Oct. 2, 1962 A. F. WICKERSHAM, JR 3,056,960

BROADBAND TAPERED-LADDER TYPE ANTENNA

Filed Aug. 31, 1959 2 Sheets-Sheet 1

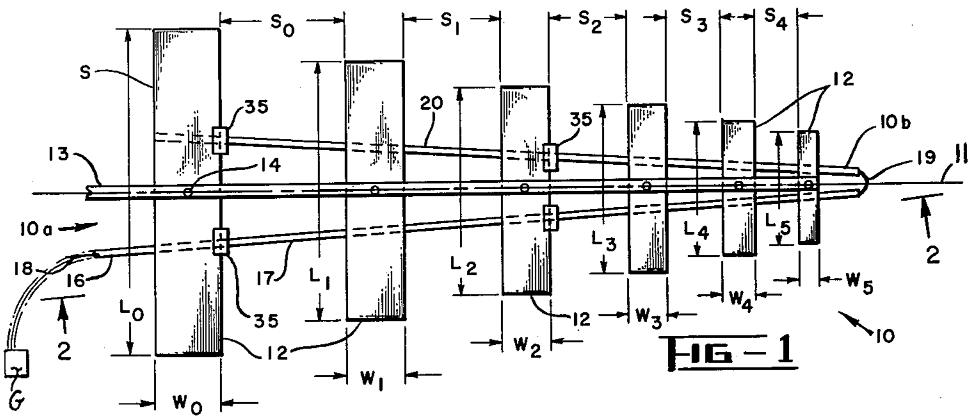


FIG-1

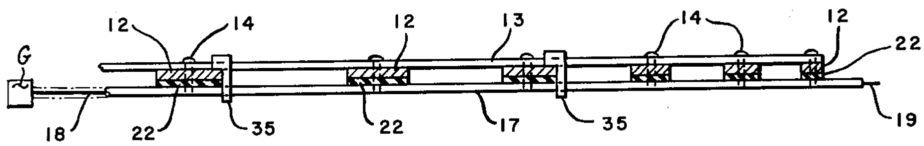


FIG-2

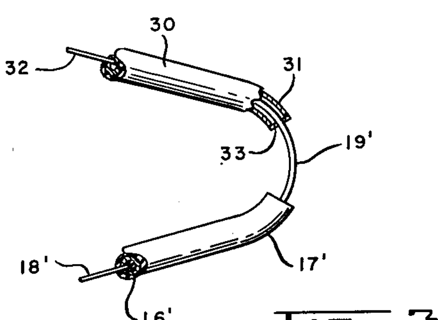


FIG-3

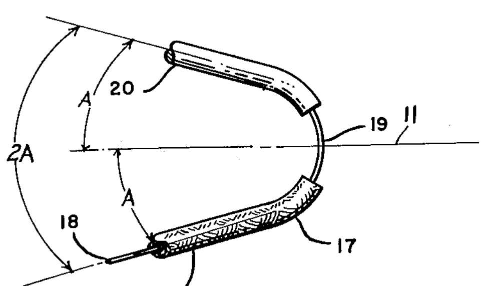
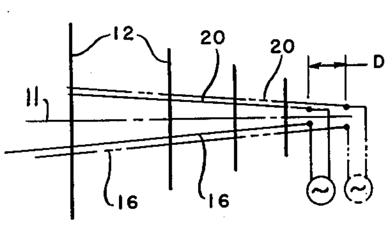


FIG-4



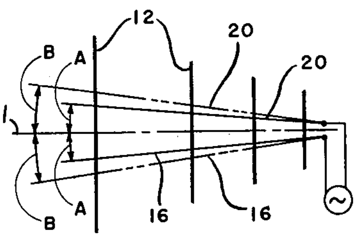


FIG-5

FIG-6

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BROADBAND TAPERED-LADDER TYPE ANTENNA

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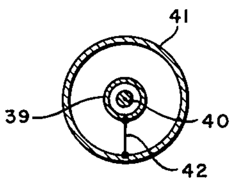


