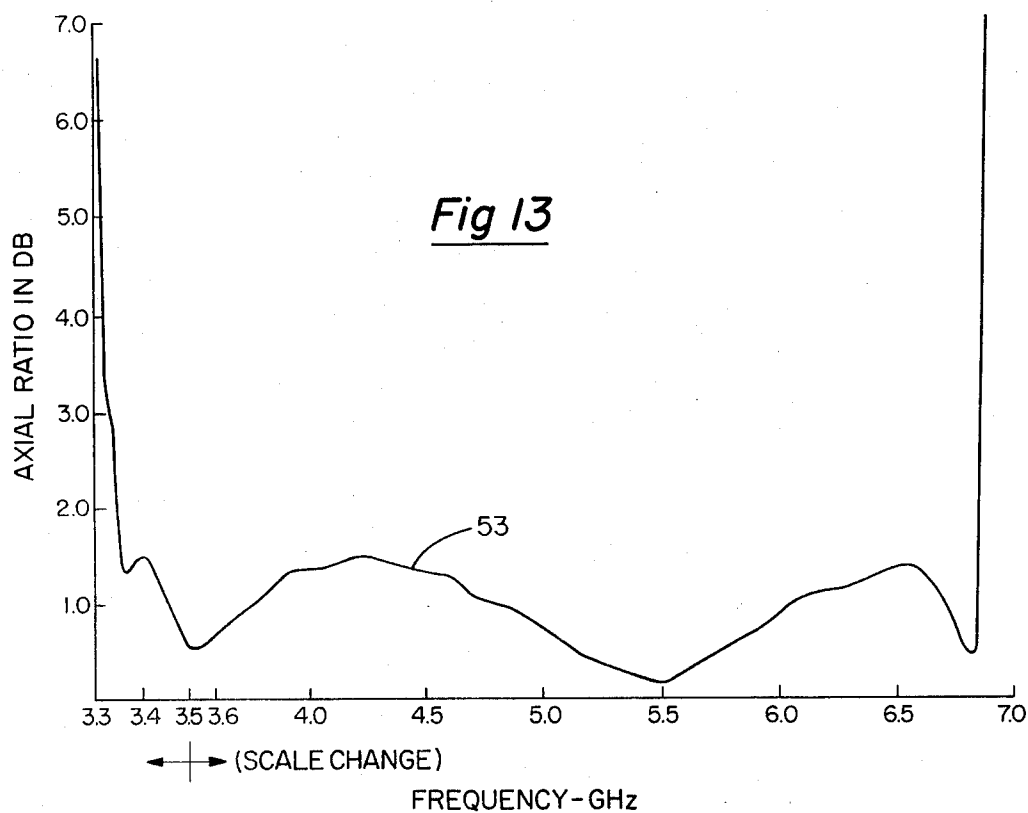


Fig 11



BROADBAND QUARTER-WAVE PLATE ASSEMBLY

BACKGROUND OF THE INVENTION

This invention relates to quarter-wave plates and more particularly to an improved broadband quarter-wave plate having a minimum axial ratio.

A quarter-wave plate is a device placed inside a square or circular waveguide and converts (in a transmitting case) an incoming or incident linearly polarized wave into a pair of outgoing, spatially orthogonal linearly polarized waves, with the latter ideally being equal in magnitude and in phase quadrature (90° out of phase, time wise). For the ideal case, the total outgoing wave is exactly circularly polarized and is said to have a zero-db axial ratio. Such performance is not achievable over practicable operating bandwidths and so design criteria for quarter-wave plates include tradeoffs between bandwidth and axial ratio.

Two main types of practical quarter-wave plates well known in the prior art and which have maximum bandwidths of about 1.75:1 for axial ratios under about 1.7 db are the dielectric slab and metallic irises or "windows," both in circular or square waveguide. This bandwidth limit of these devices is especially significant because, in contrast, the operating bandwidth capability of present receivers and horn antennas with which polarizers are used is an octave or more. Therefore, these prior art polarizers, because of their limited bandwidth, necessitate two horns and a diplexer along with two polarizers for each receiver in order to achieve octave bandwidth operation.

