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Tanner

[11] **3,765,022**

[45] **Oct. 9, 1973**

[54] **EXTENDED APERTURE LOG-PERIODIC AND QUASI-LOG-PERIODIC ANTENNAS AND ARRAYS**

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[21] Appl. No.: **172,518**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 782,201, Dec. 9, 1968, abandoned.

[52] **U.S. Cl.** **343/792.5,** 343/747, 343/793, 343/811

[51] **Int. Cl.** **H01q 11/10**

[58] **Field of Search** 343/792.5, 747, 793, 343/807, 811

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[57] **ABSTRACT**

An extended aperture log-periodic antenna in which each element is capacitively loaded to tune out a portion of the element's inductive reactance, so that at any frequency within the antenna's frequency range series resonance occurs at an element whose physical length exceeds one-fourth free space wavelength of the applied signals. An extended aperture quasi-log-periodic antenna is also disclosed, in which only selected elements are capacitively loaded resulting in increased beam sharpness which is not in a true log-periodic relationship even though the antenna impedance remains constant over the antenna's entire operating range, as in a true log-periodic antenna. Linear and circular arrays, employing capacitively loaded elements, are also disclosed.

16 Claims, 13 Drawing Figures

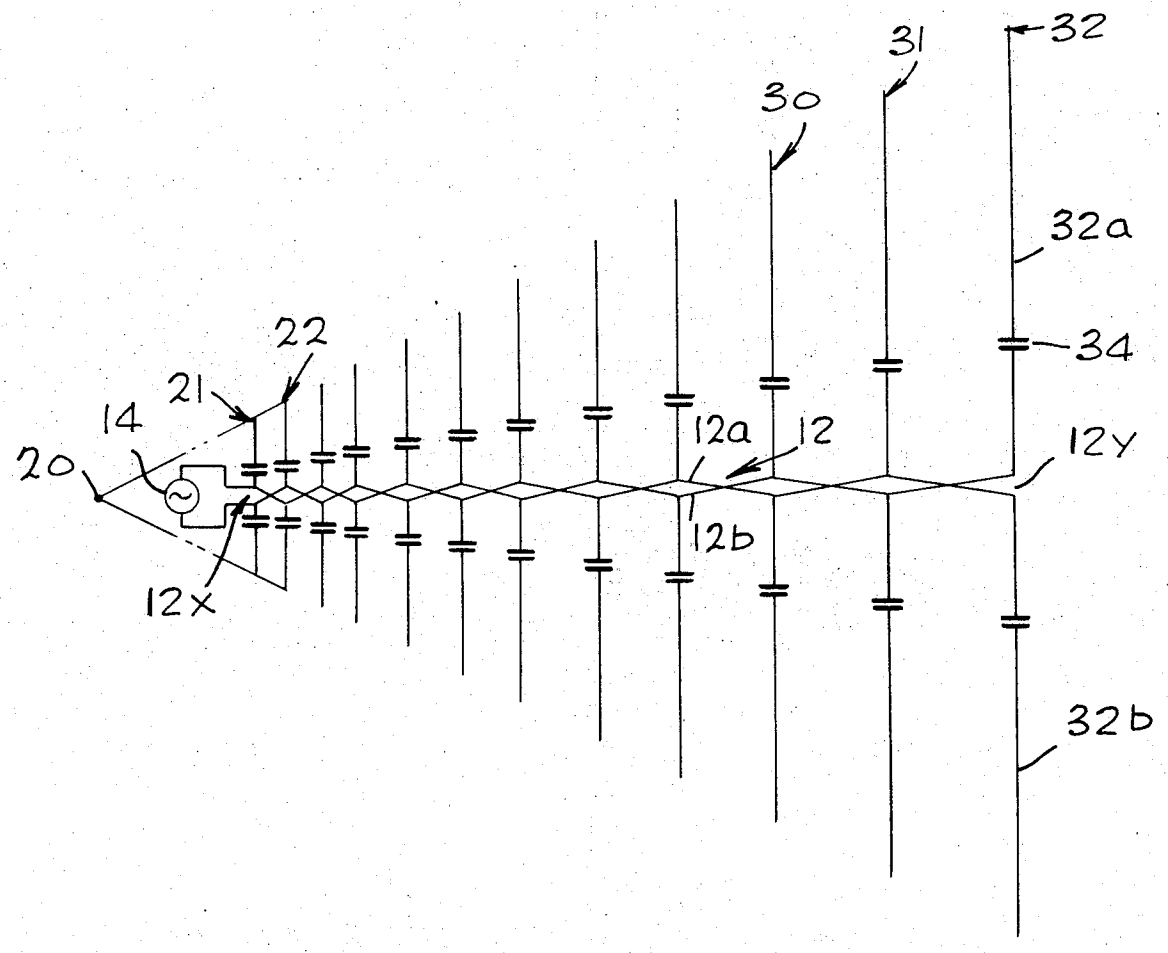


Fig. 1

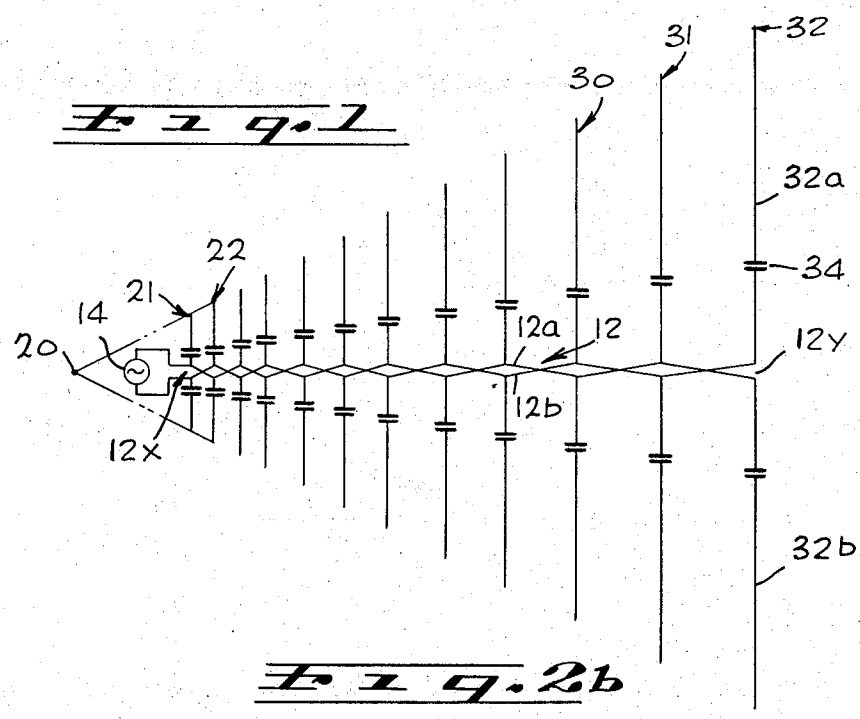


Fig. 2b

Fig. 2a

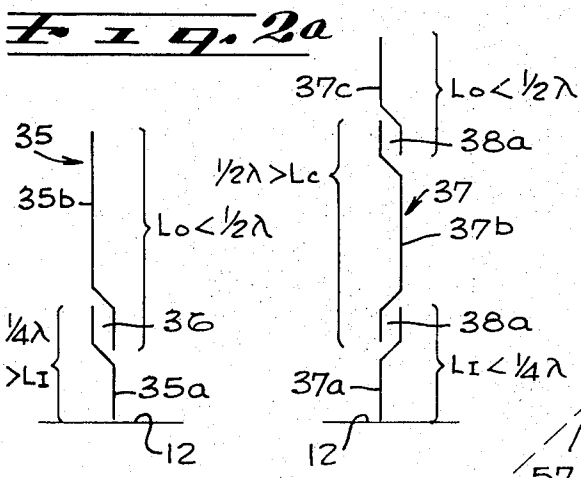


Fig. 3

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Fig. 4

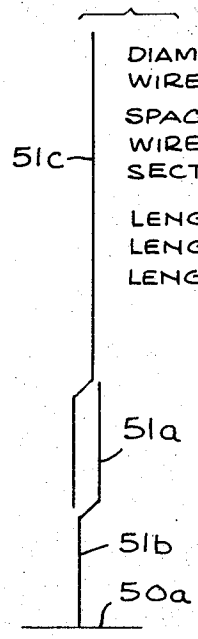


Fig. 5

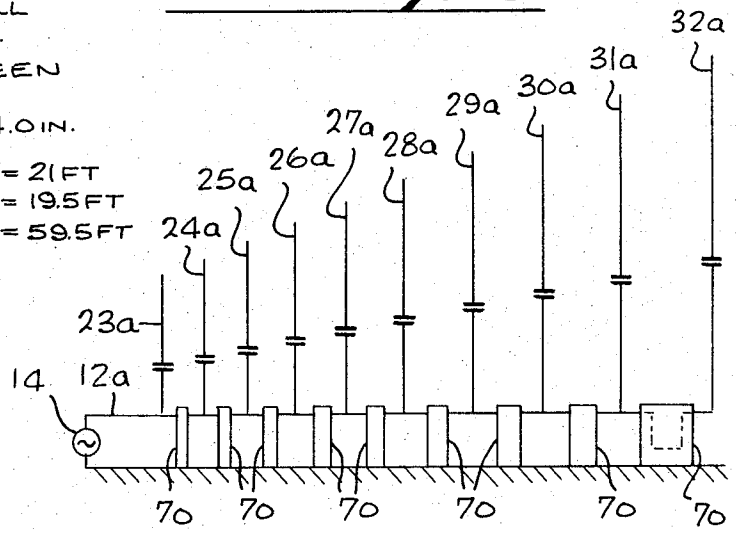
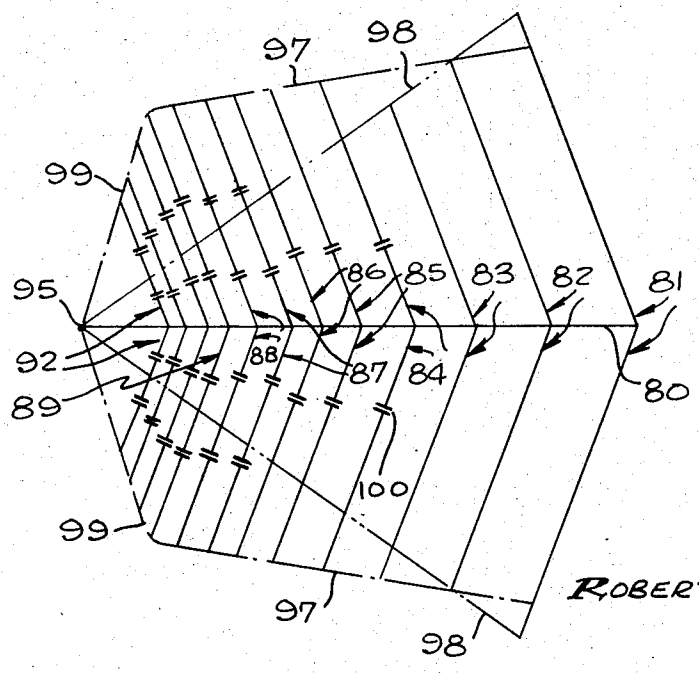


