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[54] LOW PASS MICROWAVE FILTER

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[52] **U.S. Cl.** .... **333/73 C;** 333/73 S; 333/73 W; 333/84 M

[51] **Int. Cl.²** **H01P 1/20;** H01P 3/06; H01P 3/08

[58] **Field of Search** .. 333/73 R, 73 C, 73 W, 84 M, 333/84 R, 97 R, 98 R, 73 S

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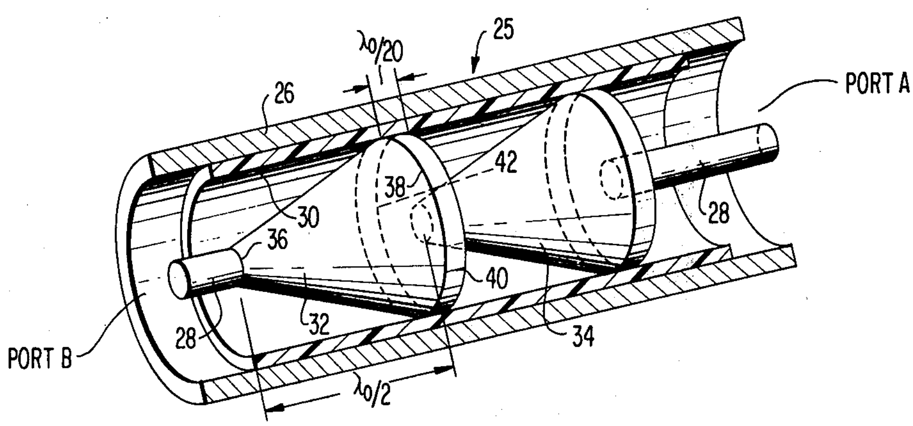
Assistant Examiner—Marvin Nussbaum
Attorney, Agent, or Firm—Nathan Edelberg; Robert P. Gibson; Kenneth J. Murphy

[57] ABSTRACT

A low pass microwave filter comprised of a two conductor transmission line including at least two cascaded tapered sections wherein one of the conductors in each filter section has a tapered surface, preferably linear, and having an electrical length substantially equal to one half the wavelength of the center frequency of operation. Geometrically and performance-wise the subject filter is unsymmetrical with respect to its input and output ports. The filter does not exhibit the usual rapid transition between the pass band and stop band which is a general characteristic of conventional low pass microwave filters utilizing reflective harmonic structures.

8 Claims, 5 Drawing Figures



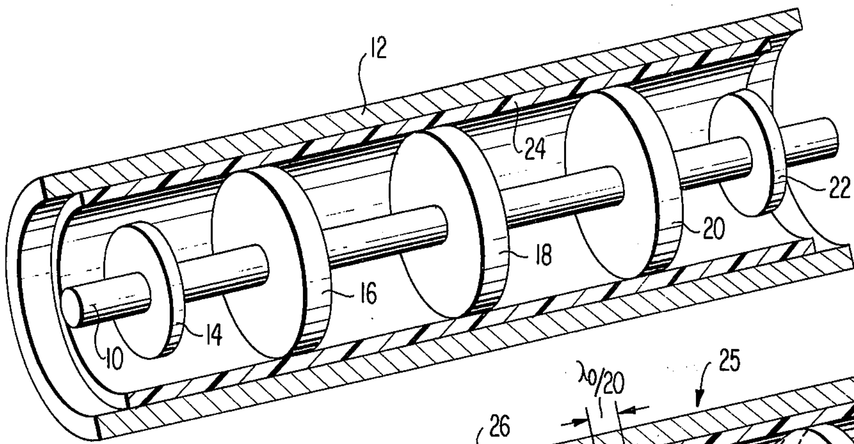


FIG. 1
(PRIOR ART)