A general object of this invention is the provision of a quarter-wave plate capable of operating over an octave bandwidth with minimum axial ratio, i.e., less than about 1.35 db.

In the course of developing a quarter-wave plate of the type described above, the need arose for providing a lumped inductance in series with the waveguide circuit. This inductive component necessarily was required to be frequency independent in order to provide the required phase compensation in the quarter-wave plate. As a result, a novel series lumped inductance element has been evolved that has utility in waveguide circuits other than quarter-wave plates.

A further object of this invention therefore is the provision of a lumped series inductance for a waveguide circuit.

SUMMARY OF THE INVENTION

In accordance with this invention, the bandwidth of a quarter-wave plate is extended by the addition of electrical equivalents of series lumped inductors to the waveguide circuit so as to affect only one of the spatially orthogonal electric wave components in a manner to offset or compensate the increased phase delay between those field components near the upper frequency limit. The key element in providing the phase compensation is a rectangular waveguide stub in the waveguide transmission line wall and having cross-sectional dimensions sufficiently small that the stub is below propagation cut-off at the highest frequency of operation. A building block comprising a pair of such stubs connected to opposite sides of a square waveguide dielectric slab polarizer provides an operating bandwidth greater than an octave.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic side elevation of a prior art antenna system showing a dielectric quarter-wave plate in the waveguide connected to a horn antenna;

FIG. 2 is an enlarged schematic section of the feed waveguide taken on line 2—2 of FIG. 1;

FIG. 3 is a transverse section of the quarter-wave plate taken on line 3—3 of FIG. 1;

FIG. 4 is a schematic partially sectioned elevational view of a square-waveguide quarter-wave plate embodying this invention;

FIG. 5 is a transverse section taken on line 5—5 of FIG. 4;

FIG. 6 is an enlarged section taken on line 6—6 of FIG. 5;

FIG. 7 is a section similar to FIG. 5 showing the invention embodied in a circular waveguide quarter-wave plate;

FIG. 8 is an enlarged section taken on line 8—8 of FIG. 7;

FIG. 9 is a modified form of the invention showing folded waveguide stubs longitudinally adjacent to the transverse dielectric slab;

FIG. 10 is a transverse section taken on line 10—10 of FIG. 9;

FIG. 11 shows a set of curves which illustrate the principal of operation of the invention;

FIG. 12 shows comparative performance curves of square-waveguide quarter-wave plates with linearly tapered dielectric slabs and with and without waveguide stubs of this invention; and

FIG. 13 is a performance curve for a square quarter-wave plate embodying the invention and having a step-tapered dielectric slab.

DESCRIPTION OF PREFERRED EMBODIMENTS

One class of equipment with which the invention may be practiced with advantage is an antenna system 10 comprising a rectangular waveguide 11, a waveguide transition section 12, a quarter-wave plate 13 and a horn antenna 14, only part of which is shown in the drawing. For purposes of illustration, the system will be shown and described as a transmitting antenna system, although it will be understood it is also operable as a receiving system. Waveguide 11 has broad walls 11a and 11b and narrow walls 11c and 11d and propagates electromagnetic waves with the electric-field vector E normal to the broad walls as shown. Quarter-wave plate 13 comprises a square waveguide 16 with side walls 16a, 16b, 16c and 16d and an internally disposed longitudinally extending dielectric slab 17 which extends between walls 16b and 16d as shown. Square waveguide 16 is angularly displaced by 45° about the waveguide axis relative to rectangular waveguide 11 and this angular orientation is accommodated by the waveguide transition 12. As a consequence, the E-vector of the waves propagating through the square waveguide 16 intersect the slab 17 at a 45° angle and then divides into a component normal to the slab, designated E_N , and a component parallel to the slab, designated E_P . The phase delay induced by the slab 17 in the E_P component relative to the E_N component ideally is 90° thereby producing circular polarization of the waves which are propagated from the horn antenna 14. A resistance card 18 is usually enclosed in transition 12 to absorb

any waves reflected from the forward part of the system.

