Jan. 17, 1961 M. J. RODRIGUEZ 2,968,774

MICROWAVE ATTENUATION UNITS

Filed Oct. 22, 1956 2 Sheets-Sheet 1

FIG. 1.

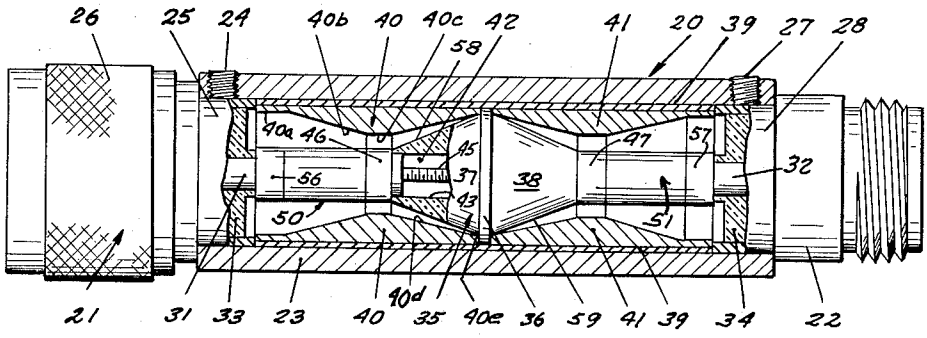


FIG. 2.

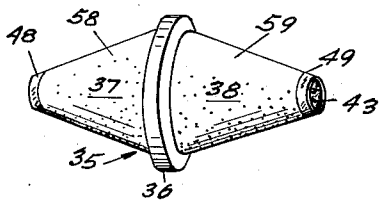


FIG. 3.

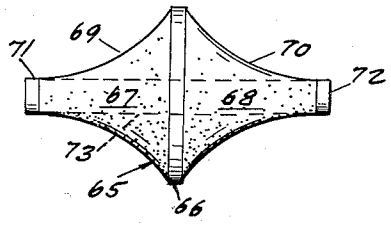
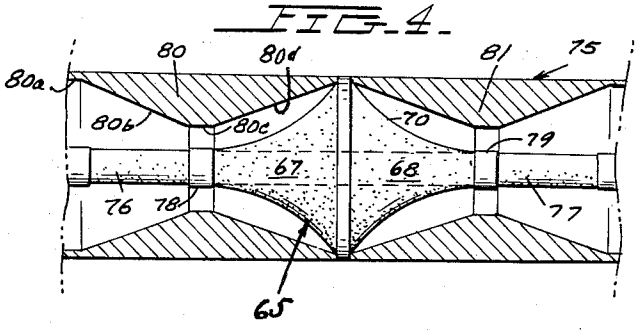


FIG. 4.



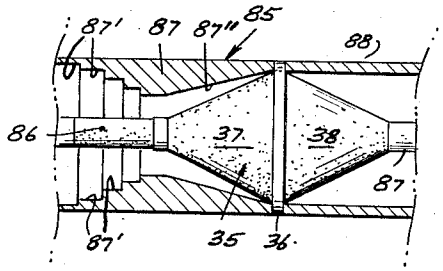


FIG. 5.

INVENTOR.
MICHAEL JOSEPH RODRIGUEZ

BY Richard A. Marsen

his ATTORNEY

Jan. 17, 1961 M. J. RODRIGUEZ 2,968,774

MICROWAVE ATTENUATION UNITS

Filed Oct. 22, 1956 2 Sheets-Sheet 2

FIG. 6.

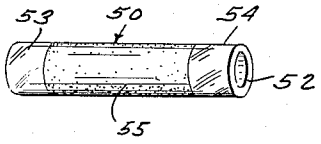


FIG. 7.

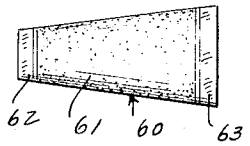


FIG. 8.

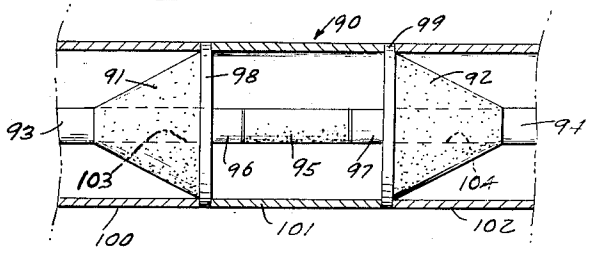
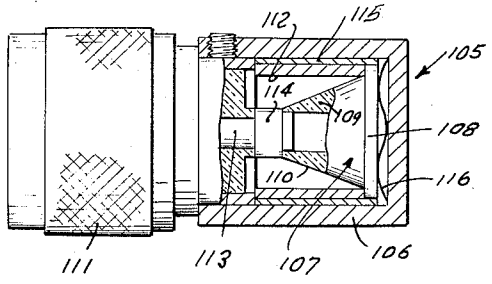


FIG. 9.



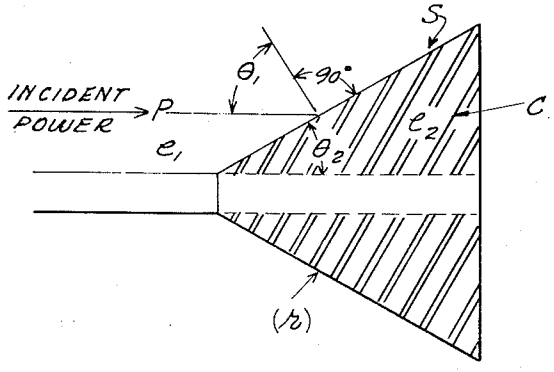


FIG. 10.