FIG-8

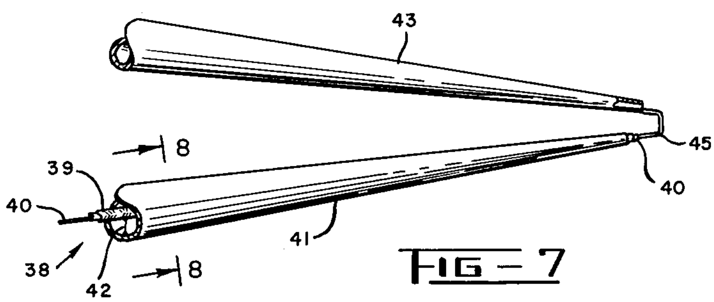


FIG-7

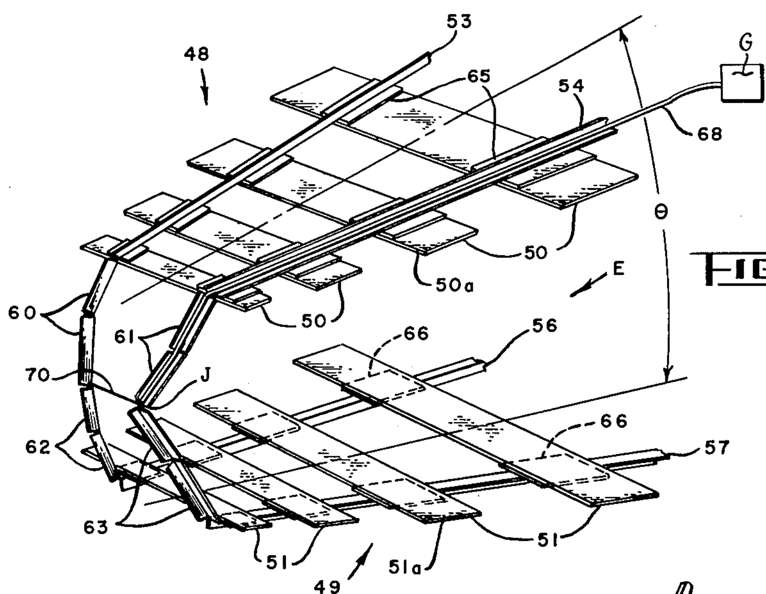
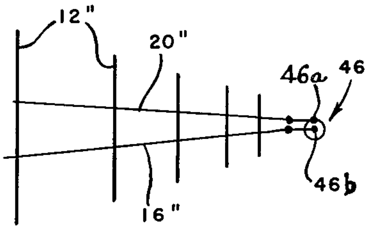
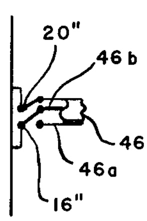


FIG-11





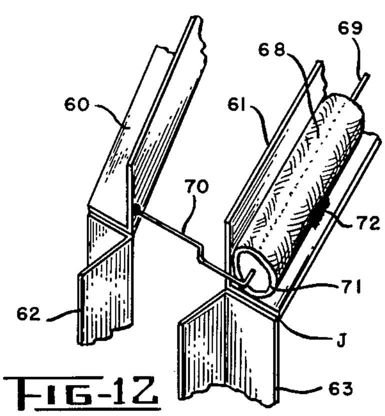


FIG-12

FIG-9 FIG-10

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BROADBAND TAPERED-LADDER TYPE ANTENNA

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Filed Aug. 31, 1959, Ser. No. 837,069
9 Claims. (Cl. 343—795)

This invention relates to antennas, and more particularly to a broadband, end-fire, "tapered" array utilizing radiating and exciting elements whose lengths are functions of element position in the array. The antenna with which this invention is concerned is somewhat related to the Yagi-Uda antenna, but will be referred to as a "tapered-ladder" antenna.

The Yagi antenna is one of the simplest, most compact, high-gain antennas known in the art. It is, however, a relatively narrow band antenna, having an operating frequency range of 1.5% or less of design frequency for a drop of 1 db from maximum gain. Such narrow band characteristics limit the useful applications of the Yagi of require complex multi-array systems in order to meet wide frequency range requirements.

A modified form of a Yagi-type antenna having a frequency band more than four times greater than the conventional Yagi antenna recently has been built and tested. This antenna is called a "straight-ladder" and is excited by a twin wire transmission line. It is described and claimed in a co-pending application of Arthur F. Wickersham, Jr., and Eric N. Harlow, Serial No. 837,005, filed August 31, 1959, entitled Broadband Antenna, assigned to the assignee of this invention.