The foregoing antenna system in which electromagnetic waves are changed from linear to circular polarization is well known in the prior art and does not constitute part of this invention.

The bandwidth over which the above described quarter-wave plate 13 is capable of operating with an acceptable axial ratio is less than an octave for practicable designs. For example, two principal types of practical prior art quarter-wave plates consisting of Tschebycheff-tapered (step-tapered) or linearly tapered dielectric slabs in either circular or square waveguide, and the multiple longitudinally spaced metallic irises or windows in either square or circular waveguide, have maximum bandwidths of approximately 1.75:1 for axial ratios less than 1.7 db. As a consequence, a receiver capable of operating over an octave bandwidth necessarily requires two prior art antenna systems of the type shown in FIG. 1.

A quarter-wave plate embodying this invention and illustrated in FIGS. 4, 5 and 6 overcomes the foregoing limitation of the prior art. The quarter-wave plate assembly 20 comprises a square waveguide 21 having walls 21a, 21b, 21c and 21d enclosing a thin dielectric slab 22 having linearly tapered ends and extending transversely of the interior of the waveguide between and perpendicular to walls 21b and 21d. The waveguide 21 is fed with linearly polarized electromagnetic waves having an electric field vector E at 45° to the plane of slab 22 so that one component E_N of the electric field is normal to plane of the slab and to waveguide walls 21a and 21c and the other component E_P is parallel to the plane of the slab.

Connected to walls 21a and 21c and longitudinally adjacent to slab 22 are a plurality of longitudinally spaced pairs of diametrically opposite rectangular waveguide stubs 24 which open into the interior of square waveguide 21. Stubs 24 are symmetrically disposed about the central plane of square waveguide 21 and each has its long cross-sectional dimension a extending transversely of the direction of propagation of waves in square waveguide 21.

The broad dimension a of each waveguide stub 24 is considerably smaller than the width or height of square waveguide 21 and its narrow dimension b is substantially smaller than dimension a . Dimension a is such that the waveguide stubs are below propagation cut-off even at the highest frequency of operation of the device. By way of example, dimension a is less than approximately $0.45 \lambda_h$, where λ_h is the wavelength at the highest frequency of operation.

Each pair of diametrically opposed stubs 24 is a basic building block which behaves essentially like a pure series inductance in the square waveguide over more than 1.5:1 bandwidth. If only one waveguide stub 24 is employed, the resultant device also behaves as a pure series inductance but only over about 1.3:1 bandwidth in square waveguide; the additional diametrically opposed stub provides the octave bandwidth operation. The number of pairs of stubs 24 employed in the quarter-wave plate is selected on the basis of the impedance match desired, the greater the number of stub pairs the better is the impedance match (lower VSWR). The inductance contributed by each pair of stubs is dependent upon the stub cross-sectional dimensions a and b which are selected on the basis of the optimum number

of stub pairs for good VSWR performance. The stubs serve as a phase compensator in the composite system. The longitudinal spacing between adjacent stub pairs preferably is less than one-quarter of the square guide wavelength ($\lambda_{g/4}$) at the compensator center frequency with the inter-stub spacing preferably increasing toward $\lambda_{g/4}$ as a limit as the number of building block pairs increases.

The lengths l of waveguide stubs 24 may be varied over wide limits with substantially no change in performance of the device. More specifically, the length l need only be sufficiently long at the highest frequency of operation that the attenuation constant in the stub waveguides decreases the electric field to a negligibly small value at the ends of those stubs. When this condition is satisfied, it is electrically inconsequential whether the outer ends of the stubs are uncovered or covered, as shown, albeit the latter is preferred for a dust-proof and moisture-proof system.