INVENTOR.
MICHAEL JOSEPH RODRIGUEZ

BY Richard A. Marsden

his ATTORNEY

United States Patent Office 2,968,774
Patented Jan. 17, 1961

2,968,774

MICROWAVE ATTENUATION UNITS

Michael J. Rodriguez, Bayside, N.Y., assignor to Empire Devices, Inc., Bayside, N.Y., a corporation of New York

Filed Oct. 22, 1956, Ser. No. 617,551

12 Claims. (Cl. 333—81)

This invention relates to microwave attenuation units, more particularly to attenuators operative from direct current to frequencies in the order of 10 kilomegacycles and higher, with low voltage standing wave ratios.

It is a general object of the present invention to provide novel attenuation units usable in microwave circuitry; of general construction related to coaxial lines and cables, and readily insertable in such cables; and operative throughout the frequency range from direct current to 10 kmc. signals and above with low reflection and with predetermined insertion or attenuation loss. Such attenuation units are constructed with specific impedance characteristic, and with physical dimensions to coact with the coaxial line or cable with which they are used.

In the practical design or operation of circuits or components at relatively low frequencies, electro-magnetic field considerations and wave propagation are usually neglected. The physical size of circuit components at low frequencies is small compared to the relative wave length of such frequencies. Thus, the effects of voltage and current may be considered as established instantaneously throughout the circuit, when transient effects are of no concern. Established engineering concepts of voltage and current utilizing Ohm's law and other formulations of circuit interactions are practical for relatively low frequencies, without the aspects and mathematics of complex electromagnetic field theories.

However, as the frequency of the electromagnetic energy utilized in the circuit is increased to the microwave region, above 1 kmc. for example, the physical size of the circuit components and elements is no longer negligible with respect to the wave length. At frequencies above 1 kilomegacycle it is impractical to neglect the field conditions of the electromagnetic energy, nor is it practical to consider the circuit components or elements as "lumped" as is done in lower frequency analysis and circuitry. In the microwave field, the line integral of the electric field strength taken between two points at one instant of time, is no longer independent of the path. The same applies to the current. The usual low frequency concepts of current and voltage do not apply in the microwave region, in fact, the ordinary concepts of capacitance and inductance tend to lose their identity.

In accordance with the present invention, novel means are utilized to transmit microwave signals from a coaxial line or cable through a conical resistive section which uniformly attenuates the signals with negligible reflections up to frequencies in the order of 10 kilomegacycles and higher. The conical surface has a film resistance which film is thinner than the smallest depth of penetration, corresponding to the highest operating frequency. It may be linear or exponential in longitudinal cross-section, as will be set forth in more detail hereinafter. The essential improvement provided by the conical resistor elements of the invention, in the path of coaxially fed microwave signals, is that they effect negligible disturbance of the electrical and magnetic fields

constituting the microwave signals in their passage across the conical resistive elements.

The passage of microwave signals along the conical resistive surfaces of the invention attenuators, results in gradual attenuation of the signals in a predetermined manner, and allows the fields thereof to vary with very little distortion. The conical structures of the present invention inhibit reflections of the electric and magnetic fields of the microwave signals, and result in a minimum practical standing wave ratio. Further in accordance with the present invention, two conical resistive units are arranged back-to-back and utilized as symmetrical or two-way transmission attenuation units, such as T-pads.

In its practical aspects, the present invention simplifies the construction, testing requirements and basic cost in the fabrication of attenuation units such as T-pads, pi-pads, terminations, and the like. The conical resistive elements of the present invention are thin films deposited upon conical dielectric structures of good low-loss dielectric material, such as glass, steatite, etc. The conical elements are molded to final shape, or cured and machined if required. The film of predetermined characteristic and resistance, as will be set forth, is thereupon applied thereto.

Such conical resistor arrangement, whether linear or exponential in longitudinal cross-section, provides the advantageous transmission and uniform attenuation action upon signals from D.C. up to the 10 to 12 kmc. range, without requiring corresponding tapering of the cylindrical shield or casing of the attenuation unit. For such applications, it is less expensive to provide conical tapering of the central resistors; and thus provide the very high-frequencies uniform passage, with negligible VSWR, than by corresponding matching by close machining of the cylindrical casing or shield. However, by providing tapering in the cylindrical shield about the invention conical resistor, a second order of close matching is afforded to further enhance the ability of the attenuation device to perform its designed function with lower VSWR, as will be set forth in detail hereinafter.

It is accordingly an object of the present invention to provide novel attenuation units operative from direct current to the 10 to 12 kmc. microwave range, uniformly, and with minimum VSWR.

Another object of the present invention is to provide coaxial attenuation units embodying novel conical resistor elements for use on signals to the order of 10 kmc., and with uniformly low VSWR.

A further object of the present invention is to provide novel coaxial attenuator pads embodying conical resistive elements rendering such pads relatively inexpensive, and for extended high frequency application in the microwave range with low VSWR.

Still another object of the present invention is to provide novel coaxial attenuator units embodying conical resistive elements, including low-loss dielectric material based structure and adapted for design and construction in various forms, such as T-pads, pi-pads, L-pads, terminations, etc.

Still a further object of the present invention is to provide a novel T-type coaxial attenuator pad, operable from direct current up through the 10 to 12 kmc. microwave range, with low VSWR throughout the range, from either direction, and for specific impedance and attenuation characteristics.