Fig. 6



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Fig. 7

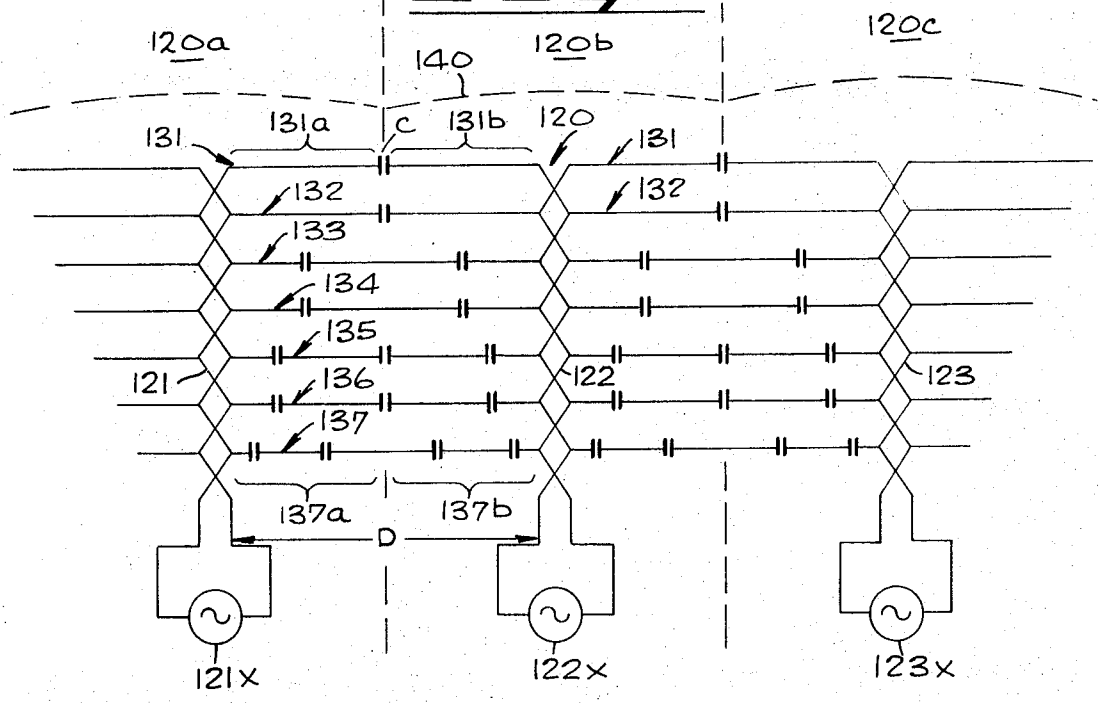


Fig. 8

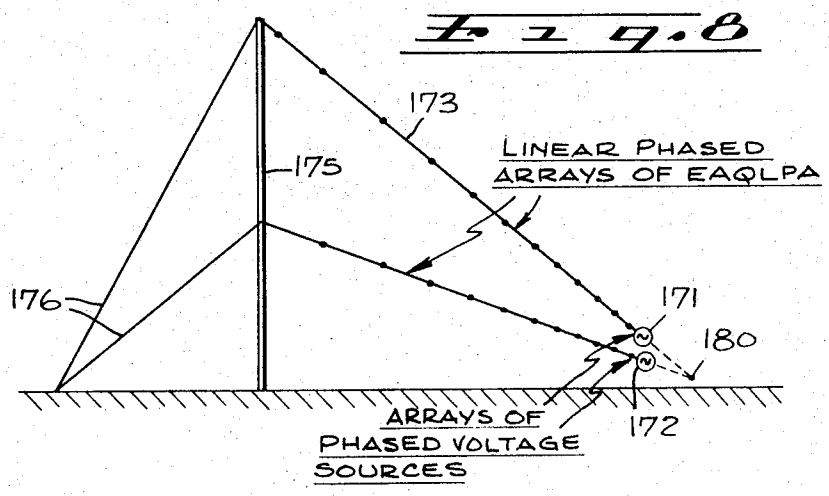
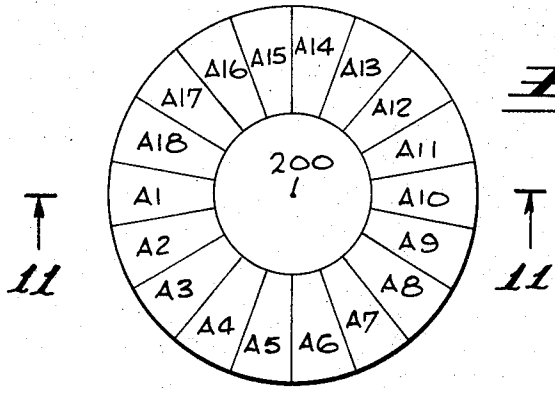


