

[54] **COMPRISING A SLAB OF SEMICONDUCTOR MATERIAL**

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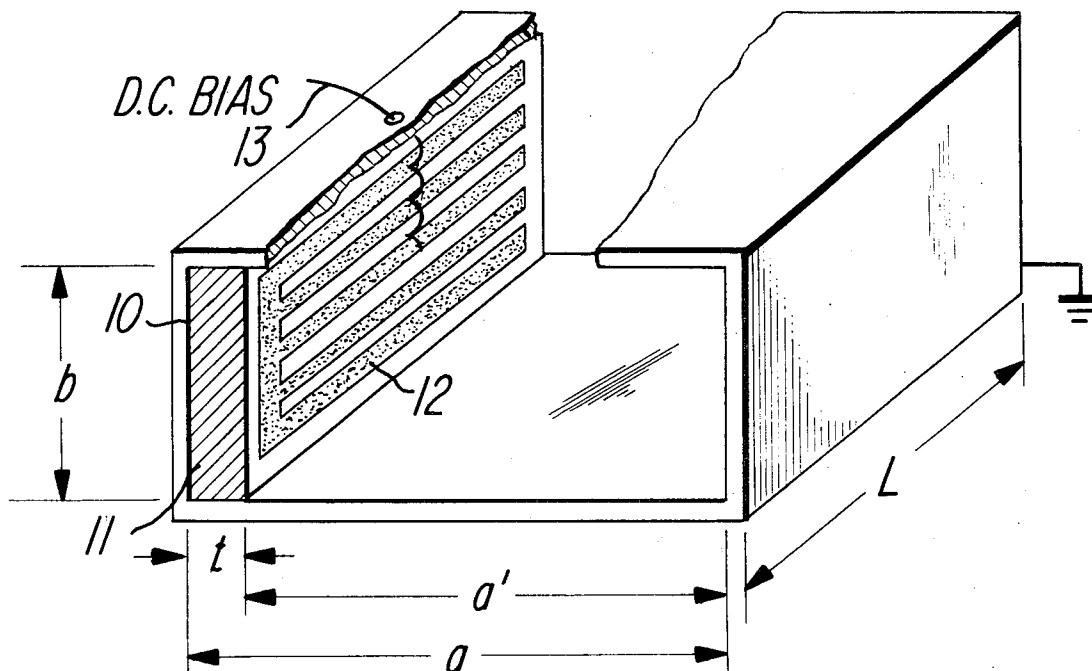
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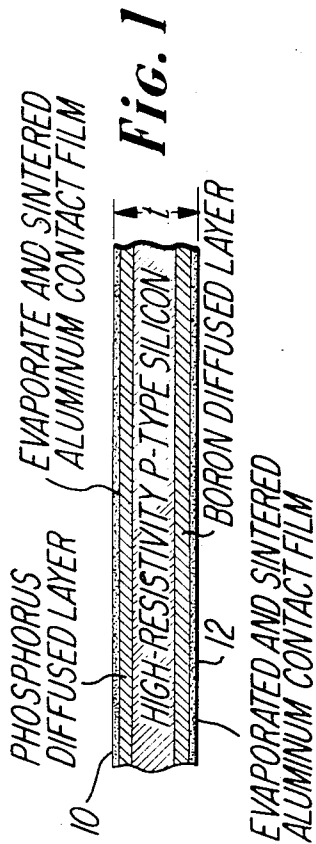
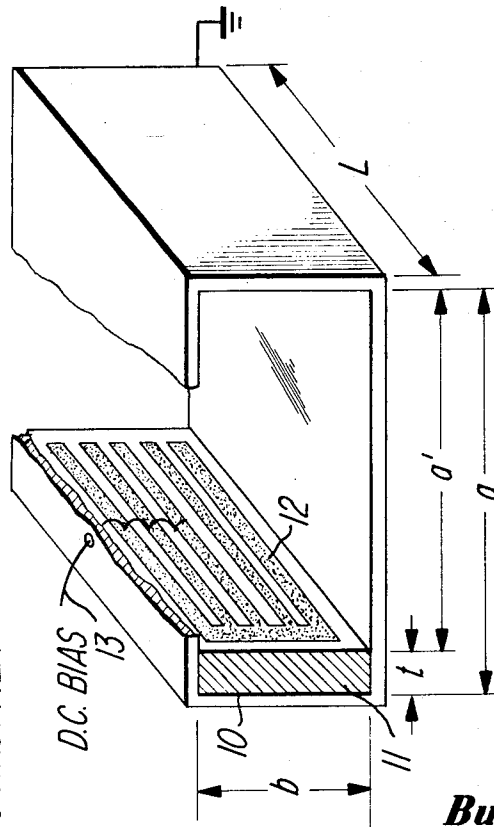
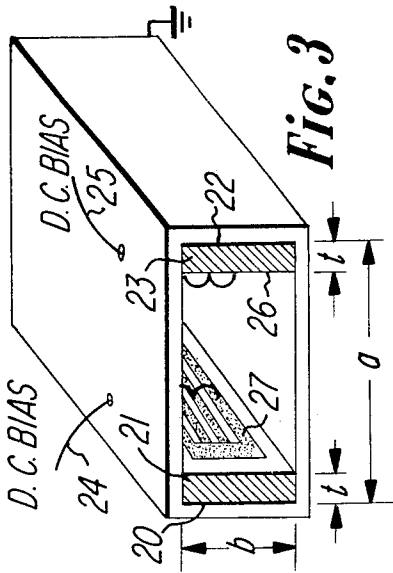
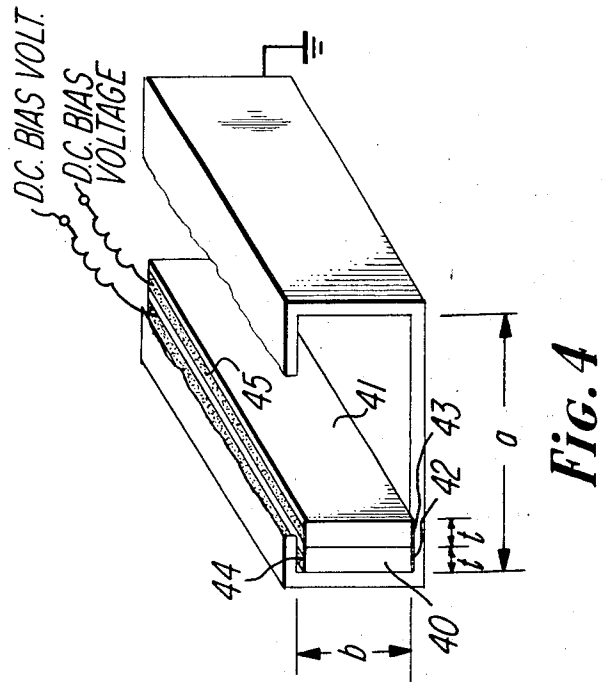
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[57] **ABSTRACT**