The stubs comprising each building block pair preferably are located opposite one another and lie in the plane perpendicular to the longitudinal axis of the square waveguide. The intersections of the stubs with the square waveguide wall preferably are also symmetrical about the longitudinal center plane of the waveguide which center plane is perpendicular to the plane of dielectric slab 20. Thus, the stubs of each pair preferably are centered in the square waveguide in alignment with each other and with the stub propagation axes at the waveguide wall perpendicular to the plane of the dielectric slab.

Summarizing, a complete phase compensator or polarization-sensitive phase shifter for providing an octave-bandwidth, minimal-axial-ratio quarter-wave plate consists of a length of square waveguide containing one or more pairs of waveguide stubs 24. The device containing the stubs shown at the right-hand side of FIG. 4 therefore comprises a complete compensator capable of providing phase delay of the fundamental mode of propagation having transverse polarization E_N and which has virtually no effect on the other transverse polarization component E_P .

The invention may also be practiced with a quarter-wave plate assembly, 26 see FIG. 7, having a circular waveguide 27 instead of the square waveguide 21 of FIGS. 4 and 5. In other respects, the assembly of FIG. 7 is substantially the same as that of FIG. 5 being provided with a plurality of diametrically opposed rectangular waveguide stubs 30 and a longitudinally extending taper-ended dielectric slab 31 within the waveguide perpendicular to the direction of projection of the stubs. While the provision of the stubs 30 in accordance with this invention usefully improves the axial ratio performance and extends the operating bandwidth of such quarter-wave plate assembly 26, the inherent bandwidth limitation of circular waveguide in this configuration has so far prevented achievement of octave bandwidth operation.

Another embodiment of the invention is the folded stub version shown in FIGS. 9 and 10 and comprises a section of square waveguide 33 having a transversely disposed dielectric slab 34 and a plurality of pairs of rectangular waveguide stubs 36 connected to the walls of the waveguide 33 parallel to and opposite slab 35 as shown. Each of the waveguide stubs 36 is folded over the exterior of the rectangular waveguide in such a manner that a wall of waveguide 33 also serves as a

broad wall of each of the waveguide stubs. The embodiment shown in FIGS. 9 and 10 has particular application where space is limited in both longitudinal and transverse directions. In all other respects the performance of the folded stub version of the quarter-wave plate shown in FIGS. 9 and 10 is substantially the same as that described above in connection with FIGS. 4 and 5 both in construction and performance.

In order to explain the principle on which this invention is based, reference is made to the solid line curve 40 in FIG. 11 which is the phase delay characteristic curve of conventional or prior art quarter-wave plates. In the plot of curve 40 in FIG. 11, the base line represents a 90° phase delay of E_p relative to E_N and the horizontal broken line 41 corresponds to the maximum acceptable axial ratio for the device. The bandwidth of the conventional quarter-wave plate can be defined by the intersections of curve 40 with the line 41.

The performance of the phase compensator embodying this invention is illustrated by curve 42 representing the equivalent phase advance of E_p provided by the compensator. The ordinate for curve 42 is phase advance of E_p and is plotted with zero at the base line as indicated at the right side of FIG. 11 with the values of the E_p phase advance increasing in a downward direction. The phase delay characteristic of a quarter-wave plate embodying this invention is shown by the broken-line curve 43 which results from the algebraic addition of curves 40 and 42. The increase Δf in bandwidth resulting from the compensated quarter-wave plate is indicated by the spacing between the points of intersection of curves 40 and 43 with line 41.

It will be noted from inspection of these curves that the phase compensator embodying this invention supplies the equivalent of an added phase advance of E_p relative to E_N , which begins to increase rapidly at approximately the center frequency of the composite quarter-wave plate. The latter can thereby provide maximum possible bandwidths as set by the first higher-order mode excited by the plate itself. It should be further noted that a phase delay added to the E_N component is the electrical equivalent of a phase advance added to the E_p component. The phase compensator embodying this invention operates in this manner, that is, it delays the E_N component.

To describe the principle of operation of the invention, consider first the basic equation for the propagation constant in a simple TEM mode transmission line, which is:

$$\beta = 2\pi f \sqrt{LC} \quad (1)$$

where

L = series inductance per unit length of line
 c = shunt capacitance per unit length of line
 f = signal frequency.