In accordance with the instant invention, the bandwidth of the foregoing ladder-type antenna is made extremely broad by "tapering" the dimensions of the antenna elements, that is, by varying the physical dimensions and spacing of the radiating elements and of the twin wire line in progressive increments of a predetermined ratio. This antenna utilizes a relatively frequency-insensitive method of excitation in combination with a tapering of the radiating elements in such a manner as to hold substantially constant the ratio of critical dimensions to operating wavelengths.

While, theoretically, an antenna embodying this invention could be constructed to have a quasi-infinite bandwidth, in a practical form the antenna is suited to operate over a given finite frequency range, the half-length $L_0/2$ of the largest radiating element roughly corresponding to the largest operating wavelength of the required band. The lengths and separations of the remaining radiating elements are uniformly decreased or tapered to vanishingly small dimensions so that essentially there is no "smallest" operating wavelength, and all other dimensions of the elements are kept in constant ratios to their lengths. The antenna characteristics, then, with respect to directivity, beam shape, gain and impedance remain substantially the same for wavelengths less than $L_0/2$ because a part of the antenna has physical dimensions corresponding to any operating frequency within that range. Because antenna arrays are discrete structures, the frequency bandwidths of individual radiating elements are chosen to overlap in order that the periodic variation of radiation patterns with changes in frequency will be minimized or eliminated entirely.

A general object of the invention is the provision of an antenna which operates over a very wide range of frequencies, such as to have a quasi-infinite bandwidth.

Another object is the provision of a broadband end-fire array capable of substantially constant radiating characteristics and having a relatively constant impedance over a quasi-infinite frequency range.

Still another object is the provision of a broadband end-fire antenna whose characteristic impedance is readily and conveniently adjusted to match that of the input transmission line.

A further object is the provision of a simple, compact and inexpensive antenna structure which achieves the above objects. A more specific object is the provision of a broadband tapered antenna having a twin wire feed line by means of which the antenna is well matched to the input feed line over a wide range of frequencies.

Another specific object is the provision of a Yagi-type antenna whose impedance can be matched to the line simply by adding loading elements to the existing array.

Still another object is the provision of a broadband end-fire antenna having an efficiency in excess of 90%. Efficiency, as used in this sense, means the ratio of the realized gain of the antenna with respect to the observed directivity of its radiating pattern.

These and other objects of my invention will become apparent from the following description of preferred embodiments thereof, reference being had to the accompanying drawings in which:

FIGURE 1 is a plan view of a tapered-ladder antenna embodying my invention;

FIGURE 2 is a generally longitudinal section of the antenna taken on line 2—2 of FIGURE 1;

FIGURES 3 and 4 are enlarged fragmentary views of different forms of the twin wire feed system used in the tapered-ladder antenna;

FIGURES 5 and 6 are schematic plan views of a tapered-ladder antenna illustrating the manner of adjusting the antenna impedance by varying the angular and linear spacing of the twin wire feed lines;

FIGURE 7 is a fragmentary plan view of another form of twin wire feed line wherein the diameters of the conductors are tapered;

FIGURE 8 is a transverse section taken on line 8—8 of FIGURE 7;

FIGURES 9 and 10 are schematic plan and end views, respectively, of a modified form of tapered ladder antenna showing a coaxial input feed line disposed perpendicularly to the plane of the antenna.

FIGURE 11 is a perspective view of a two-bay array comprising two laterally spaced tapered-ladder antennas of the type shown in FIGURE 1; and

FIGURE 12 is an enlarged view of a portion of FIGURE 11 showing the junction of the two bays and the connection of the coaxial feed line to the array.

The antenna embodying my invention may be used to transmit electromagnetic wave energy into space when used with a transmitter, or it may be employed with a receiving system as a receiving antenna. In the description which follows and in the claims, reference is made to the antenna in a transmitting sense, the dipole elements being described as "radiating" elements and the transmission lines being referred to as "feed" or "input" lines. It is understood, however, that these terms are intended to include as well the antenna and its parts when used in a receiving system wherein "radiating" elements are "receiving" elements, and "input" lines are "output" lines.