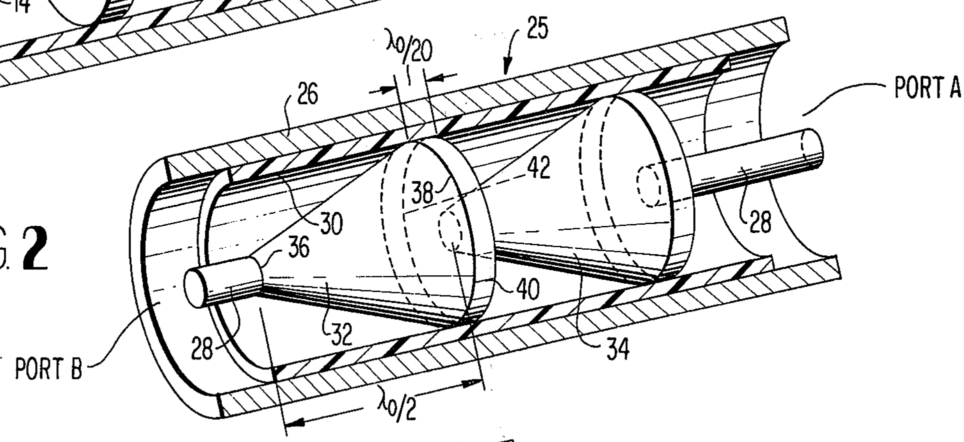


FIG. 2

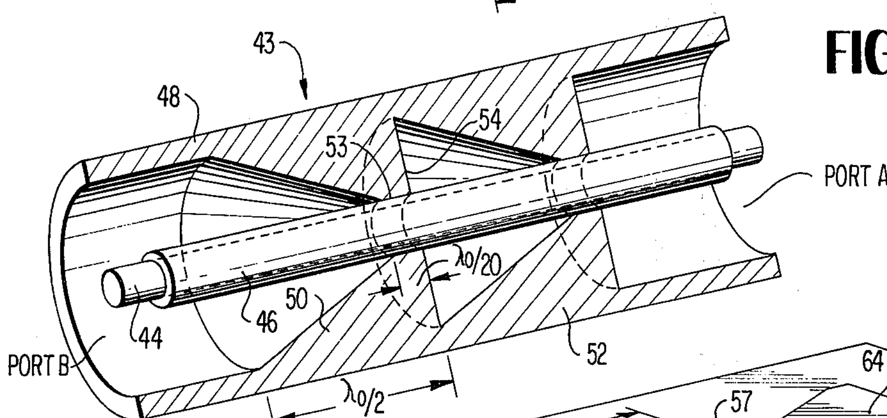


FIG. 3

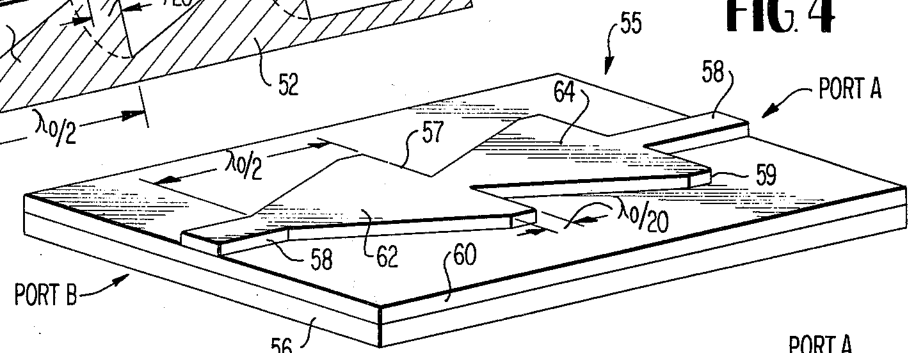


FIG. 4

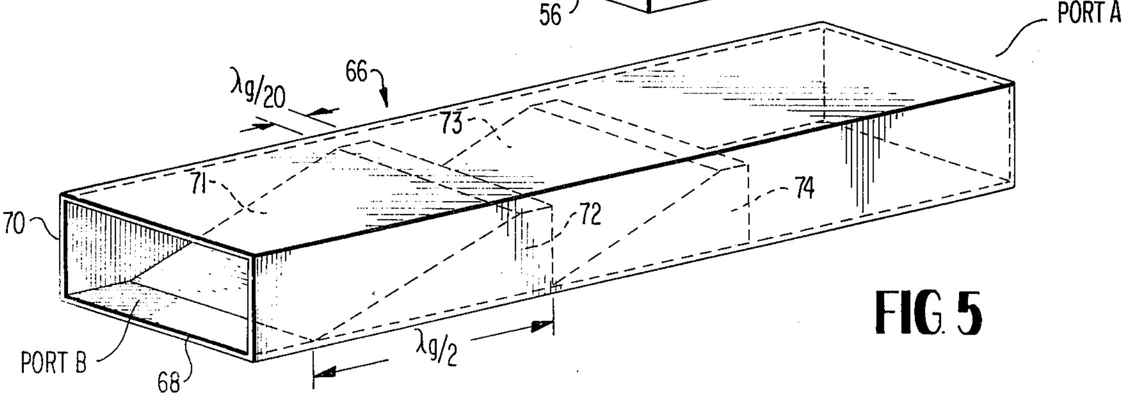


FIG. 5

LOW PASS MICROWAVE FILTER

The invention described herein may be manufactured and used by or for the Government for government purposes without payment of any royalty thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to transmission line systems for transmitting high frequency electrical energy at a desired frequency while rejecting energy at one or more undesired frequencies and more particularly to a low pass transmission line filter for microwave applications where it is desirable, for example, to couple a pulse source and/or a DC bias injection feed to an active microwave device.

2. Description of the Prior Art

It is well known that the operating frequency of an active microwave device depends not only on the device characteristics and optimum circuit configuration for the fundamental frequency f_o, but also on the optimum tuning or idling of harmonic frequencies nf_o, where n is an integer greater than one. Simple known filter techniques for bias injection or driving pulse feed such as the use of disc capacitors or one or more quarter-wave sections of low surge impedance lines are only adequate for a limited fundamental tuning range. Regarding quarter-wave section microwave filters, all of the even harmonics are not prevented from escaping from the resonator to the outside of the microwave enclosure causing radio frequency interference and loss in DC to microwave conversion effeciency. Moreover, the shape of pulses fed to the microwave device through such filters is seriously affected by the excessive capacitance of low impedance quarter-wave sections.

Thus in many cases the conventional low pass filter is not acceptable for pulse and DC feed applications because the reactive component of the filter impedance at the location of the junction of the filter to the microwave resonator has an excessive range and varies at an excessive rate causing excessive frequency pulling at certain portions of the frequency band of interest. One type of low pass microwave filter commonly utilized for such applications is a coaxial filter consisting of several sections of high impedance line such as a relatively thin conductor rod or wire surrounded by air dielectric for simulating series inductances alternating in combination with short sections of very low impedance line consisting of conductive discs of various axial thicknesses and axial spacings which simulate shunt capacitances.

At the junction point between the filter and microwave resonator, i.e. at the feed point to the microwave circuit to which it is coupled, a filter should have consistently low resistance and reactive impedance components in the stop band over the entire range of operating frequencies including all related harmonics with major contribution to the device efficiency. At the same time, the upper frequency components of the spectrum of a driving pulse which are in the pass band below the operating frequency range should be affected as little as possible to preserve pulse shape.