Thus the phase delay through a length "l" of transmission line is:

$$\phi(f) = \beta l = 2\pi f l \sqrt{LC} \quad (2)$$

By letting L and C be functions of frequency, equation (2) can validly be applied to unloaded and loaded waveguides. Thus,

$$\phi(f) = 2\pi f l \sqrt{L(f) C(f)} \quad (3)$$

which, in the present case, is valid for both of the orthogonal E_N and E_p "channels" of a quarter-wave plate. The phase delay of E_p relative to E_N is, therefore, equal to

$$\theta(f) = \left\{ 2\pi f \right\} \left\{ l_p \sqrt{L_p(f) C_p(f)} - l_N \sqrt{L_N(f) C_N(f)} \right\} \quad (4)$$

which will be decreased if L_N , the equivalent series inductance per unit length in the " E_N -channel," is increased by means of an added device which affects substantially only that channel of the square (or circular) waveguide. This is accomplished by the small rectangular waveguide stubs of the present invention.

It should be noted that the foregoing rectangular waveguide stub for square or circular waveguide provides series inductance in the circuit and has unique application as a lumped inductance element in waveguide circuits other than quarter-wave plates. Other applications for such a series inductance device are in waveguide filters and diplexers. In the latter devices rectangular waveguide is most likely the preferred type of main transmission line, in which case the stubs need not be connected in diametrically opposed relation or pairs. In other words, the stubs operate effectively as inductors when connected either to both broad walls as coplanar pairs, or to just one broad wall of the main rectangular waveguide.

Quarter-wave plates embodying this invention which have been constructed and successfully operated have the following physical characteristics:

Waveguide 21	Square
Type	1.834 inch
Width and Height (internal)	
Stubs 24	
Number	2 pairs
Dimensions	
a	0.812 inch
b	0.157 inch
l	1.500 inch
Interstub spacing h	0.777 inch

FIG. 12 shows the measured axial ratio of a quarter-wave plate having a linearly tapered dielectric slab both with and without the waveguide stubs; the broken-line curve 50 showing performance without the stubs and solid line curve 51 showing performance with the stubs. These tests show that without the stubs of this invention, bandwidth was 1.88:1 for an axial ratio of 3 db and 1.69:1 for an axial ratio of 1.35 db. In contrast, the quarter-wave plate embodying the invention had a 2.05:1 bandwidth at 3 db axial ratio and a 2.00:1 bandwidth at 1.35 db. Curve 53 in FIG. 13 shows the measured performance of the quarter-wave plate described above with a step-tapered dielectric slab and with the waveguide stubs of this invention. The bandwidth at an axial ratio of 3 db was 2.07:1 and at an axial ratio of 1.45 db was 2.05:1.

There is no theoretical lower limit with regard to the value of the maximum axial ratio of the quarter-wave plate embodying this invention. A lower axial ratio is obtained by use of thicker or longer dielectric plates or slabs and more than two pairs of diametrically opposite rectangular waveguide stubs. Such construction means the total length of the composite device would likely be increased. For example, a maximum axial ratio of approximately 0.7 db is obtainable over at least a 2.05:1

bandwidth through use of a compensator comprising four pairs of waveguide stubs having dimensions a smaller than that described above. However, for most applications, a maximum axial ratio of 1.35 db or 1.45 db over an octave bandwidth is considered to be very favorable so that the foregoing physically longer or more complicated compensated quarter-wave plate with a maximum axial ratio of about 0.7 db would be warranted only in special cases requiring such performance.

While the invention has been described in conjunction with a quarter-wave plate having a dielectric plate or slab as the primary phase changing element, the invention is also useful in providing substantial improvement of the axial ratio performance and bandwidth of quarter-wave plates having phase changing elements in the form of metallic irises; however, octave bandwidth performance for the latter type of quarter-wave plate is not practicably achievable. The use of the metallic-iris quarter-wave plate compensated with the waveguide stubs of this invention may be employed to improve axial ratio performance of antenna systems required to transmit very high powers over bandwidths as broad as 1.85:1.