A slab of semiconductive material is positioned inside a rectangular waveguide transmission line to electrically change the phase shift within a waveguide. The slab is provided with two electrodes to which a D.C. bias signal is applied; the bias signal varies the conductivity of the semiconductor material to produce the desired phase shift by changing the effective dimensions of the waveguide.

8 Claims, 4 Drawing Figures





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COMPRISING A SLAB OF SEMICONDUCTOR MATERIAL

BACKGROUND OF THE INVENTION

This arrangement relates to an electrically variable waveguide phase shifter. Various techniques based on different theories of operation have been employed in the design and construction of electrically variable waveguide phase shifters. The most common are non-reciprocal ferrite phase shifters and reciprocal diode phase shifters. The operation of the non-reciprocal ferrite phase shifter is dependent upon the interaction between a slab of ferrite material and a magnetic biasing field for its phase shifting effect. However, the relatively high attenuation of microwave signals by ferrite material at millimeter wavelengths has precluded this method of phase shifting in this frequency range.

The diode phase shifters employ one or more diodes mounted inside a waveguide. The diodes are responsive to a D.C. bias voltage applied across the diode electrodes. The field produced by the bias voltage induces a change in the electrical characteristics of the diode, which in turn affects the microwave impedance at various points within the waveguide. The change in impedance causes a change in phase shift in a microwave signal transmitted through the waveguide. The position of the diode inside the waveguide is critical for proper phase shifter performance; usually a combination of one or more strategically positioned diodes is needed to minimize the overall impedance mismatch at the input port of the phase shifter.

At millimeter wavelength frequencies, the internal dimensions of the waveguide are relatively small so that accurate positioning of a diode is a problem. Also, the attenuation of a microwave signal by a variable reactance diode increases with increasing frequency.

SUMMARY

A section of rectangular waveguide transmission line and a slab of variable conductivity semiconductive material having two electrodes thereto, the slab having a thickness t , is used to provide a change of phase shift for a microwave signal coupled to the waveguide. The waveguide has internal broad and narrow phase determining conductive wall dimensions, in a plane transverse to the direction of signal propagation. The semiconductive slab is in contact with substantially the entire surface area of only one of the internal narrow dimensioned waveguide walls. The microwave conductivity of the semiconductive slab is responsive to the polarity of a D.C. bias voltage applied across the slab electrodes. The polarity of the applied bias voltage changes the conductivity of the slab and causes the phase determining broad wall dimension to electrically change.