These and further objects of the present invention will become more apparent from the following description of specific embodiments thereof, taken in connection with the drawings, in which:

Fig. 1 is a cross-sectional view of the coaxial T-pad constructed in accordance with the present invention, for

use from direct current through the 10 kmc. range, and above.

Fig. 2 is a perspective view of the central double-conical resistive element utilized in the T-pad of Fig. 1.

Fig. 3 is an elevational view of a modified form of double-conical unit, of the exponential type.

Fig. 4 is a cross-sectional view of the basic portion of a modified bidirectional T-pad attenuator, utilizing the double-conical exponential resistor of Fig. 3.

Fig. 5 is a further form of attenuation unit, being an L-pad utilizing the double-conical element of Fig. 2.

Figs. 6 and 7 are alternate forms of the series resistor elements for the attenuation units.

Fig. 8 is a cross-sectional view through the central section of a pi-pad coaxial attenuator, utilizing conical resistive elements in accordance with the present invention.

Fig. 9 is a cross-sectional view through a termination unit utilizing a conical resistor element.

Fig. 10 is a schematic diagram for the conical resistor surface angle analysis.

Attempts have been made to construct coaxial attenuation units incorporating "lossy" dielectric material. However, it is known to those skilled in the art, that while such units encompass microwave frequencies, they are selective over particular band-widths. The embodiment of lossy dielectrics in an attenuation unit restricts its operation at low frequencies and direct current, and does not lend itself to uniform VSWR characteristics.

The attenuation units of the present invention embody thin resistive layers, coatings or films on cores of good or low-loss dielectric material, such as steatite, zirconium, glass, quartz, and the like. Bushings, contacts, sleeves, etc. of the attenuation units are made of a good conducting metal, with smooth or closely machined surfaces, and without burrs or other irregularities that would introduce distortions in passing microwave signals. Fig. 1 is a cross-sectional view of an exemplary embodiment of a T coaxial attenuation pad constructed in accordance with the present invention. The coaxial attenuator pad **20** is arranged with the usual terminal hardware **21** and **22** for coaxial lines or cables to which the attenuator unit **20** is inserted in series. It is to be understood that the characteristic impedance design of attenuator **20** is made equal to that of the characteristic impedance of the associated cable or line circuit. The insertion loss or attenuation of attenuator unit **20** is predetermined, and for example may be 10 db, 20 db, or any other desired value to which the unit lends itself constructionwise.

Attenuator pad **20** comprises outer cylindrical metallic support and shielding member **23**. Coaxial fitting **21** is secured to the left end of sleeve **23** through set screw **24**, engaging collar **25** of member **21**. A rotatable knurled sleeve **26**, having internal threading, is for engaging a cooperative section of the coaxial line or cable to which pad **20** is circuitally attached. Similarly, the right end of pad **20** has threaded hardware member **22** secured to sleeve **23** by set-screw **27** engaging collar **28** of member **22**. The connection members **21** and **22** have central conducting stems which engage the central elements of the T-pad through respective conductive rods **31**, **32** supported within collars **25**, **28** by respective dielectric bead supports **33**, **34**. The outer sections of members of **21**, **22** are of metal and conductive through their respective collar **25**, **28**, and are contiguous electrically with conductive shield **23** of pad **20**. Such outer conductive members constitute the return electrical path for the microwave signals, and provide continuous shielding for the cable connections and pad **20**. As the connection hardware members **21**, **22** do not constitute part of the present invention, further details thereof are not shown.

Centrally of T-pad **20** is a double-conical resistor element **35**. Bi-conical resistor **35** has a central annular ridge **36** extending from the basic juncture of the two cones **37**, **38** extending toward the shielding sleeve **20**. Central ridge **36** is conductive. The annular ring **36** is locked into position between opposing internally tapered cylinders **40** and **41**. The juncture of annular ridge **36** on either side with the contiguous surfaces of cylinders **40**, **41** is made firm, and closely proportioned for accurate positioning and rigid maintenance of contact of the cylinders **40**, **41** and the cones **37**, **38** of bi-conical resistor **35**, for reasons to be more fully set forth hereinafter. A thin conductive metallic shim **39** of resilient material is interposed between the inner surface of outer cylinder **23** and the cylinders **40** and **41**, as well as the outer surface of the annular conducting ring **36** of unit **35**. The purpose of resilient shim **39** is to coordinate the electrical and mechanical factors of pad **20**, whereby firm electrical and mechanical interconnections are made between units **40**, **41** and ring **36** with the surrounding shielding cylinder **23** throughout the associated circumferential areas thereof.

Fig. 2 is a perspective illustration of bi-conical resistor **35**. It is to be noted that the hollow interior **42** (Fig. 1) of resistor **35** is cylindrical and concentric with outer sleeve **23**. The internal surface **43** of the hollow cylinder **42** with bi-conical resistor **35** is preferably conductively plated, such as with silver, to establish a uniform conduction path through the interior of the resistor **35**. Also, it is to be noted that centrally through hollow cylinder **42** within resistor **35** is a brass rod or screw **45** for mechanically securing conducting cups or clips **46**, **47** to the end openings **48**, **49** of the bi-conical resistor **35**. The open end circular portions **48**, **49** of bi-conical resistor **35** each contain an annular area which is silvered or otherwise made conducting, for establishing, with the sliver surfaced interior **43** firm electrical connection with the respective contacting clips **46** and **47**. The conduction path between resistor end-clips **46** and **47** is basically provided by the conductive cylinder surface **43** in central region **42** of unit **35**.

