A novel slow wave structure capable of ultrabroad-band operation includes a meander line of a predetermined length on a layer of insulative material, a first series of spaced metal fingers forming a comb line are attached to the layer and extend in parallel from a front edge of the layer into the facing concave portions of the meander line and a second series of spaced metal fingers forming a comb line are attached to the layer and extend in parallel into the concave portions of the meander line from the opposed back edge of the layer. A metal layer or ground plane is connected to the underside of the layer and both series of metal projecting fingers are placed electrically in common together with the bottom ground plane. In a preferred method of manufacturing of the invention the insulative layer is completely coated or covered with metal on all surfaces and using a photoresist etching process the insulative spaces between the meander lines and the fingers are etched out leaving the desired structure.

8 Claims, 6 Drawing Figures
Fig. 4

Fig. 5

Fig. 6
PLANAR-SHIELDED MEANDER SLOW-WAVE STRUCTURE

FIELD OF THE INVENTION

This invention relates to slow wave structures and, more particularly, to a shielded slow wave structure capable of broadband operation.

BACKGROUND OF THE INVENTION

Microwave and other types of electromagnetic energy propagate at a velocity, approximately, equal to the speed of light. In many known applications it is desired for the microwave energy to be propagated over a predetermined distance at a substantially slower velocity. For this purpose circuits have hitherto existed which are denoted approximately by the terms “delay line” or “slow wave circuit.” In one type of conventional slow wave circuit the velocity of travel of electromagnetic energy between two points is “slowed” down effectively by causing the electromagnetic energy to travel in a circuitous path in between those two points. One such type of common slow wave circuit is the meander line, a line of a geometry which in part zigs and zags back and forth laterally in the space between those two given points as it extends over the distance between the two points.

Typically, slow wave circuits of this type find prime application in both high frequency microwave tubes such as the conventional M-type traveling wave tube and in the high frequency cathode ray tubes. In traveling wave tubes an electron beam containing electrons traveling at a predetermined velocity, suitably 1/10th the speed of light, is caused to interact with electromagnetic energy applied to and traveling along the slow wave circuit at approximately the same velocity. Through electronic interaction the energy in the electron beam is transferred in part to the propagating electromagnetic energy. And in deflection circuits of cathode ray tubes having very, very fast rise times the slow wave circuit provides a means of providing sufficient rapid deflection to permit display of very transient signals typically on the order of 0.1-1 nanoseconds.

In each application a slow wave circuit is best if it has a large frequency bandwidth or, as otherwise termed, is capable of broadband operation; that is, the velocity with which a microwave signal propagates effectively along the slow wave circuit should remain essentially constant regardless of the frequency of that signal. Typically a slow wave circuit which is capable of providing such uniform velocity of travel over a 1-octave range of frequencies, such as from 2 to 4 Gigahertz, is considered to be “broadband” and in the past the helix has been considered the best available broadband slow wave circuit.

The meander line configuration of slow wave structure, referred to previously, in itself has limited bandwidth characteristics, particularly at lower frequency ranges relative to the midband frequency at which the line is designed to be used. It is possible for the electromagnetic fields to “jump” across or bridge turns rather than follow the circuitous path of the meander line. In jumping turns the electromagnetic field takes a “short cut” over a portion of the defined transmission path and thereby travels the length of the meander line at a faster effective velocity than is the case in which the meander path is followed. This jumping or coupling from turn to turn in the meander line is largely dependent upon the frequency of the propagating signal and the delay of the line varies. Thus in that low frequency region the line is not broadband and does not provide a uniform delay.

To prevent the electromagnetic signal from bridging the turns of the meander line, various forms of shielding have been proposed. In such construction an electrically conductive member is interposed between the turns in the meander line and connected electrically to ground potential so as to shield one turn from another and prevent the fields from jumping or coupling between turns. With this type of line a metal ground plane was placed underlying the line and the shielding members were projected upward from this metal base between the turns of the meander line. Pat. U.S. No. 3,504,222 is an example of such construction. That proposed construction is necessarily difficult to construct because it involves a series of three-dimensional teeth which project upward from the ground plane into the space between the turns. In particular, this difficulty is understood in that at a frequency of about 5 Gigahertz (GHz) the turn-to-turn spacing is on the order of 0.040 inch and must be made to a tolerance of ± 0.001 inch.