Referring now to the drawings, FIGURE 1 shows an antenna **10** having a longitudinal axis **11** and comprising a plurality of radiating elements **12** which are in a row in a common plane and are arranged parallel to each other and symmetrically about and perpendicular to the axis **11**. An elongated axially extending structural member **13**, called a "boom," furnishes mechanical support for the elements **12** which are secured to the boom by suitable means, such as bolts **14**. In order to feed electromagnetic energy to the antenna, in the event it is used for transmission purposes, or to receive such energy from the antenna, when it is used in a receiving system, I employ tapered twin wire feed lines **17** and **20** which are electromagnetically coupled to the several radiating elements. These twin lines may additionally function as support members or booms for support of the entire structure in place of the central member **13**. In a preferred form of the invention, one line **17** of the twin lines is connected to a source (or receiver) G of electromagnetic energy, and comprises the outer conductor **16** of a coaxial cable, see FIGURE 4, which extends from the end **10***a* of the antenna adjacent to the radiating elements and on one side of the axis **11** for the full length of the antenna. This cable terminates at the opposite end **10***b* of the antenna where its center conductor **18** connects directly by means of jumper **19** to an elongated conductor **20** which extends along elements **12** for the full length of the row of elements and on the opposite side of the axis **11** from cable **17**. The twin wire feed line, then, consists of the outer conductor **16** of the coaxial cable, and conductor **20** which is an extension of the inner conductor **18**. Both of the conductors **16** and **20** are electrically insulated from the radiating elements **12** to permit broadband operation of the antenna. Such insulators, by way of example, may take the form of dielectric plates **22**, see FIGURE 2, which space the feed lines from the elements **12**. The twin lines **16** and **20** are, however, coupled to the elements **12** electromagnetically so that there is a full transfer of electromagnetic wave energy between the lines and elements.

In accordance with my invention the physical dimensions and spacings of elements **12** and of the twin wire feed lines **16** and **20** vary in progressive increments at a pre-determined ratio throughout the length of the antenna. This uniform dimensional change, referred to in this description and in the claims as a "taper," is accomplished by reducing the size of successive elements **12** in steps. For example, the lengths L_0 through L_5 of the elements comprising the six-element antenna shown in FIGURE 1 are successively reduced in a constant ratio, for example, 78%; that is, L_1 is 78% of L_0, L_2 is 78% of L_1, and so on. Similarly, widths W_0 through W_5 of these elements are successively reduced by the same factor and finally the percent reduction in width of successive spaces S_0 through S_4 between adjacent elements is the same. The twin wire feed line is tapered by causing cable **17** and conductor **20** to converge from one end **10***a* of the antenna to the other end **10***b*, while these lines remain symmetrical about antenna axis **11**. The angle between each feed line and the axis **11** is equal to A, see FIGURE 4, so that the angle of convergence is equal to 2A. By way of example, the angle 2A between the feed lines preferably is of such magnitude that the linear spacing between the lines as they cross over the radiating elements is about two-tenths of the length of the adjacent element.

The broadband operation of the tapered-ladder antenna described above pre-supposes that the length L_0 and the width W_0 of the largest radiating element are optimum for radiating (or receiving) of microwave energy having the longest wavelength λ_0 in the desired operating frequency range for the antenna. For operation at wavelengths shorter than λ_0, then, the active or radiating part of the antenna will comprise that element which is dimensionally related to the given operating wavelength so as to function most efficiently as the radiator. For example, under operating conditions wherein the wavelengths of the electromagnetic energy is equal to λ_1 (less than λ_0), the radiating element having a length L_1 and width W_1 is most effective to radiate the energy. Thus, for all wave lengths less than L_0, the antenna characteristics with respect to directivity, means shape, gain and impedance tend not to vary with frequency, and thus the antenna is said to have a quasi-infinite bandwidth. Since the antenna is a discrete structure, the bandwidths of the individual radiating elements which comprise the antenna array are designed to overlap to a certain degree in order to prevent periodic variation of antenna radiation characteristics with changes in frequency. While it is not possible to eliminate completely such periodic variation in the radiation characteristics of the tapered-ladder antenna, judicious selection of the number of elements and of the tapering ratio will result in reduction of the variation to an inconsequential perturbation.