In the drawings:

FIG. 1 is a cross section of a PIN semiconductive slab structure.

FIG. 2 is a rectangular waveguide phase shifter using one PIN semiconductive slab of the type shown in FIG. 1.

FIG. 3 is a rectangular waveguide phase shifter using two PIN semiconductive slabs of the type shown in FIG. 1.

FIG. 4 is a rectangular waveguide phase shifter using two adjacent PIN semiconductive slabs of the type shown in FIG. 1.

DETAILED DESCRIPTION

Referring to FIG. 1, there is shown a bulk PIN semiconductive slab, which is one type of variable conductivity semiconductive device. The active semiconductor is a high resistivity p-type silicon material with boron and phosphorus diffused into each of the broad flat faces of the silicon material, to form p^+ and n^+ layers respectively. The outer surfaces of the p^+ and n^+ layers are metallized with a contact film of a conductive material such as aluminum to form the electrodes of the device. The conductivity of the PIN semiconductive slab is responsive to the polarity of a D.C. bias voltage which may be applied across the device electrodes. In its low conductivity state, when the polarity of the applied D.C. voltage is such as to reverse bias the p-n junction between the high resistivity p-type silicon material and the low resistivity n^+ phosphorus diffused layer, a microwave signal will penetrate the semiconductive material. In its high conductivity state, when the polarity of the applied D.C. voltage is such as to forward bias the p-n junction, the penetration depth of the semiconductive material for a microwave signal is relatively small.

Referring to FIG. 2, there is shown a rectangular waveguide phase shifter internally dimensioned to operate in the dominant waveguide mode, TE_{10} . The n^+ side conductive electrode 10 of a PIN semiconductive slab 11, which may be of the type shown in FIG. 1, is in electrical contact with substantially the entire area of one of the narrow internal waveguide walls having the dimension b . The p^+ side electrode 12 of the slab 11 is parallel to and separated from the n^+ side electrode 10 by an overall slab thickness t . The p^+ side conductive electrode 12 of the slab 11 is in the form of a conductive comb-like pattern. The fingers of the comb-like pattern are oriented in the direction of microwave propagation and therefore cause a minimal perturbation of microwave signals.

It is not critical for phase shifter performance that an electrode 10 or 12 of the semiconductive slab 11 be in contact with the narrow dimensioned waveguide wall. The electrodes 10 and 12 may be located on whichever surfaces of the semiconductive slab 11 most convenient for applying a D.C. bias signal. In some structures it may be desirable to place the electrodes on the front and rear or upper and lower edges of the slab, although such arrangements may require the provision of apertures in the waveguide walls.

A D.C. bias voltage, from a source not shown, having a magnitude of approximately 50 volts has its negative terminal connected to one end of a high inductance lead 13 and its positive terminal connected to the waveguide and therefore to the electrode 10. The other end of the high inductance lead 13 is connected to the p^+ side electrode 12 of the slab 11. The (negative) bias voltage reverse biases the p-n junction within the slab 11 and therefore maintains the slab in its low conductivity state so that the slab allows the transmission of microwave energy from the p^+ side electrode 12 to the n^+ side electrode 10 of the slab. Thus, under these bias conditions, the effective electrical internal broad wall dimension of the waveguide is a .

The reversal of the polarity of the D.C. bias voltage, i.e., application of a bias voltage of approximately 1 volt to the p^+ side terminal 12 of the slab 11 via the high inductance lead 13 which is positive with respect

to the waveguide (and therefore with respect to the electrode 10) forward biases the p-n junction within the slab 11 and maintains the slab in its high conductivity state so that the slab prevents the transmission of microwave energy from the p⁺ side electrode 12 to the n⁺ side electrode 10 of the slab. Thus, under these new bias conditions the effective internal broad wall dimension of the waveguide is electrically reduced by the thickness, t , of the semiconductive structure 11. The new internal broad wall dimension is a' .