OBJECTS OF THE INVENTION

Accordingly, it is an object of my invention to provide a novel slow wave structure capable of broadband operation.

It is an additional object of my invention to provide an improved shielded meander line slow wave structure.

And it is a still further object of my invention to provide a shielded meander line structure which eliminates the need for critical three-dimensional constructions and which is of a simple geometry.

BRIEF SUMMARY OF THE INVENTION

In accordance with the invention, an elongated thin layer of electrically nonconductive or other dielectric material, suitably aluminum oxide ceramic or boron nitride ceramic, serves as a base or supporting substrate. A pair of electrically conductive comb-like lines, suitably of gold chromium, are oriented geometrically with their teeth projecting in opposite directions on the plane of the base surface with the comb teeth interdigitally arranged and spaced on the top surface of the base and with some spacing between the teeth of one comb line and any portion of the teeth of the opposed comb-like line. An electrical conductor is spaced from and meanders about and in between those projecting interdigitally arranged teeth and is coupled, suitably bonded, to the base surface. This conductor is of the geometry of a meander line. A metal layer is coupled, suitably bonded, to the bottom or underside surface of the base and provides a ground plane. And each of the comb-like lines and the ground plane are placed electrically in common so as to form an electrical shield for the meander line.

Further in accordance with a preferred embodiment of my invention, all of the side edges of the base support are covered with a metal coating which provides electrical contact with both the comb-like lines and the ground plane with which same are connected electrically in common.

In accordance with the preferred method of construction of my invention, an elongated layer of insula-
tive material is first coated, suitably by conventional deposition or metallizing techniques, on all surfaces with a thin metal layer. A conventional photoresist process is used to mask the outline of the desired configuration of comb and meander lines on a top surface of this coated insulative material and the space between each of the metal members is thereupon etched out to expose the dielectric base and provide the desired configuration.

The foregoing objects and advantages of my invention, together with equivalents and substitutions for the elements thereof and the functional relationship between the elements, are better understood from a consideration of a preferred embodiment of my invention as described in the detailed description which follows taken together with the illustrations of the drawings.

DESCRIPTION OF DRAWINGS

In the drawings:

FIG. 1 illustrates one embodiment of the slow wave structure of the invention;

FIG. 2 illustrates schematically a top and side view of the slow wave structure of FIG. 1;

FIG. 4 illustrates the relationship between the elements comprising the shield and meander line of FIG. 1;

FIG. 3 illustrates the ω-β characteristics of the line;

FIG. 5 illustrates the normalized phase velocity characteristic of the embodiment of the invention; and