For a more detailed treatment of typical prior art low pass filters for microwave applications, reference can be made to the text entitled "Microwave Filters, Impedance Matching Networks and Coupling Structures", by G. L. Mattahei, et al., McGraw-Hill Company, Inc., New York, N.Y., 1964, at pages 355–359, inclusive.

SUMMARY

It is an object of the present invention therefore to provide a new and improved low pass filter for the purpose of feeding power supply voltages and/or modulating signals such as pulses with all essential harmonics into a microwave resonator without distortion or loss. Briefly, the filter is comprised of a length of transmission line such as but not restricted to a coaxial line including therein at least two cascaded tapered conductor sections wherein one of the conductors, for example the inner conductor, in each section has a preferably linear, tapered length wherein the electrical length is substantially equal to one half the wave length of the center frequency of the operating frequency band. Both sections are substantially identical in configuration and orientation with the first section acting as a matching section whose smaller end dimension is coupled to the energy source via the input port while the second section has its smaller dimension beginning at and tapering outwardly from the larger end of the first section. The larger end of the second section terminates abruptly and couples to a microwave resonator. The two sections thus constitute two periodically tapered sections of a transmission line connected in cascade. When desirable, a still third such section can be added for greater effect.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a longitudinal cross sectional view of a typical prior art low pass microwave filter with parts shown in elevation;

FIG. 2 is a similar longitudinal cross sectional view of a first embodiment of the present invention;

FIG. 3 is a longitudinal cross sectional view of a second embodiment of the subject invention;

FIG. 4 is a perspective view of yet a third embodiment of the subject invention; and

FIG. 5 is a perspective view of still another embodiment of the subject invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Prior to discussing the preferred embodiments in specific detail, apparatus of the type related to the subject invention utilizes guiding means such as a two conductor transmission line system in the TEM mode of propagation which may be, for example, a concentric line transmission system such as shown in FIG. 1 for transmitting energy between a source and a load at a given frequency and provides several circuit elements effectively in cascade embodied in one conductor of the transmission line. These filter sections present a high impedance at the rejection frequency while simultaneously causing much less disturbance to the transmission of energy at the desired frequency. The load impedance accordingly will, in general, reflect a significant portion of the wave energy at the undesired frequency.