Conductor **20** may be a solid rod-like conductor as shown in FIGURE 4, or alternatively may comprise a second coaxial line **30**, see FIGURE 3, whose outer conductor **31** is connected by jumper **19′** to the center conductor **18′** of the other coaxial feed line **17′**. In this embodiment, the outer conductors **16′** and **31** of coaxial lines **17′** and **30**, respectively, constitute the twin wire feed lines for the antenna while center conductor **32** of cable **30** has virtually no effect on the operation of the antenna. Center conductor **18′** is part of the input or feed line. A conducting washer **33** is used to short the jumper **19′** to the outer conductor **31**. Cable **30** terminates at the opposite end **10***a* of the antenna (see FIGURE 1) whereas cable **17′** connects to a high frequency energy source for transmission purposes, or to a receiver if it is used for reception purposes.

The matching of the impedance of the tapered-ladder antenna described above involves two considerations: first, the twin wire line must be matched to the shunt excited radiation elements **12**, and secondly, the so-loaded twin wire line must be suitably matched to the energy input means. When the twin lines are mismatched to the elements, the radiation pattern quickly breaks up and the voltage standing wave ratio (VSWR) is high. A mismatch of the entire antenna to the input means produces a high VSWR although the radiation pattern is substantially unaffected.

Matching of the twin lines to the radiation elements has been achieved successfully by adjustment of the linear and angular spacing between the twin conductors **16** and **20**. The angular spacing adjustment is illustrated in FIGURE 5 wherein the included angle 2A between conductors **16** and **20** is expanded to 2B. The linear adjustment is shown in FIGURE 6 wherein the twin lines are shifted axially relative to the elements **12** by a distance D while holding the angle of convergence constant. Spring clamps **35** are used to adjustably support conductor **20** and cable **17** on certain of the elements **12** so that adjustment of the angular and linear spacing of the lines is facilitated.

Adjustment of the impedance of the loaded twin lines to the input means, that is, the matching of the entire antenna to the input means, is accomplished by uniformly reducing the diameters of the twin lines in the direction of their convergence, to the right as viewed in the drawings.

One of these tapered twin lines, shown in FIGURE 7, comprises a conventional coaxial cable **38** having an outer conductor **39** and an inner conductor **40**, and a hollow truncated cone conductor **41** within which the coaxial cable is supported. The outer conductor **39** of the coaxial cable is directly electrically connected to cone conductor **41** as indicated at **42**. The other of the twin lines comprises a truncated cone conductor **43**, which may be tubular as shown. The two cone conductors **41** and **43** extend the full length of the array and converge toward one end of the array, to the right as viewed, and the inner conductor **40** of the coaxial cable **38** is directly electrically connected to the smaller end of cone conductor **43** by a jumper lead **45**. The opposite end of the coaxial cable, to the left as viewed in the drawing, connects to the input line from the source of electromagnetic energy which feeds the antenna.

By varying the linear and angular spacing between the two conical conductors forming the twin line and by employing conical twin lines as described above, we have constructed a tapered-ladder antenna having a VSWR that is relatively low, i.e., a maximum of 2.6 over a range of 850 to 2100 megacycles, and having radiation patterns which are substantially free of periodicity. Tests on this antenna show a gain of about 8.3 db with respect to an isotropic radiator and a graphical integration of the radiation patterns shows approximately 8.56 db of directivity. Near-field measurements of tapered-ladder antennas with and without conically shaped feed lines shows that within the bandwidth of the antenna essentially no electromagnetic energy reaches the open end of the twin wire transmission line, that is, the end to the left as viewed in FIGURE 1. Furthermore, shorting the end of the line at S, see FIGURE 1, has substantially no effect on antenna performance. By means of the matching techniques described above, it is possible to match the tapered-ladder antenna to an input of any given characteristic impedance within limits of approximately 50 to 90 ohms. Furthermore, test indicate that the directivity and gain of a tapered-ladder antenna are increased by decreasing the taper of the antenna; however, under such circumstances, in order to maintain the bandwidth, it is necessary to lengthen the antenna by adding more radiating elements to the structure.

In order to facilitate construction of relatively small or miniature antennas which are useful in the S, X and K bands, without the awkwardness attendant upon use of large size coaxial cable, such as 50 ohm cable, I have devised another and simpler feed arrangement as shown in FIGURES 9 and 10. Here, the tapered antenna elements 12" are electromagnetically coupled to the two converging lines 16" and 20", and the latter are coupled directly to input means comprising a coaxial line 46 which is perpendicular to the plane of the antenna. Cable 46 has an outer conductor 46*a* connected to conductor 20", and a center conductor 46*b* connected to line 16", as shown. The bandwidth of the antenna and the match of its impedance to the input line is unimpaired in this arrangement. In one experimental model, an impedance "match" was achieved wherein the VSWR at no point exceeded 1.8 within an 5:1 bandwidth.