FIG. 6 illustrates the impedance characteristics of the embodiment of FIG. 1 of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The preferred embodiment of the slow wave structure in FIG. 1 includes a thin elongated rectangular slab or wafer base, which is, by way of specific example, approximately 1.150 inches in length, 0.360 inches in width, and 0.040 inches thick in dimension. This base material is electrically non-conductive dielectric material, suitably boron nitride, and is visible in the embodiment of FIG. 1 at the locations 3 on the top surface of the base and location 5 in cutaway portion 4. A series of straight spaced parallel metal projecting fingers or teeth, 7a, 7b, 7c, 7d and 7e, extend along the upper surface from a metal bar 9 which extends parallel along the back edge of the base. Each of the fingers 7a through 7e is seen to project from bar 9 perpendicularly thereto from the back edge or side 11 of the base. A plurality of like spaced parallel metal fingers or teeth, 15a, 15b, 15c, 15d, 15e and 15f, are attached to the base and extend along the upper surface of a metal bar 13 which extends parallel along the front edge of the base. Each of these teeth 15a through 15f is seen to project perpendicularly from bar 13 from the front side of the base. The teeth 15 are laterally displaced from the teeth 7 so as to fit in the space between teeth in the oppositely arranged structure without contact and the tips of the teeth extending in one direction do not contact the bars attached to the teeth that extend from the other direction. Suitably bar 9 and projecting teeth 7 form a comb-like structure conventional in the prior art and known as a "comb line". Likewise, bar 13 and projecting teeth 15 also form appropriately a comb-like structure or comb line. It is seen in the figure that the teeth of comb 15 fit in between and are spaced from the oppositely directed teeth 7 of the oppositely directed comb, and in this relationship the comb lines are essentially interdigitally arranged relative to one another. Suitably the distance center-to-center between the teeth 15 and 7 in a specific example is on the order of 0.040 inch and the teeth-to-teeth center-to-center spacing of any one comb line is approximately 0.080 inch for operation up to a frequency of 5 Gigahertz (GHz). In one specific example of the preferred embodiment at that frequency the teeth 7 and 15 are approximately 0.270 inch in length, 0.010 inch in width, and 0.001 inch in thickness.

An additional electrical conductor 17, suitably of gold-chromium material, is attached or coupled to the dielectric base material. Conductor 17 follows a path in the figure which winds or "zig zags", as variously may be termed, in between the projecting teeth 7 and 15 of the lines without contact therebetween. Starting from the end 20 located near the back end of bar 13, line 17 extends parallel and spaced from tooth 15a to within a predetermined distance of bar 9, wherein the line thereupon extends parallel to bar 9 to pass the tip of tooth 15a. Line 17 then reverses direction and extends parallel and in between teeth 15a and 7a to a predetermined distance of bar 13. In the space between the tip of tooth 17a and bar 13, line 17 extends toward the front edge of the base parallel to bar 13 and extends past the tip of tooth 17a to a position in between teeth 17a and 15b, whereupon line 17 is again reversed in direction and extends in between and parallel to teeth 7a and 15b to within a predetermined distance of bar 9. At this point line 17 again extends parallel to bar 9 toward front bar 13 to a predetermined distance in between teeth 15b and 7b. The further description of the path taken by line 17 to its end 21 is apparent from FIG. 1. By such a circuitous course or geometry, line 17 meanders or zig zags, as is variously termed, back and forth between front edge and back edge of the layer extending forward in steps between the points of beginning 20 and end 21 of this line. A line of this geometry is conventionally described in the prior art as a "meander line". As oriented in the embodiment the teeth of the comb lines extend into the confronting concave portions of the meander line from each side. In the specific example cited previously, the center-to-center spacing between the meander line 17 and adjacent teeth is on the order of 0.020 inch and line 17 is approximately 0.010 inch in width, the same as the width of each of the comb line teeth and is approximately 0.001 inch in thickness. The overall length of line 17 is approximately 0.270 inch or, expressed in wavelengths, 3/8λ at the upper frequency of 5 GHz.

A metal layer 23, as is visible in cutout portion 4, covers the entire bottom of the dielectric base. Each of the side edges 11, 12, the back edge, not visible in this figure, as well as the left side edge 18 and portions of the right and left side surfaces, are covered entirely with a thin layer of metal material, suitably gold chromium, and join to the metal bars 9 and 13 of the comb lines. In this manner the bottom metal layer 23 forms a "ground plane". In this way, each of the ground plane 23, the comb lines comprised of teeth 7 and 9, and teeth 15 and bar 13, are coupled together electrically in common. As becomes apparent, the metal layer 23 need not cover the bottom surface entirely and can include openings in less preferred embodiments. And the electrical paths between the ground plane and the comb lines can be made by electrical wires as an obvi-
ous alternative to the plating of edge surfaces for less preferred embodiments.