What is claimed is:

1. A broadband quarter-wave plate assembly comprising

a waveguide having a wall and adapted to propagate electromagnetic waves therethrough, a substantially planar phase changing element extending transversely of the interior of said waveguide, and

at least one waveguide stub having a rectangular cross-section with one dimension longer than the other and communicating with the interior of said waveguide through said wall with the axis of said stub at said wall normal to the plane of said element,

the longer of the cross-sectional dimensions of said stub being smaller than the width of the interior of said waveguide.

2. The assembly according to claim 1 comprising at least a pair of said stubs connected to said waveguide on opposite sides thereof, said stubs being aligned with each other in a direction transversely of said waveguide.

3. The assembly according to claim 2 comprising a plurality of said pairs of stubs spaced longitudinally along said waveguide.

4. The assembly according to claim 2 in which said waveguide has a square cross-section.

5. The assembly according to claim 2 in which said waveguide has a circular cross-section.

6. The assembly according to claim 1 in which said stub projects outwardly from said waveguide in a direction transverse to the direction of electromagnetic wave propagation in said waveguide.

7. The assembly according to claim 1 in which said stub extends generally parallel to the direction of propagation of the electromagnetic waves through said waveguide.

8. A broadband quarter-wave plate assembly adapted to change electromagnetic waves propagating therethrough between linearly and circularly polarized states, said assembly comprising

a square waveguide having a longitudinal axis defining the direction of propagation of electromagnetic waves therethrough,

a substantially planar dielectric slab extending transversely of the interior of said waveguide whereby to convert linearly polarized electromagnetic waves (E) into an undelayed component normal to the plane of the slab (E_N) and a phase-delayed component parallel to the plane of the slab (E_P), at least one pair of waveguide stubs connected to said waveguide on opposite sides of said axis, each of said stubs having a rectangular cross-section defined by a long dimension and a shorter dimension and oriented with said long dimension extending generally parallel to the direction of said E_P component,

said long cross-sectional dimension of said stub being smaller than the width of said waveguide.

9. The assembly according to claim 8 in which said long dimension of the stub is not longer than one-half the width of said waveguide.

10. The assembly according to claim 8 with a plurality of longitudinally spaced pairs of said stubs, the longitudinal spacing between adjacent stub pairs being less than one-quarter of the wavelength of waves propagating in the square waveguide at approximately the center frequency of the assembly operating bandwidth.

11. The assembly according to claim 8 in which said stubs project outwardly from said waveguide in a direction transverse to said longitudinal axis.

12. The assembly according to claim 8 in which said stubs are folded so as to extend generally parallel to said longitudinal axis.

13. The assembly according to claim 12 in which each of said stubs and said waveguide have a common wall.

14. The assembly according to claim 8 in which said waveguide stubs are longitudinally spaced from said dielectric slab.

15. The assembly according to claim 8 in which said waveguide stubs are transversely aligned with said dielectric slab.

16. A broadband quarter-wave plate assembly adapted to change electromagnetic waves propagating therethrough between linearly and circularly polarized states, comprising

waveguide means through which said waves propagate,

a primary phase changing element disposed transversely of said waveguide in a predetermined plane whereby the linearly polarized wave propagating in the waveguide having an electric field vector E is divided into an undelayed component E_N normal to said plane and a phase-delayed component E_P parallel to said plane, and

means for adding to said waveguide means an equivalent of series lumped inductors which affect only said E_N component whereby to compensate the increasing phase delay between the E_N and E_P components from approximately the center frequency of the operating bandwidth to the upper frequency thereof.

17. The assembly according to claim 16 in which said waveguide means is defined by a waveguide wall and said last named means comprises at least one rectangular waveguide stub having long and short cross-sectional dimensions, said stub being connected to said

18. The assembly according to claim 17 in which the

cross-sectional dimensions of said stub are such that the stub is below propagation cut-off at the highest frequency of operation of the assembly.

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