Colinear with connector clips **46**, **47** and extending outwardly therefrom are series resistors **50**, **51** respectively. Resistors **50**, **51** are made preferably with similar ceramic core material as bi-conical resistor **35**, such as of steatite, or zirconium, etc. and are faced with a suitable film of resistance material such as of carbon, boron, etc. Such resistance material may be deposited, diffused, plated or otherwise suitably secured to the ceramic core, in a manner well known in the art.

Fig. 6 is a perspective illustration of series resistor **50**, which is identical to resistor **51**. Resistor **50** has a thin ceramic core **52** which is otherwise hollow, but may be a solid cylinder if desired. The ends **53**, **54** of ceramic cylinder **52** are conductive annular strips such as of silver, for connection to corresponding connector clips. Conductive annular areas **53**, **54** are preferably formed after the resistor film **55** is deposited upon the ceramic base **52**, to insure continuity of connection across the series resistor **50**.

Annular conductive section **54** of series resistor **50** nests within connector clip **46** in Fig. 1. The opposite end annular connection area **53** nests within connector clip **56**, that extends from central conductor rod **31** of coaxial hardware member **21**. Similarly, the left end of series resistor **51** is in firm electrical contact with connector clip **47**; and its right end, with connector clip **57** extending from central conductor rod **32** of coaxial member **22**. The use of the connector clips and the silvered annular areas on the resistors **50**, **51**, as well as on bi-conical unit **35**, is to afford firm electrical interconnection and support of the parts of the T-pad, and to permit practical and economical mass-production of the elements separately and effective assembly of the pad in its manufacture. These respective elements and components, when assembled, constitute a unitary body due to their alignment, their fitting, and their respective dimensions, for all practical applications of the pad.

It is important that the relative dimensions of the components, and mechanical stability of the unit be maintained in service, as the uniform attenuation characteris-

tics of T-pad 20 up through 10 to 12 kmc. microwave signals is dependent upon the parameters of design and the relative tolerances of the parts, as will be understood by those skilled in the art. Towards this end, the annular ridge 36 is a very important factor in maintaining a basic anchor for the integral conical resistors 37 and 38 of member 35, and also through the extending connector clips 46, 47 maintaining series resistors 50, 51 in their concentric position in pad 20. The initial coaxial alignment and maintenance of conical resistors 37, 38 within pad 20 is assured by proper fabrication of annular ridge 36, and its coaction with the tapered cylinders 40, 41 as heretofore described.

It is well established in the microwave art that the characteristic impedance Z_0 of a section of a coaxial structure is expressed as follows:

$$Z_0=\frac{60}{\sqrt{e}}\log_n\frac{D}{d}$$

where Z_0 is the characteristic impedance along a plane in the line, the outer diameter is D, d is the (inner) diameter of the elements in the center; and e is the dielectric constant of the material therewithin along which the signals pass. For air e equals 1. Maintenance of the characteristic impedance close to a predetermined value, or changing it gradually where necessary, minimizes or maintains the VSWR figure low for the frequency range. Towards this end, I will now detail the novel features and factors of T-pad 20 in accordance with the present invention.

Starting at the left end, we have connection clip 56, which is conductive and of uniform diameter across its axial extent. Accordingly, the corresponding portion 40^a of tapered cylinder 40 is made "flat," namely of uniform axial diameter, to correspond with the uniform diameter of clip 56. The characteristic impedance Z_0, which is determined by the diameters in the above formula, is made equal to the impedance of the system for which pad 20 is designed. We next come to linear series resistor 50, having a uniform resistive film deposition across its outer surface in the axial direction of pad 20.

It is established in the microwave art that for a coaxial pad embodying a linear resistance and a uniform resistive change R per unit of length, that its characteristic impedance is $Z=R\cdot dx$. The result, as is established in the art, and shown for example in U.S. Patent No. 2,399,645, is to use a logarithmic cone as the shielding cylinder about the linear resistor 50, to maintain a mathematically perfect transition or uniform characteristic impedance (z). However, a linear taper 40^b subtends linear resistor 50, to provide a practical smooth characteristic impedance transition throughout the microwave signal path across linear resistor 50. It is more expensive to provide a true logarithmic shape for surface 40^b of cylinder 40. For frequencies from D.C. to 12 kmc., I have found that a linear taper for surface 40^b of cylinder 40 maintains the VSWR well within 1.2 throughout the range. Should a higher frequency range be desired, the linear cylindrical resistor 50 may be replaced with the tapered resistor 60 described hereinafter in connection with Fig. 7.

The next section in the T-pad 20 is connection clip 46 between resistors 50 and 37. Since the charracteristic impedance across the axial path of clip 46 is constant, a "flat" section 40^c is built into cylinder 40 to keep the characteristic impedance at that section of pad 20 constant and equal to the impedance appearing at the right end of resistor 50, and is determined by the contiguous smallest diameter in the taper of surface 40^b.

We next arrive at the left terminus of conical resistor 37 of bi-conical unit 35. It is to be noted that resistor 37 progresses conically by increasing diameter in the planes perpendicular to the path of the microwave signal, from left to right herein, namely from the diameter of clip 46 to the portion of the annular connection ring 36 where it meets cylinder 40. The conical surface 58 of resistor section 37 has deposited firmly thereon a resistive film such as of carbon, boron, or the like well known in the art, and of proper resistive value to serve as the shunt element in the T-pad 20. The transitional characteristic impedance change from the position at clip 46 of conical resistor 37 to the annular connection ring 36 thereof is linear in effect, resistively, and also physically linear by its tapering.