Line 17 terminates at its front and back ends 21 and 20 just short of the comb lines. Electrical leads can be connected to line 17 at ends 20 and 21 as input and output connections to other circuitry and a ground lead may be connected to the metal layer 23. However it is noted that the ends of line 17 can alternatively be connected in common with the comb lines. Inasmuch as the length of the line is many wavelengths long at the microwave frequencies coupled to the meander line, the line possesses a definite impedance and hence the coupling in this manner does not act as an electrical short circuit. In such a modification external signal connection to the line 17 is accomplished by an available non-contacting coupling, such as inductive or capacitive.

FIG. 2 schematically shows the slow wave structure of the invention, the ends 20' and 21' of the meander line 17' which meanders between teeth 15' and 7' of the interdigitally arranged comb line, and electrical input and output connecting leads coupled to the input and output ends of line 17' represented by the dashed lines 25 and 27.

The $\omega$-$\beta$ diagram of FIG. 3 shows the theoretical relationship, calculated for the embodiment of FIG. 1, between the frequency and the phase shift of the fundamental mode. As is conventional, this type of diagram is useful for design purposes since phase and group velocity can be determined by inspection. It can be seen, for example, that the phase velocity of the fundamental forward mode is nearly constant while the fundamental backward mode is very dispersive.

The fundamental backward wave mode propagates between $\omega_1$ and $\omega_2$. These frequencies $\omega_1$ and $\omega_2$ are controlled by the distance, $W$, to the ground plane, and the bandwidth, ($\omega_2-\omega_1$), can be made small by close ground plane spacings. For frequencies less than $\omega_1$, the structure propagates only the fundamental forward mode.

The sectional drawing of the embodiment of FIG. 1 as is illustrated in FIG. 4 represents those dimensions of the circuit, pitch of the line, $P$ and $L$, a factor related to the length of the line, which determine essentially the relationship between $\omega$ and $\beta$ in the curve of FIG. 3. Thus to decrease the upper frequency of operation of the line, $L$ is made greater in length. By increasing $P$, the phase velocity increases. As is apparent, many other variations in these parameters are possible.

FIG. 5 graphically illustrates the normalized phase velocity vs frequency, the dispersion characteristics, for the embodiment of FIG. 1. It is seen that the dispersion characteristic is essentially nondispersive from 0 (d.c.) to 5 GHz. By theoretical calculation at 1.5 GHz and 5 GHz the normalized phase velocity varied between 0.087 and 0.084 as represented by the two square points and this determines the illustrated curve 31. The round plotted points determined by test of the structure fall essentially on that dispersion curve, and confirms that the slow wave characteristic in practice conforms to theoretical behavior.

The dispersion ($\omega$-$\beta$) curve of FIG. 3 for the particular embodiment of the invention illustrated in FIG. 1 is derived from the following mathematical equation. The equation characterizes the slow wave structure for that particular example in which the width dimension of the meander line is the same as the width dimension of the teeth of the comb line, which were both 0.01 inch in the example given, and is not valid for other possible variations of my invention in which the width of the two differs:

$$4Y_1Y_2[(\tan(\omega h/2))^2-(Y_1Y_2+Y_3Y_4(1+\tan(\beta p)^2)]+(Y_1Y_2+Y_3Y_4)(1-\tan(\beta p)^2)(\tan(\omega h/2)) + 4Y_2Y_4(\tan(\beta p)^2 = 0$$

where

a. $k = \omega/c$

b. $\omega = 2\pi f$, where $f$ is frequency in GHz

c. $c = \text{velocity of light}$

$$Y_1 = Y(\theta)$$

$$Y_2 = Y(\theta + \pi/2)$$

$$Y_3 = Y(\theta + \pi)$$

$$Y_4 = Y(\theta + (3\pi/2))$$

where $\pi = 3.14 . . .$

$\theta = \beta p$, where $\beta$ is the variable phase and $p$ is the pitch

and

$\cos(1/2)+2(1-\cos(1/2))(S_1(W,\alpha)+S_2(W,\alpha))$

where $W$ is the dielectric gap distance between the comb line tooth and the meander line $\alpha$ is $q/p$ previously defined and

$$S_1(W, \alpha) = \sum_{m=-\alpha}^{\alpha} (-1)^m \coth W(\theta + 2\pi m)$$

$$\sin \left[ \left( 1-\alpha \right) \left( \frac{\xi}{2} + m\pi \right) \right]$$