Directing attention now to FIG. 1, which represents a typical coax filter illustrative of the prior art, it is shown comprising a two conductor transmission line including an inner conductor **10** and an outer conductor **12**. A plurality of conductive discs or pucks **14, 16,** 18, 20 and **22** of selective axial thicknesses and mutual spacings are symmetrically arranged along the inner conductor **10.** The diameter of the first and last disc **14** and **22** is of a relatively smaller diameter than the intermediate discs **16, 18** and **20,** which are additionally adapted to support the inner conductor **10** by having diameters which contact the inner surface of a tubular dielectric spacer member **24** fitted interiorally of the outer conductor **12.**

That the structure of the coaxial filter shown in FIG. **1** is readily known to those skilled in the art is shown by the fact that such a device is manufactured and marketed by the Microlab Corporation, being identified as FXR Model LA–60N. Additionally, a similar configuration is disclosed as one element in the teaching of U.S. Pat. No. 3,600,711, issued to Richard Z. Gerlack, on Aug. 17, 1971, said patent being identified as "Coaxial Filter Having Harmonic Reflective and Absorptive Means".

The filter shown in FIG. **1** is symmetrical in its configuration and when one end of the device is terminated for example with a 50 ohm resistive termination and a signal applied to the other end, the following typical impedance resistive and reactive values results as a function of frequency for the filter looking back toward the signal source from the load end:

TABLE I

freq. (GHz)	Resistance Ohms	Reactance (Ohms — {+=induc. / −=capac.})	
1.0	46.3	−2.0	PASSBAND
2.0	39.0	+5.7	
4.0	73.3	+14.0	
8.0	3.34	+147.9	STOPBAND
10.0	0.21	−322.5	
12.0	0.002	−113.5	
16.0	<0.001	−54.2	
20.0	<0.001	−33.6	
24.0	0.005	−17.2	

It has already been noted that in order for a filter to optimally perform, it must consistently exhibit a low output impedance, both resistive and reactive in the stop band over the entire range of operating frequencies. It can be observed with respect to Table I that although the resistance exhibited in the stop band is relatively low compared to the pass band, the reactance components are relatively large and undergo sudden changes in polarity resulting in excessive frequency pulling effects. Thus a certain limitation inherently exists in such a device, even though it is widely used and has performed adequately under predetermined operating conditions.

Turning attention now to the subject invention, the embodiments shown in FIGS. **2–5** disclose an improved approach to low pass filtering at microwave frequencies. In contrast to prior art filter apparatus, the filter according to the subject invention is unsymmetrical about its input and output ports insofar as geometry is concerned and its performance characteristics as will be shown does not exhibit the usual rapid transition between the pass band and stop band. Although this peculiarity may be undesirable in certain applications where a sharp discrimination between the stop band and pass band is required, the subject invention is particularly adapted for feeding power supply voltages and/or modulating signals, e.g. pulses with all essential harmonics into microwave loads coupled to the filter without distortion or loss. Additionally, the microwave frequency band whose center frequency is defined as f_o and all major harmonics thereof defined as nf_o where n is an integer greater than one, are confined to the microwave load circuitry without the introduction of appreciable losses or tuning discontinuities caused by the rapid changes of the filter reactance as a function of fundamental or harmonic frequency components as evidenced in Table I with respect to the noted prior art device shown in FIG. **1.**