The tapering configuration of conical shunt resistor 37 affords a first order logarithmic compensation effect for the characteristic impedance along the axial direction of pad 20 thereat, which per se has been found to effect a smooth transition in the characteristic impedance commensurate with the linear resistance change. In other words, if the opposing surface 40^d of cylinder 40 were untapered, namely "flat," the very factor of tapering the surface 58 of conical resistor 37 compensates for the linear resistance change and produces a smooth transition of the characteristic resistance from one end of conical resistor 37 to the other. It is inherently compensating for all practical purposes, and gives a first order compensation or correction corresponding to the formulation otherwise required by more complex construction, and is effective in all the practical attenuation units hereindescribed. I have found by experimental determination on a unit as per T-pad 20, that uniform passage and attenuation of microwave frequencies to 10 to 12 kmc. and extending through all frequencies down to direct current, are attenuated uniformly and with VSWR below 1.2 in all cases.

For practical purposes, the concentric portion of cylinder 40 about conical resistor 37, namely surface 40^d, is tapered by a straight taper from the smaller diameter at 40^e to the maximum diameter at the resistive portion of cone 37 at sleeve portion 40^e where it is contiguous with conductive annular ring 36 at the central hub of the bi-conical resistor 35. The practical tapering of section 40^d extends thereby a further correction effect about the otherwise tapered disc resistor 37, producing a second order of correction and closer to the theoretical. In practice, I have found that such arrangement is sufficient to provide uniform attenuation with uniformly low VSWR for the frequencies from direct current up through 12 kmc., and even higher.

It is to be noted that the right-hand half of attenuator pad 20 is identical in construction, electrically and mechanically, with the section left of the annular ring 36, and in effect, is a mirror symmetry. The theory and practical operation of the right-hand section embodying conical resistor 38, connection clip 47, series linear resistor 51, and clip 57, are otherwise identical to that hereinabove described for the left half of attenuation unit 20. Transition of the signals from the central sector at the annular connection ring 36, to the right end 32 of attenuation pad 20 will now be understood by those skilled in the art. Pad 20 is symmetrical for signals from either direction.

The pad 20 is designed to handle direct current as well as the upper microwave frequencies referred to. It is readily seen that the impedances of elements 50, 51 and 35 are predetermined, and maintain their resistive values for the whole signal range to 10 to 12 kmc., with constant attenuation, minimum reflection or distortion, and maintenance of low VSWR. For example, in a 50 ohm characteristic impedance T-pad (20) for 20 db attenuation, series resistors 50 and 51 are slightly over 40 ohms, and each of the conical sections 37 and 38 are about 20 ohms. Thus the characteristic impedance and the amount of attenuation for a unit of the invention is prescribed by predesign as set forth above.

Fig. 3 is a modified form of the bi-conical resistor 35 of Fig. 2. The bi-conical resistor 65 of Fig. 3 has a central annular connection ring 66 as in unit 35. However,

its individual conical resistor sections 67 and 68 are formed on logarithmic shaped conical surfaces 69 and 70 respectively. The elevational view Fig. 3 of unit 65 shows the logarithmically tapered contour of the surfaces 69, 70 established between the respective conducting termini or annular ends 71 and 72 and the central annular ring 66. A hollow cylindrical core 73 extends centrally through unit 65 between conductive ends 71, 72, and is coated with a silver layer which also interconnects rings 71, 72. Signal conduction between rings 71 and 72 is thus afforded.

Utilization of the logarithmically shaped conical resistors 67 and 68, constituting biconical unit 65, affords an additional order of correction for the characteristic impedance change, in a practical attenuation unit, per the formula for (Z) above. In other words, logarithmic bi-conical resistor unit 65, or separated half-sections thereof corresponding to 67 and 68 of unit 65, extends the upper frequency range to which an attenuation unit will have uniform performance, namely to 12 kmc. and above in the present examples. Also, for a given range, such as up to 12 kmc., the logarithmic unit 65 will perform with somewhat lower VSWR ratios than linear conical unit 35.

Fig. 4 is a cross-sectional illustration of the basic portion of an attenuator T-pad embodying the logarithmically shaped bi-conical resistor 65 of Fig. 3. T-pad attenuator 75 of Fig. 4 corresponds in every way to T-pad 20 of Fig. 1, with the exception that logarithmic bi-conical unit 65 is used in place of linear bi-conical unit 35. The outer sleeve and the connector fixtures of pad 75 are not shown, but are understood to be the same as those for T-pad 20. The series resistors 76 and 77 are connected to the opposite end of bi-conical unit 65, contiguous with the respective resistor sections 67 and 68 through associated connection clips 78 and 79.

The tapered cylinders 80 and 81 are arranged about the respective left and right halves of T-pad 75, in the manner of cylinders 40 and 41 of unit 20. The internal surfaces 80^a, 80^b, 80^c and 80^d of cylinder 80 correspond identically to the similar sections of cylinder 40 of T-pad 20. The only differing feature of T-pad 75 from that of pad 20 is the logarithmic configuration of the surface 69 of conical resistor 67, and of surface 70 of conical resistor 68. It is to be noted that section 80^d about the logarithmic surface 69 of conical resistor 67 is a linear taper. As seen in Fig. 4, a corresponding condition prevails with respect to conical resistor 68, and the whole right-hand half of T-pad 75.