$\frac{\sin \left( \alpha \left( \frac{\xi}{2} + m\pi \right) \right)}{\left( 1-\alpha \right) \left( \frac{\xi}{2} + m\pi \right)}$ where $W$ is distance from the circuit to a ground plane and which equals $W_1$, the thickness of the dielectric layer, and $W_2$ is the distance to a sole electrode (if any) in equation (c).

By inserting the appropriate dimensions and constants for a particular embodiment as indicated the curve can be plotted. And by dividing each value of $\omega$ by $\beta$, the value of $\nu_0$ is obtained. This is normalized further by dividing by $c$, the velocity of light, to obtain the normalized dispersive curve of FIG. 4.

FIG. 6 graphically illustrates the generalized coupling impedance of the slow wave circuit of my invention. In this the coupling impedance $K(\Omega) \sqrt{\varepsilon}$ is plotted against frequency. The factor $\varepsilon$ is dimensionless and represents the relative dielectric constant or permittivity of the base material. Thus obtaining the generalized coupling impedance value specified on the graph in ohms at a specific frequency and dividing by the square root of the permittivity, $\varepsilon$, of the particular base material, such as that for boron nitride in the specific example, the true coupling impedance may be obtained.

In the graph the square points represent values obtained by calculation. Thus at 2 Gigahertz the generalized impedance is approximately 58 ohms and the true
impedance is 29 ohms, where \( \varepsilon_r \) for boron nitride is 4.1. It is noted that the coupling impedance is less than 100 ohms in the range of 0 to 5 GHz and this is considered low impedance.

There are numerous ways to form the essentially thin flat two-dimensional structure of the slow wave circuit. It is preferred to form the slow wave structure by taking the dielectric base material of the appropriate dimension as determined from the foregoing considerations and covering all surfaces suitably with a coating of approximately 0.001 inch of chromium-gold layers by conventional thin film deposition techniques. In this a small flash of chromium is first deposited followed by depositing the gold. The chromium serves to bond the gold to the ceramic base of boron nitride. A photosist material is then applied to all surfaces and the upper surface is then exposed to a photographic or masked image to establish the pattern of comb lines and meander lines as illustrated in FIG. 1. Thereupon the formed structure is placed in a conventional etchant bath which etches out the gold chromium material in the places where the photosist material was not exposed and this etching is carried through until the dielectric surface underlying the metal is removed leaving the pattern of insulative spaces between the metal lines as illustrated in FIG. 1. Thereupon the photosist material is removed and the slow wave circuit is additionally cleaned.

In the practice of the invention what is derived is a precise and yet simple to construct configuration which in the example of the preferred embodiment possesses an essentially dispersionless characteristic between 0 and 5 Gigahertz. Obviously, this form of packaging permits many such structures to be stacked one upon another with suitable insulator spacing therebetween in some desired applications. Also, inasmuch as machining and other crude methods of fabrication are avoided entirely, and accurate photographic techniques are used in its construction, a more reliable and at the same time less expensive structure is obtained.

The foregoing details of the preferred embodiment of my invention are presented to enable the reader to clearly understand the nature of the invention and how to make and use the invention as required by the patent laws and not by way of limitation to my invention. It is understood that my invention is not to be limited to the details illustrated in the preferred embodiments inasmuch as many equivalents and substitutions to the foregoing disclosed elements suggest themselves to one of ordinary skill in the art upon reading this specification. Accordingly, my invention is to be broadly construed within the spirit and scope of the appended claims.