The phase shift, ϕ , of a microwave signal transmitted through a length, L , of rectangular waveguide is

$$\phi = 2\pi L/\lambda_g \quad (1)$$

where the waveguide wavelength, λ_g , is

$$\lambda_g = \lambda_0/[1 - \lambda_0/\lambda_c]^{1/2} \quad (2)$$

The wavelength in free space, λ_0 , is

$$\lambda_0 = c/f \quad (3)$$

where $c = 30 \times 10^9$ cm/sec and f is the frequency of operation in hz. The cutoff wavelength, λ_c , is dependent on the waveguide mode of operation and the internal waveguide dimensions. The cutoff wavelength, λ_c , for the dominant waveguide mode, TE₁₀, in rectangular waveguide is

$$\lambda_c = 2a \quad (4)$$

where a is the internal broad wall dimension of the waveguide.

A microwave signal transmitted through a length, L , of rectangular waveguide transmission line is shifted in phase when the waveguide wavelength, λ_g , is changed. The waveguide wavelength, λ_g , of a microwave signal propagating in the TE₁₀ mode is changed by electrically varying the internal broad wall dimension of the waveguide from a to a' . The change in phase shift, $\Delta\phi$, is

$$\Delta\phi = 2\pi L \frac{[1 - \lambda_0/2a']^{1/2} - [1 - \lambda_0/2a]^{1/2}}{\lambda_0} \quad (5)$$

The change in phase shift, $\Delta\phi$, is independent of the direction of propagation of the microwave signal, so that the phase shifter herein described is of the reciprocal type. Attenuation of the microwave signal propagated through the phase shifter is minimized by positioning the semiconductive slab 11 in a region of minimum electric field, i.e., in the vicinity of the internal waveguide side wall b .

Referring to FIG. 3, there is shown a rectangular waveguide phase shifter having a first semiconductive slab 21 of similar construction to the slab 11, and with its p⁺ electrode 20 in electrical contact with a narrow internal waveguide wall of height b . The p⁺ electrode 22 of a second semiconductive slab 23, of similar construction to the slab 11, is in electrical contact with the opposite narrow internal waveguide wall, also of height b . The semiconductive slabs 21 and 23 each have second parallel comb-like conductive electrodes 26 and 27 parallel to the first electrodes 20 and 22, the electrodes 26 and 27 being connected to the n⁺ regions of the slabs 21 and 23 respectively. Each of the slabs 21 and 23 has a thickness, t , which separates the conductive terminals 20, 27 and 22, 26.

The microwave conductivity of the semiconductive slabs 21 and 23 is dependent upon the polarity of a D.C. voltage from a bias source applied to the second terminals 26 and 27 via a pair of high inductance leads

24, 25, the other terminal of the bias source being connected to the waveguide, and therefore to the n⁺ electrodes 26 and 27. A forward bias voltage of approximately 1 volt applied across the electrodes of each of the semiconductive slabs 21 and 23 electrically reduces the internal broad wall dimension of the waveguide from a to $a - 2t$.

The internal broad wall dimension is a controlling factor in the determination of the relative phase shift of a microwave signal transmitted through a rectangular waveguide supporting the TE₁₀ mode (see Equations 1, 2 and 4). A reverse bias voltage of approximately 50 volts applied across the electrodes of each of the semiconductive slabs 21 and 23 causes the semiconductive slabs 21 and 23 to revert to their low conductivity state and allow microwave propagation in the full internal width, a , of the rectangular waveguide. The semiconductor slabs 21 and 23 are reverse biased by a bias source, not shown, when the positive terminal of the bias source, is coupled to the n⁺ electrodes 26 and 27 of the slabs 21 and 23 via the high inductance leads 24 and 25 and the negative terminal of the bias source is coupled to the p⁺ electrodes 20 and 22 of the slabs 21 and 23 via the waveguide. The semiconductor slabs 21 and 23 are forward biased by a bias source, not shown, when the positive terminal of the bias source is coupled to the p⁺ electrodes 20 and 22 of the slabs 21 and 23 via the waveguide and the negative terminal of the bias source is coupled to the n⁺ electrodes 26 and 27 of the slabs 21 and 23 via the high inductance leads 24 and 25.

A different phase shift change is obtained by applying a reverse bias voltage across the electrodes of one of the semiconductive slabs and applying a forward bias voltage of proper magnitude across the electrodes of the other semiconductive slab. The effect of such biasing is to electrically change the internal broad wall dimension of the waveguide from a to $a - t$.

Referring to FIG. 4, there is shown a microwave phase shifter having a continuous pair of semiconductive slabs 40 and 41 inside a rectangular waveguide. The first semiconductive slab 40 has a surface in contact with an internal waveguide wall having the dimension b . The semiconductive slabs 40 and 41 each have a thickness, t , and a height substantially equal to the internal waveguide wall dimension b . The semiconductive slabs 40 and 41 may be of the type shown in FIG. 1. The semiconductive slabs 40 and 41 have first electrodes 42 and 43 respectively in electrical contact with a common internal wall having the dimension a . The semiconductive slabs 40 and 41 also have second electrodes 44 and 45 respectively on opposite semiconductive surfaces thereof. The second electrodes 44 and 45 are electrically isolated from each other and the internal waveguide walls.