The result of utilizing logarithmic shaped surfaces 69 and 70 for the shunt conical resistors 66, 67 is to introduce a higher order of correction for the characteristic impedance (Z) referred to hereinabove, in the T-pad. The electric and magnetic fields of microwave signals passing through attenuator pad 75 maintain proper characteristic impedance to minimize reflections and introduce the requisite attenuation from direct current up through the top range of 12 kmc., and higher, with low VSWR.

The pad 75 construction, with logarithmically corrected surfaces 69, 70 for shunt resistances 67, 68, together with tapers surrounding these logarithmic surfaces, corrects to frequencies even up to 15 kmc., with uniform attenuation, and with VSWR values below 1.2. The configuration of attenuation pad 75 affords a first order correction for the series linear resistor elements 76, 77 by the associated linear tapers corresponding to 80^b of unit 80; and a third order correction for the shunt resistors 67, 68 due to the combined logarithmic and conical configurations 69 and 70 of resistors 67, 68 as well as in the cooperating sleeve linear taper corresponding to 80^d.

Fig. 5 illustrates an L-attenuation pad. The L-pad 85 is illustrated in cross-sectional view incorporating a basic bi-conical linear tapered resistive unit 35, corresponding to that shown in Fig. 2. The L-pad is illustrated with the outer cylindrical sleeve and cable terminal hardware elements omitted, but understood to correspond to those of Fig. 1. L-pad 85 is essentially a unit having a series resistor 86 corresponding to linear cylindrical resistor 55 of Fig. 6, and a bi-conical shunt resistor 35 in series with one end of resistor 86; and a conductive connection 87 back to the central connector of the coaxial cable hardware.

A metal cylindrical shield 87 is arranged about series resistor 86 and shunt resistor 37. Cylinder 87 comprises internal configurations which contain a series of steps 87′ subtending linear series resistor 86; and a linear taper 87″ subtending conical shunt resistor 37. For many applications herein a stepped configuration about linear resistors as 86 has been found suitable in place of a logarithmic taper or of a linear taper as (40^b of unit 20). However, in place of the stepped section 87′ of cylinder 87, a linear taper or logarithmic taper may be used. The utilization of linear taper 87″ about conical resistor 37 provides a smooth gradual characteristic impedance change across this shunt resistive section of pad 85, for minimizing reflections and keeping the VSWR low, in the manner heretofore described for pads 20 and 75.

The section of pad 85 to the right of annular connection ring 36 and embracing conical resistor 38, is a simple cylinder 88 subtending resistor 38 and connection clip 87. I have found that for many practical applications the first order of correction afforded by a conical resistor section as 38 is sufficient for most applications even up to the 10 kmc. range, with minimum reflections and low VSWR. It is feasible to taper the internal section of cylinder 88 in the manner of tapered section 40^d of Fig. 1, for further extensions of the frequency range for unit 85, or reduction of its VSWR. Fig. 5 is an illustrative embodiment of the application of a bi-conical resistor in an L-pad.

An alternate form for the series linear resistors is usable in the various attenuation units described herein. The linear cylindrical resistor 50 of Fig. 6 has been described hereinabove. The conical linear resistor 60 of Fig. 7 is similar to resistor 50, with the exception of the conical configuration of its body. Resistor 60 has a resistive film 61 deposited thereon between the terminal annular conduction surfaces 62, 63. When, for example, a conical series resistor such as 60 is utilized in place of series resistors 50, 51 in T-pad 20, or in place of series resistor 86 in the L-pad of Fig. 5, a higher order of compensation is realized, for the signals passing through the associated sections of the attenuation units, resulting in an extension of the microwave range to higher regions for a given VSWR, or lowering of the VSWR across that section, as will now be understood by those skilled in the art.

Figs. 8 and 9 are illustrative exemplary applications of attenuation units utilizing single conical resistors rather than bi-conical resistors. Fig. 8 is a pi-attenuator pad showing the essential elements thereof in cross-section, with the outer sleeve and hardware members omitted. The pi-pad 90 comprises essentially two conical shunt resistors 91 and 92, connected to central conductors 93, 94 respectively of the coaxial system, and containing a series linear resistance 95 in series therebetween. Series resistor 95 is supported at its left end at conical resistor 91 through connection clip 96. Connection clips 93 and 96 are electrically interconnected through central conduction layer 103. The right end of resistor 95 is electrically and mechanically connected with connection clip 97 extending from resistor 92. Conduction layer 104 centrally through resistor 92 interconnects clips 94 and 97. The conical resistors 91, 92 contain annular support and connection rings 98 and 99 respectively, corresponding to ring 36 of bi-conical element 35. Annular rings 98 and 99 are plated with conducting material and electrically connect the corresponding ends of conical resistors 91, 92 to outer cylindrical shield members 100, 101 and 102 respectively.

Cylindrical members 100, 101, and 102 are in turn

connected to an outer pi-pad cylinder (not shown, but corresponding to cylinder **23** of Fig. 1). The securement of annular rings **98** and **99** between cylinders **100**, **101** and **102** are for firm electrical connection and for accurate positioning of the conical resistors **91**, **92** in the pad **90** assembly. The conical resistors **91**, **92** through their central bores **103**, **104** support the connection clips **93**, **94**, **96**, **97**, and in turn linear resistor **95**, to complete the pi-pad circuit. A tie-rod or screw may be used to interconnect clips **93—96** and **94—97** mechanically, as rod **45** of Fig. 1. It is to be noted that there is no tapering of outer cylinders **100**, **101**, **102** with respect to either the linear tapered conical resistors **91**, **92** or the cylindrical series resistor **95**. A first order of compensation is afforded by conical resistors **91** and **92**, as heretofore described. It has been found unnecessary to compensate by tapering for series resistor **95** in this pi-pad configuration. Should a higher order of compensation be desirable, further tapering and matching by logarithmic or linear tapering means subtended over the conical resistors and/or the linear resistor may be used.