Another form of my invention is shown in FIGURES 11 and 12 wherein two tapered-ladder type antennas 48 and 49 are stacked and are longitudinally divergent so that their respective longitudinal axes form an angle θ. The respective transversely disposed radiating elements 50 and 51 of the two bays have axes lying in planes substantially perpendicular to the respective planes containing the longitudinal axes of the arrays. The angle θ is selected that the spacing between corresponding elements such as elements 50*a* and 51*a* is about λa, where λa is the wavelength at which the elements 50*a* and 51*a* are most effective ("resonant") as radiators.

The tapering of the elements of the stacked antennas 48 and 49 is substantially the same as for the antenna 10, described above in connection with FIGURE 1. In the embodiment shown in FIGURES 11 and 12, antenna 48 has a pair of structural members 53 and 54, such as angle iron strips, spaced from and converging toward each other from the open end of the antenna and to which the several radiating elements 50 are secured. Similarly, coextensive laterally-spaced converging members 56 and 57 provide support for radiating elements 51 of antenna 49. Members 53 and 54 are mechanically and electrically connected and secured at the closed end of the antenna to members 56 and 57, respectively, by means of interconnecting structural members 60, 61, 62 and 63, see FIGURE 12. The radiating elements 50 and 51 take the form of rectangular plates of conducting material mechanically supported on the structural members. The radiating elements 50 of the top bay 48, as viewed, are insulated from direct electrical contact with the supporting members 53 and 54 by suitable insulating means such as plates 65 of dielectric material and the elements 51 of the lower bay 49 are similarly insulated from members 56 and 57 by plates 66, also made of dielectric material.

The two antenna bays are fed from the open end E, to the right as viewed in FIGURE 11, by a coaxial line 68 which connects to energy source G and extends along structural members 54 and 61 to the junction of the latter with member 63 at point J, see FIGURE 12. At this point, the coaxial line terminates but its center conductor 69 is connected by jumper conductor 70 to the opposite structural member 60. Outer conductor 71 of the cable is in direct electrical contact with members 54 and 61, and may be soldered thereto as indicated at 72. Since members 61, 63 and 57 are electrically as well as mechanically connected together, the effect is that structural members 56 and 57 of the lower bay are parallel fed twin wire feed lines. These twin wire feed lines, then, energize the radiating elements of the two bays by electromagnetic coupling. The match of the impedance of the antenna to the feed lines is improved by converging members 60, 61, 62 and 63 toward the center feed point as shown in FIGURE 11. These variably spaced members, in effect, function as a transformer and hold the voltage standing wave ratio to a minimum. The two-bay array of FIGURE 11 provides in the order of 3 db additional gain over that of the single-bay array and has an end-fire radiation pattern that is substantially uniform over a wide frequency range.

Dimensions and characteristics of antennas of the type described above which have been successfully tested and operated are:

Figure 1

Elements:	
Number	7.
Lengths (inches)	9.06; 6.30; 4.38; 3.05; 2.12; 1.47; and 1.024.
Thickness (inches)	0.080 (all).
Widths (inches)	2.37; 1.64; 1.14; 0.795; 0.553; 0.384; and 0.267.
Spacing	Spacing equal to the width of the smaller neighboring element.
Overall length of antenna	12.9 inches.
Design frequency	700 to 2800 mc. (megacycles per second).
Operating bandwidth (1 db down from max. gain)	700 to 2900 mc.
VSWR (max. over bandwidth)	2.6.
Gain (relative to isotropic radiator)	8 db.
Efficiency	Approx. 90%.

In the embodiment featuring the conical transmission line (FIGURE 7), the diameters of the truncated cones tapered from 1.2 inches to 0.055 inch (at apex) in 10.24 inches of length.

Changes, modifications and improvements to the above described embodiments of our invention may occur to those skilled in the art without departing from the precepts of the invention. Accordingly, the scope of the invention is defined in the appended claims.