Referring now to FIG. **2,** there is disclosed a coaxial configuration of a two section filter according to the subject invention comprised of a length of two conductor transmission line **25** including an outer conductor **26** and an inner conductor **28** separated by a cylindrical or tubular dielectric spacer **30.** The center conductor **28** contains two cascaded or series connected tapered sections **32** and **34** which have respective electrical lengths substantially one half wavelength $\lambda_o/2$ of the center frequency f_o. Defining port A as the output port which is adapted to be connected to a microwave load circuit, not shown, port B is defined as the input port which is adapted to be connected to a DC bias supply or pulse generator, not shown, by means of a suitable interconnecting cable, also not shown. The section **32** closest to the signal source i.e. port B acts as an impedance transformer whereas section **34** closer to the load i.e. port A acts as the filter section. When desirable, one or more additional sections can be fabricated and inserted intermediate the section **34** and port A to enhance the filtering effect. Considering the geometrical shape of the two sections **32** and **34** shown in FIG. **2,** the constant relatively small normally circular dimension of the inner conductor **28** is interrupted, for example, at the point **36** and a generally conical shaped enlargement of the center conductor takes place, enlarging towards port A providing a generally linear increasing tapered surface of the inner conductor to the point **38** whereupon a generally flat surface **40** having a width dimension equal to or less than $\lambda_o/20$ exists for supporting the section against the spacer **30.** Section **32** abruptly terminates in a generally flat planar surface **42** normal to the central axis whereupon the second section **34** becomes axially contiguous therewith having an initial dimension equal to the dimension of the inner conductor **28.** As mentioned above, the length of the section **32,** i.e. from one terminal end which is at point **36** to the other terminal end, i.e. surface **42** is substantially $\lambda_o/2$ in length. Both sections **32** and **34** as well as any additional sections are preferably substantially identical in configuration and dimensions being typically 0.552 inches long with a periodic 28° taper.

Where for example a variable frequency source is coupled to the coaxial filter as shown in FIG. **2** by means of a 50 ohm cable, the following typical impedance values are provided at the output port A as a function of input frequency:

TABLE II

freq. (GHz)		Resistance (Ohms) 2 sections	Resistance (Ohms) 3 sections	Reactance (Ohms {+ = induc., − = capac.}) 2 sections	Reactance (Ohms {+ = induc., − = capac.}) 3 sections	
0.1		41.1	34.0	−18.8	−22.7	PASSBAND
0.5		8.3	4.7	−16.8	−11.1	PASSBAND
1.0		3.1	2.5	− 7.9	− 2.2	PASSBAND
2.0		3.9	25.1	+ 3.0	−26.4	PASSBAND
4.0		0.15	0.08	− 7.6	−10.4	PASSBAND
8.0	f_o Fundamental Band	0.009	0.00015	− 2.41	− 2.8	STOPBAND
10.0 =	f_o Fundamental Band	0.014	0.00018	− 1.47	− 1.9	STOPBAND
12.0	f_o Fundamental Band	0.052	0.001	− 0.20	− 1.15	STOPBAND
16.0	$2f_o$ Harmonic Band	0.014	0.018	− 1.71	− 7.2	STOPBAND
20.0 =	$2f_o$ Harmonic Band	0.008	0.0001	− 0.46	− 1.0	STOPBAND
24.0	$2f_o$ Harmonic Band	0.0748	0.	− 6.38	− 0.18	STOPBAND

It can be seen with reference to Table II that both low resistive and reactive impedance values are obtained in the stop band frequencies adjacent the transition region which is between 4 and 8 GHz.

Considering the theory of operation of the embodiment shown in FIG. **2**, an equivalent short circuit is effectively presented to microwaves and their harmonics at port A. This equivalent short circuit can be explained by consideration of the resistive component of the impedance value along the tapered sections **32** and **34** from port B to port A. With a 50 ohm pulse generator connected to port B by means of a 50 ohm coaxial cable, port B can be considered as terminated with a matched load for microwave frequencies and their harmonics. This match is preserved in the first tapered section **32** toward output port A until the first section ends at the planar face **42**. The beginning of the succeeding section **34** starts off with a relatively high surge impedance Z_{OH} in the 50 ohm region, but it is now mismatched by the relatively low value of the transformed input impedance at face **42** provided by the first tapered section **32** which happens to coincide with the value of the effective surge impedance, e.g. $Z_{OL} = 1$ ohm. Typically the surge impedance Z_O on the tapered section varies from $Z_{OH} \cong 50$ ohms to $Z_{OL} \cong 1$ ohm, but it is not restricted to these values at all. This typical 50 to 1 mismatch continues along the second tapered section **34** and results in an effective gap impedance of $1/50 = 0.02$ ohms in the first approximation at the output port A for frequencies near f_o. A third section, not shown, would reduce the resistive component to a value in the region of $1/50^2 = 0.0004$ ohms. The presence of reactive components complicates this transformation. Thus low resistive components of the gap impedance at port A occur over a wide frequency range from 0.5 f_o to well above $4f_o$ and provide a low loss short circuit effect at the modulation or feed bias plane at the input of any microwave circuit connected to the filter, i.e. port A. Specifically for the embodiment shown in FIG. **2**, the surge impedance Z_O variation from Z_{OL} to Z_{OH} as a function of distance x along each coaxial tapered section is defined by the equation:

$$Z_{Ox} = \frac{60}{\sqrt{\epsilon \text{ eff}}} \ln \frac{D_i}{D_x}$$

where D_x is the diameter of the tapered center conductor at the location x along the respective tapered section **32** or **34**, D_i is the constant inner diameter of the outer conductor **26**, and ϵ_{eff} is the relative dielectric constant at the location x. The equations for the effective surge impedances, however, for the configurations shown in FIGS. **3** and **4** and for the intrinsic impedance for the waveguide case in FIG. **5** are different.

The reactive component of the filter impedance of the embodiment shown in FIG. **2** at the output port A dominates and remains relatively low in magnitude and uniform in sign over the lower portion of the stop band frequency range (8.0 – 12.0 GHz) and over the major harmonics up to the fourth harmonic. This behavior is significant where the microwave load circuit has a tuning capability in that the filter maintains the tuning relatively smooth and the unloaded circuit Q as a function of the ratio of reactive over resistive filter components relatively high and substantially constant. Furthermore, the injection of lower than operating frequencies into the microwave load circuit up to **1/10** of the center frequency f_o presents no significant problem because each filter section represents only a very small portion of the wavelength of pass band frequencies and thus the entire filter resembles a lumped capacitance consisting essentially of the effective capacitances of the lower surge impedance portions of the filter.

It should be pointed out that the linear taper of the section shown in the embodiment in FIG. **2** has been shown for purposes of illustration and is most economical to produce. It is not meant to be considered in a limiting sense since a non linear taper can be utilized when more advantageous; nor is it necessary that taper sections be identical in length or surge impedance variation. Also, the length of the tapers are not necessarily restricted to half wavelength sections as long as they remain in the vicinity of half wavelength of the center frequency of the microwave frequency of operation. Moreover, the ports A and B can be reversed for certain applications.

Referring now to the other embodiments of the subject invention which constitute equivalent structures to the configuration shown in FIG. **2**, reference is now made to FIG. **3** which constitutes a reversed modification of the coaxial filter in that whereas in the first embodiment the tapered sections were fabricated on the inner conductor, in the configuration shown in FIG. **3**, the tapered sections are included in the outer conductor of a length of coaxial transmission line **43**. More particularly, the inner conductor **44** having a relatively small constant diameter is covered by a dielectric sheath **46** and the outer conductor **48** is modified from a constant diameter transmission line to include at least two inwardly tapered sections **50** and **52** wherein the inner diameter gradually reduces as the distances increases away from the input port B to the outer surface of the dielectric sheath **46** wherein a relatively small flat surface **53** is maintained to a planar face **54** whereupon an abrupt return to a larger inner diameter exists providing the beginning of the second section **52.** Again the electrical length of the sections **50** and **52** are preferably identical being in the order of one half wavelength $\lambda_o/2$ of the center frequency. The embodiment shown in FIG. **3** thus constitutes a reversal of parts, so to speak, from the previous embodiment.

A stripline version of a filter according to the subject invention is shown in FIG. **4** and is comprised of a two conductor microstrip transmission line **55**, one conductor of which comprises a metallic substrate **56** acting as the ground plane while the other conductor comprises the strip conductor **58** fabricated on a dielectric layer **60**. The dielectric layer **60** is contiguous with the metallic substrate **56**. In the stripline configuration, the constant thickness strip conductor **58** is configured to include two tapered sections **62** and **64**. Whereas in the first embodiment shown in FIG. **2**, the tapered sections consisted in solid surfaces of revolution defining a generally conical shape, the stripline conductor strip **58** consists in a flat layer of conductor material which is suitably etched or otherwise fabricated to include diverging or widening portions of the conductor as it proceeds away from the input port B for a distance substantially equal to $\lambda_o/2$ whereupon it abruptly returns to the smaller width dimension at point **57** whereupon it again diverges forming the second section **64**. After a second distance of $\lambda_o/2$, the second section again abruptly returns to the smaller width of the strip **58** at point **59** and proceeds to the output port A which is adapted to be coupled to a microwave load circuit, not shown. This causes the effective surge impedance to change along the tapered section similar to the configuration in FIGS. **2** and **3**. This embodiment can be further modified such that the tapered section is sandwiched between two conductive planes for a match to modern microwave circuitry utilizing the technique of stripline circuits between two ground planes.