Fig. 9 is a cross-sectional view through a coaxial line termination unit utilized for absorbing all incident energy at a given characteristic impedance. Termination unit **105** comprises cylindrical cup member **106** within which is supported a single conical resistor **107**, having an annular conducting ring **108**. The conical resistor **107** is constructed in a manner as hereinabove set forth, and comprises a low loss dielectric core material **109** and a linear (or logarithmically) shaped surface **110** upon which the resistive film is deposited. Coaxial cable hardware connection member **111** is arranged at the left end of termination **105** in the manner of member **21** of T-pad **20** of Fig. 1. Hardware member **111** is utilized to electrically and mechanically connect termination unit **105** to the microwave circuit at a usual cable member.

A coacting metal cylinder **112** is arranged about conical resistor **107** which in the illustrated embodiment is not tapered, but parallel to the axis of unit **105**. The left end of the shunt resistor **107** is connected to the central conductor **113** of cable member **111**, through connection clip or cup **114**. A resilient shim **115** is arranged between cylinder **112** and the outer surface of annular connection ring **108**. A further spring member **116** is arranged between the conical resistor **107** and the cylindrical exterior member **106** of termination unit **105**. It is to be noted that the assembly of termination unit **105** is mechanically and electrically stable, suitable for all practical conditions of utilization. Electrically, the conical taper of resistor **107** affords compensation for frequencies from direct current up to 10 to 12 kmc. with low VSWR ratios. The heat dissipation is found to be adequate and where higher energy absorption is required, heat conduction from termination unit **105** may be arranged by well known means.

An important feature of the present invention is the utilization of conical and bi-conical shunt resistor elements to provide a resistive current path between the inner and the outer conductors of attenuation units with minimum distortion of the microwave signal fields, and the prevention of standing waves. The basic angle of the resistive surface of such conical resistors corresponds to the rise of the linear surfaces **58**, **59** of unit **35**, and of units **91** and **107**; as well as the basic angle rise of the logarithmic surfaces **69**, **70** of unit **65**. Construction of the conical resistor surface at an angle to provide "total internal reflection" of the signal, results in very little energy being reflected back toward the source of the signal, with all incident power being developed across the conical resistive face. Such conical angle is the optimum, as will now be set forth.

Fig. 10 schematically indicates the basic angle θ_2 (axially) of the conical surface s with respect to the axis or direction of incident microwave signal power. The conical surface s has a resistive film (r) upon it. The optimum angle θ_2 is such as to present surface s to the direction P of incident power (axially) at the angle θ_1 of "total internal reflection." Angles θ_1 and θ_2 are complementary, totalling 90°. The dielectric constant e_1 is that for the medium ahead of surface s, and is usually air where $e_1=1$. The dielectric constant e_2 is that of the dielectric material chosen for the conical unit.

The following relations set the optimum determination of θ_1 and θ_2 in the practical design of conical shunt resistors for the attenuation units of the invention.

(1) $$\text{Sin } \theta_1=\sqrt{\frac{e_1}{e_2}}$$

or

(2) $$\text{Sin } \theta_1'=\frac{1}{\sqrt{e_2}}$$

where e_1 is air.

Thus

(3) $$\theta_1=\sin^{-1}\sqrt{\frac{e_1}{e_2}}$$

and

(4) $$\theta_2=\left(90°-\sin^{-1}\sqrt{\frac{e_1}{e_2}}\right)$$

Where θ_2 (and θ_1) are proportioned in accordance with these formulae, the Poynting vector in the cone C medium (e_2) is parallel to the boundary surface (s) and consequently no average power crosses the boundary surface. All the power incident on surface s is developed across the resistive face (r).

The Formulae 1 to 4 are only to a first approximation, since the presence of resistive face (r) affects the final value of θ_2. Thus the optimum value for conical angle θ_2 is best determined empirically, beyond the first approximation per Formula 4, with the resistivity of the material used for (r) included as a factor. Basically however, the angle θ_2 depends upon the choice of dielectric material (e_2) since e_1 is usually air. In practice, the angle θ_2 may lie between 20° and 70° dependent upon the dielectric material for cone C as well as the resistive material for (r).

An optimum angle θ_2 for surface s in a practical attenuator results in the incident microwave power P impinging on shunt resistor (r) of cone C at the angle (θ_1) of "total internal reflection." However practical results are feasible for conical surfaces (s) at angles other than the prescribed optimum, in the invention attenuator pads. The order of compensation by use tapered shields or logarithmic conical resistive surfaces, further minimizes reflections and VSWR.

While I have described and illustrated my invention with several exemplary embodiments and explanations of its functional aspects, variations will be apparent to those skilled in the art, and I do not intend to be limited except as set forth in the following claims.

What I claim is:

1. A high frequency tubular attenuation unit comprising a shunt resistor with a solid core of homogeneous low-loss dielectric material having an outer conical surface, and a uniform film of resistance material across the outer conical surface thereof, the conical core being supported longitudinally of the unit in coaxial relation therewith, and the resistance material thereon extending over a substantial axial path along the unit at a predetermined inclination thereto as a conical envelope tapered from the axial region of the unit transversely across the tubular interior thereof to constitute a shunting impedance contiguous with the homogeneous dielectric core therein for progressively intercepting microwave signal energy passing through the unit with relatively low VSWR over a wide frequency range.