I claim:

1. A broadband antenna having an axis and comprising a plurality of conducting elements in a single plane and symmetrically arranged about said axis, the physical dimensions of said elements successively decreasing from a maximum at one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, and means for feeding electromagnetic wave energy to said elements comprising a pair of spaced coextensive conducting lines closely spaced to said elements for the full length of the antenna, the spacing between said lines decreasing in the direction toward said other end of the antenna, and input means connected to said lines for energizing said elements.

2. A broadband antenna having an axis and comprising a plurality of conducting elements in a single plane and symmetrically arranged about said axis, the physical dimensions of said elements successively decreasing from a maximum at one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, and means for feeding electromagnetic wave energy to said elements comprising a coaxial cable and a conducting member disposed symmetrically about said axis and adapted to be electromagnetically coupled to said elements, said cable and said conducting member converging toward each other in a direction toward said other end

of the antenna, said cable having an outer conductor and an inner conductor, said inner conductor being directly electrically connected to said conducting member at said other end of the antenna, and input means connected to said coaxial cable for energizing said elements.

3. A broadband antenna having an axis and comprising a plurality of conducting elements in a single plane and extending transversely of said axis, the physical dimensions of said elements successively decreasing from a maximum at one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, and means for feeding electromagnetic wave energy to said elements comprising a pair of spaced coextensive conducting lines, support means for adjustably supporting said lines in closely spaced relation with said elements for the full length of the antenna, and input means connected to said lines for energizing said elements, the spacing between said lines decreasing toward said other end of the antenna and being adjustable whereby to match the impedance of the antenna to said input means.

4. A broadband antenna having an axis and comprising a plurality of axially spaced parallel conducting elements in a single plane and symmetrically arranged about said axis, the physical dimensions and axial spacings of said elements tapering from a maximum at one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, and means for feeding electromagnetic wave energy to said elements comprising a pair of laterally spaced conducting lines closely spaced to said elements for the full length of the antenna and adapted to be electromagnetically coupled to said elements, said lines converging toward each other in a direction toward said other end of the antenna and each having a transverse dimension which decreases uniformly from said one end of the antenna to the other, and input means connected to said lines for energizing said elements.

5. The antenna according to claim 4 in which said input means comprises a coaxial cable having an inner conductor and an outer conductor connected respectively to said conducting lines at said other end of the antenna.

6. A broadband antenna having an axis and comprising a plurality of conducting elements extending transversely of said axis, the physical dimensions of said elements successively decreasing from a maximum at one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, and means for feeding electromagnetic wave energy to said elements comprising a coaxial cable and a conducting member, means to support said cable and conducting member in proximity to said elements for the full length of the antenna, said cable and said conducting member being laterally spaced apart and converging toward each other in a direction toward said other end of the antenna, said support means being adjustable to provide for adjustment of the spacing between the cable and conducting member, said cable having an outer conductor and an inner conductor, said inner conductor being directly electrically connected to said conducting member at said other end of the antenna, and input means connected to said coaxial cable for energizing said elements.

7. A broadband antenna comprising a pair of linear arrays of conducting elements, said arrays having spaced longitudinal axes which diverge in a direction toward one end of the antenna, each array having a plurality of said conducting elements arranged in a row in a common plane and extending transversely of and generally symmetrically about the array axis, the physical dimensions of said elements successively decreasing from a maximum at said one end of the antenna to a minimum at the other in progressive increments of a predetermined ratio, means for feeding electromagnetic wave energy to the conducting elements of one of said arrays comprising an axially extending conducting member traversing and being insulated from said elements for the full length of said one array, a coaxial cable spaced from and coextensive with and diverging from said member in a direction toward said one end of the antenna, said cable having an inner conductor and an outer conductor, means connecting said inner conductor to said member at the end of said one array opposite said one end of the antenna; the other of said pair of arrays having a pair of axially extending conducting members diverging in a direction toward said one end of the antenna and being insulated from and electromagnetically coupled to the conducting elements of said other array, and means for electrically connecting the conducting members, respectively, of the other array to said conducting member and said outer coaxial conductor of said one array whereby both arrays are fed in parallel.

8. The antenna according to claim 7 in which the point of connection of the inner conductor and the conducting member of the first named array is intermediate the planes of the two arrays.

9. A tapered-ladder antenna comprising a linear array of spaced conducting elements having uniformly decreasing physical dimensions and spacings over the length of the array, and a transmission line adapted to be electromagnetically coupled to said elements comprising a pair of conductors converging toward each other in the direction of the element of minimum dimension.

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