A D.C. bias voltage of the proper polarity causes an increase in the semiconductive conductivity when it is applied across the electrodes of each semiconductive slab. The increase in semiconductive conductivity effectively reduces the waveguide dimension a by an amount equal to the thickness, t , of the slab. Thus the bias voltage has the effect of electrically varying the critical phase determining waveguide dimension a .

A phase shift, ϕ , is obtained when the polarity of the applied bias voltages is such that the first slab 40 is in its

high conductivity state and the second slab 41 is in its low conductivity state. Under these bias conditions, the phase determining waveguide dimension is changed from a to $a - t$. A phase shift ϕ_2 is obtained when the polarity of the applied bias voltages is such that both slabs 40 and 41 are in their high conductivity states. Under these bias conditions, the phase determining waveguide dimension is changed from a to $a - 2t$.

What is claimed is:

1. An electrically variable phase shifter, the phase shift of which may be controlled by a variable polarity bias signal, comprising a waveguide having internal broad and narrow phase determining conductive wall dimensions measured in a plane transverse to the direction of electromagnetic wave propagation, a slab of semiconductive material located inside said waveguide and having oppositely disposed major surfaces and a predetermined thickness therebetween, said slab having a first electrode on one semiconductive surface thereof and a second electrode on an opposite semiconductive surface thereof, said slab exhibiting relatively high electrical conductivity when said signal is of a given polarity and a relatively low electrical conductivity when said signal is of opposite polarity, one major surface of said slab being parallel to and touching the surface area of one of said internal narrow dimensioned waveguide walls, and means for applying said bias signal between said electrodes, whereby change of the polarity of said applied bias signal changes the electrical conductivity of said slab and thereby changes the effective value of said broad wall dimension.

2. A phase shifter according to claim 1, wherein one of said electrodes is parallel to and in electrical contact with said one narrow dimensioned internal waveguide wall.

3. A phase shifter according to claim 1, including a second slab of semiconductive material located inside said waveguide and having a given thickness and first and second electrodes thereto, said second semiconductive slab being responsive to the polarity of an electric bias signal applied to the electrodes thereof, one major surface of said second semiconductive slab being parallel to and touching the surface area of the narrow dimensioned waveguide wall opposite said one narrow dimensioned waveguide wall, whereby the polarity of the bias signal applied to the first and second electrodes of said second slab changes the conductivity of said second slab and thereby changes said internal broad

wall dimension.

4. A phase shifter according to claim 1, wherein said first electrode is in the form of a conductive comb-like pattern on the major semiconductive surface remote from said waveguide walls, said comb-like pattern having conductive fingers oriented in the direction of electromagnetic wave propagation.

5. A phase shifter according to claim 1, wherein said semiconductive slab comprises a p^+ region separated from an n^+ region by a layer of high resistivity material, said p^+ and n^+ regions having conductive electrodes thereon.

6. An electrically variable phase shifter, the phase shift of which may be controlled by a variable polarity bias signal, comprising a waveguide having internal broad and narrow phase determining conductive wall dimensions measured in a plane transverse to the direction of electromagnetic wave propagation, first and second slabs of semiconductive material located inside said waveguide and each having oppositely disposed major surfaces and a predetermined thickness, said slabs each having a first electrode on one semiconductive surface thereof and a second electrode on an opposite semiconductive surface thereof, each slab exhibiting relatively high electrical conductivity when said signal is of a given polarity and a relatively low electrical conductivity when said signal is of opposite polarity, one major surface of said first slab being parallel to and touching the surface area of one of said internal narrow dimensioned waveguide walls, and means for applying said bias signal between the electrodes of each slab, said bias signal applying means having a first condition wherein the bias signal applied to each of said slabs is of said given polarity, and a second condition wherein the bias signal applied to said first slab is of said given polarity and the bias signal applied to said second slab is of said opposite polarity, whereby change of the polarity of said applied bias signal changes the electrical conductivity of said first and second slabs and thereby changes the effective value of said broad wall dimension.

7. A phase shifter according to claim 6, wherein one major surface of said second slab is parallel to and touching the internal narrow dimensioned waveguide wall opposite said one narrow dimensioned wall.

8. A phase shifter according to claim 6, wherein a first slab major surface opposite said one major surface is parallel to and touching a major surface of said second slab.

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