2. A microwave attenuation unit as claimed in claim

1, in which the resistance surface of the conical core is inclined to the direction of incident signal power at an angle between 20° and 70° such that the signal power is substantially all developed across the resistive layer.

3. A high frequency tubular microwave attenuation unit comprising a shunt resistor composed of a solid conical homogeneous core of low-loss dielectric material with a uniform conical outer coating of resistance material and a transverse conductive outer ring at each end of the conical core in contact with the adjacent edge of the resistance material, said transverse rings being in individual planes perpendicular to the axis of the resistor and spaced across the unit for interconnection of the resistor in the attenuation unit, the conical core being supported longitudinally of the unit in coaxial relation therewith, and the resistance material thereon extending over a substantial axial path along the unit at a predetermined inclination thereto as a conical envelope tapered from the axial region of the unit transversely across the tubular interior thereof to constitute a shunting impedance contiguous with the homogeneous dielectric core therein for progressively intercepting microwave signal energy passing through the unit with relatively low VSWR over a wide frequency range.

4. A microwave attenuation unit as claimed in claim 3, in which the resistance surface of the conical core is inclined to the direction of incident signal power at such effective angle as to create total internal reflection, wherein the signal power is substantially all developed across the resistive film.

5. A microwave attenuation unit as claimed in claim 3, further including an integral annular ridge projecting outwardly from said core at the plane of the larger transverse conductive ring and integrated therewith for firmly supporting the resistor within the unit across the ridge with its conical body held in substantially precise coaxial alignment therewithin with the smaller conductive ring extended across the axis of the unit for engaging with and supporting the coacting end of an adjacent resistance element of the unit.

6. A microwave attenuation unit as claimed in claim 5, further including a cylindrical shield about said shunt resistor with one end abutting the annular ridge to support the resistor therewithin with its narrower end projecting into the shield, the internal surface of said cylindrical shield being tapered substantially across its whole section that is opposite the shunt resistive coating, the taper inclining in the longitudinal direction from the ridge end towards the smaller coating diameter to establish low VSWR characteristics therethrough over a wide frequency range.

7. A high frequency tubular attenuation unit comprising a shunt resistor composed of a solid conical dielectric core with a uniform film of resistance material on the outer conical surface and an annular conductive ring at each end of the conical core in contact with the adjacent edge of the resistance material, said transverse rings being in individual planes perpendicular to the axis of the resistor and spaced across the unit for interconnection of the resistor in the attenuation unit, and conductive material arranged along the surface of a central longitudinal opening in the conical core to establish a substantially uniform conduction path through the interior of the dielectric core along the axial region of the attenuation unit, the conductive ring at the narrower resistor end being electrically connected to said interior conduction path.

8. A microwave attenuation unit as claimed in claim 7, in which the resistance surface of the conical core is inclined to the direction of incident signal power at an angle substantially the complement of

$$\sin^{-1}\sqrt{\frac{1}{e_0}}$$

(where e_0 is the dielectric constant of the dielectric core), wherein the signal power is substantially all developed across the resistive film.

9. An attenuation unit as claimed in claim 7, further including an annular ridge projecting integrally outwardly from said core at the plane of the larger transverse conductive ring and integrated therewith for firmly supporting the shunt resistor within the unit across the ridge with its conical body held in substantially precise coaxial alignment therewithin with the smaller conductive ring extended across the axis of the unit for engaging with and supporting the coacting end of an adjacent resistance element of the unit.

10. An attenuation unit as claimed in claim 9, further including a second conical shunt resistor the same as the first conical shunt resistor, said first and second shunt resistors being integral across a common central annular ridge to constitute a symmetrical bi-directional shunt resistor assembly supported in the unit across the central ridge with both narrower core ends extending on opposite sides to engage with axial series resistors of the unit, the interior conduction path being coextensive through the shunt resistor assembly and in electrical interconnection with both smaller conductive rings thereof, and both larger conductive rings being in electrical connection across the common ridge.

11. An attenuation unit as claimed in claim 10, further including a cylindrical shield about each of said shunt resistors, each shield having an end abutting the common annular ridge on each sde for firmly supportng the resistor assembly in the precise alignment and for its engagement with the axial series resistors, said shields electrically connecting with the larger conductive rings at the ridge region.

12. An attenuation unit as claimed in claim 11, further including a series resistor supported within each of said shields, one end of each series resistor being electrically engaged with and supported by the projecting narrower end of the associated shunt resistor, and the internal surface of each of said shields being tapered opposite the resistive portions of said shunt resistors, the shield tapering extending in the longitudinal direction from the ridge towards the respective smaller shunt-resistor diameters to establish low VSWR characteristics therethrough over a wide frequency range.

References Cited in the file of this patent

UNITED STATES PATENTS

2,262,134	Brown	Nov. 11, 1941
2,471,732	Feenberg	May 31, 1949
2,557,122	Leiphart	June 19, 1951
2,620,396	Johnson et al.	Dec. 2, 1952
2,672,591	Wallauschek	Mar. 16, 1954

FOREIGN PATENTS

882,871	Germany	July 13, 1953

OTHER REFERENCES

German application T7634 VIIIa/21a4, June 14, 1956.