What I claim is:

1. A slow wave structure comprising:
   a continuous layer of dielectric material of a first predetermined thickness;
   a first metal comb-like structure, said comb-like structure comprising a plurality of flat spaced projecting teeth connected to a common flat bar-like member;
   a second metal comb-like structure, said second comb-like structure comprising a plurality of flat spaced projecting teeth projecting from a common flat bar-like member;
   said first and second comb-like structures having a second predetermined thickness less than said first predetermined thickness;

   each of said first and second comb-like structures being attached to an upper surface of said insulative layer with the teeth of said combs projecting in opposed directions along said upper surface and being interdigitally arranged, leaving space between said adjoining teeth and between the tips of said teeth and said bar to define a meander-shaped insulative space therebetween;

ground plane conductive metal layer attached to and covering the bottom surface of said insulative layer; a conductive metal coating on one side wall of said layer for electrically connecting said ground plane layer in common with said first comb-like structure and a conductive metal coating on another side wall of said layer for electrically connecting said ground plane in common with said second comb-like structure; and

a meander-shaped electrically conductive flat metal strip applied to said upper surface and located in said meander-shaped insulative space.

2. The invention as defined in claim 1 wherein each of said first and second comb-like structures and said meander-shaped strip comprise the metals gold and chromium, and wherein said insulative layer comprises boron nitride.

3. The invention in a slow wave structure comprising: an elongated slab of insulative material having a first predetermined thickness, a coating of electrically conductive material of a second predetermined thickness less than said first predetermined thickness covering all surfaces of said insulative slab except a first exposed insulator portion on said upper surface, said exposed insulator portion comprising a geometry of a meander line of a predetermined length and a predetermined pitch and a predetermined width, and meander line shaped electrical conductor means located within said exposed portion and attached to said slab surface and spaced from said first metal coating, said electrical conductor means having a width less than said predetermined width and the same predetermined pitch whereby shielding fingers are formed between the turns of the meander line which shielding fingers do not extend through the slab to the bottom metal surface but are connected from one end to the bottom metal layer via the metal coating on the sides of the slab of insulative material.

4. The invention as defined in claim 3 including an input terminal means connected to one end of said meander line and output terminal means connected to the other end of said meander line.

5. The invention as defined in claim 3 further including first electrical conductor means joining one end of said meander line to an adjacent portion of coating, and second conductor means joining the remaining end of said meander line to an adjacent portion of coating.

6. The invention as defined in claim 3 wherein said insulative slab comprises a fired ceramic dielectric material and wherein said first metal coating comprises gold chromium and wherein said meander line comprises the metal gold chromium.

7. A slow wave structure comprising a thin metal meander line, a relatively thick layer of insulative material, said meander line being coupled to and traversing over a top surface of said layer of insulative material; a plurality of thin metal fingers spaced from one another and projecting from a thin metal bar perpendicular to said fingers to form a thin comb-like structure on
the top surface of said layer; said metal fingers being bonded to said insulative material and protruding from one side of said meander line within a corresponding concave portion of each meander in said meander line and spaced therefrom; a second plurality of metal fingers spaced from one another and projecting from a thin metal bar perpendicular to said fingers to form a thin comb-like structure on the top surface of said insulative layer; said metal fingers being bonded to said insulative material and protruding from the other side of said meander line within a corresponding concave portion of each meander in said meander line and spaced therefrom; an electrically conductive metal ground plane attached to and covering the bottom surface of said layer of insulative material; and thin metal electrical conductor means attached to the sides of said layer for connecting each of said first and second bars of said comb-like structures electrically in common with said ground plane.

8. The invention as defined in claim 7 wherein said last-named means comprises a first thin metal layer coupled to and covering a side surface of said layer adjoining said top and bottom surfaces of said layer for electrically connecting said metal bar of said first comb-like structure to said metal ground plane and a second thin metal layer coupled to and covering another side surface of said layer adjoining said top and bottom surfaces of said layer for electrically connecting said metal bar of said second comb-like structure to said metal ground plane.

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