Directing attention now to FIG. **5**, there is disclosed a waveguide embodiment of the subject invention in which a length of waveguide **66**, having a pair of broadwalls **68** and a pair of narrow walls **70**, include two wedge shaped sections **72** and **74** shown for purposes of illustration being located along the lower broadwall providing inclined faces **71** and **73** towards the input port B thus providing sections wherein the dimension of the narrow walls periodically decreases. The sections **72** and **74** can either be solid material inserted in and secured to the inside of the waveguide or may consist of flat plate elements which are inclined upwardly toward the upper broadwall to a predetermined distance therefrom for permitting the passage of microwave energy without electrical breakdown between the broadwall surfaces thus described. Here the mechanical section length is approximately one half of the effective guide wavelength λ_g.

It should be pointed out that the flat portions of each section at the end of the taper for the coaxial embodiment shown in FIGS. **2** and **3** are primarily for purposes of support of the inner conductor. The stripline emodiment shown in FIG. **4** and the waveguide embodiment shown in FIG. **5** also are illustrated as having a flat portion at the end of the tapered segment. This is shown merely for sake of disclosing the similarity of equivalent structures for it should be appreciated that when desirable, the taper of the sections of the embodiment shown in FIG. **4** can extend to the abrupt return to the smaller dimension at the end of the section contiguous with the beginning of the second section (unless there is a sharp edge arcing problem in high power applications).

Thus what has been shown and described is an improved low pass microwave filter comprised of at least two cascaded tapered conductor elements formed in one of the two transmission lines of a microwave transmission line for coupling energy from a power source to a microwave circuit. The filter sections describe periodic tapers whose length preferably comprises one half the wave length of the center frequency of the frequency band of operation.

Having thus described what is at present considered to be the preferred embodiments of the subject invention, I claim:

1. A low pass microwave transmission line filter having input and output end ports and being unsymmetrical about its ports, for inclusion in a transmission line having first and second continuous guiding surfaces, said filter comprising,

spaced conductive means providing third and fourth guiding surfaces facing toward each other,

the third guiding surface having, at each port of said filter, a configuration to form a continuation of the first guiding surface of the transmission line,

the fourth guiding surface having, at each port of said filter, a configuration to form a continuation of the second guiding surface of the transmission line,

said third guiding surface being geometrically continuous longitudinally throughout the extent of the filter,

the fourth guiding surface including more than one tapered segment, the direction of taper of all segments being the same,

each segment having a transition that is essentially perpendicular to the length of the filter,

whereby said filter is operable in a frequency band having a center frequency corresponding to a wavelength that is substantially twice the length of each tapered segment measured longitudinally of the filter.

2. The filter as defined by claim **1** wherein said tapered segments have substantially linear periodic tapers.

3. The filter as defined by claim **2** wherein said guiding surfaces are on inner and outer coaxial conductors.

4. The filter as defined by claim **3** wherein said tapered segments are generally frusto-conical in configuration and each segment is terminated by a short cylindrical integral extension at its end of maximum departure relative to the fourth guiding surface, said filter additionally including a dielectric spacer between the inner surface of said outer conductor and said inner conductor at the region of said tapered segments and wherein said integral extensions of said tapered segments contact said spacer for supporting said tapered segments of inner conductor within said outer conductor.

5. The filter as defined by claim **2** wherein said inner conductor provides said third guiding surface and said outer conductor provides said tapered segments formed along the inner surface of said outer conductor.

6. The filter as defined by claim **5** wherein said inner conductor is substantially circular in cross section and additionally including a dielectric sleeve around said inner conductor in the region of said tapered segments provided by the inner surface of said outer conductor.

7. The filter as defined by claim **1** wherein said transmission line is a strip transmission line and wherein said third guiding surface is provided by a metallic substrate acting as a ground plane, and additionally including a dielectric layer on said metallic substrate, and wherein said fourth guiding surface is provided by a strip conductor of substantially constant thickness located on said dielectric layer.

8. The filter as defined by claim 1 wherein said transmission line is hollow rectangular waveguide with a pair of parallel broadwalls and a pair of parallel sidewalls, said filter being hollow rectangular waveguide having one broadwall that is geometrically continuous and providing said third guiding surface, the other broadwall of said filter having substantially parallel inclined inner surface segments formed therealong.

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