Fig. 9



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Fig. 10

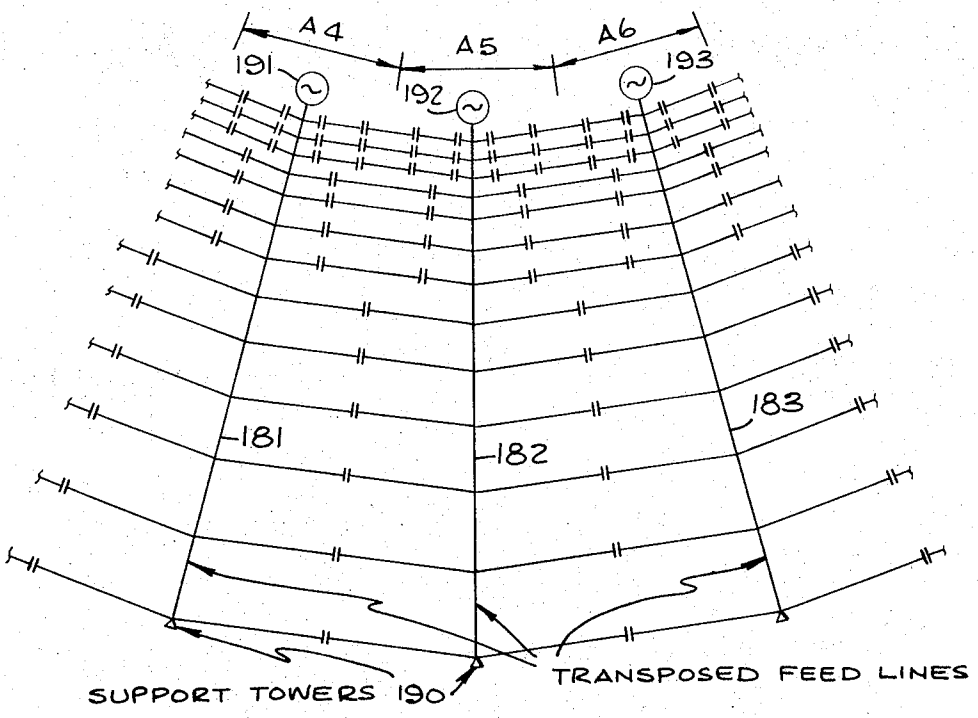


Fig. 11

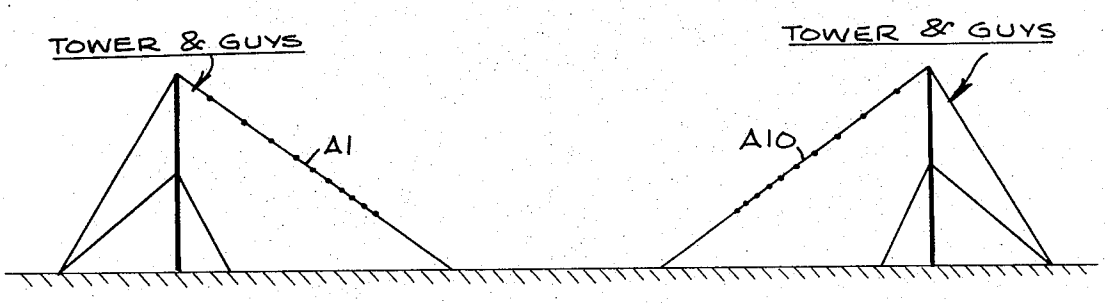
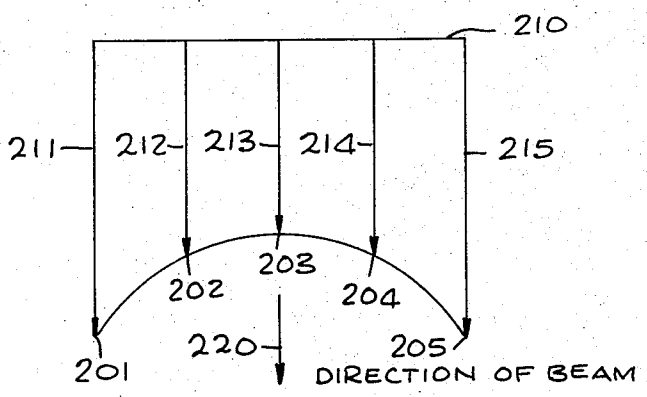


Fig. 12



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EXTENDED APERTURE LOG-PERIODIC AND QUASI-LOG-PERIODIC ANTENNAS AND ARRAYS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Ser. No. 782,201, filed Dec. 9, 1968 and now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to antennas and, more particularly, to antennas and arrays of the log-periodic type.

2. Description of the Prior Art

The advantages which characterize a log-periodic antenna are well known in the art. Antennas of the log-periodic type are described in the literature, including references made to them in "Antenna Engineering Handbook," by Henry Jasik, Editor, chapter 18, sections 18.3 and 18.4, published by McGraw-Hill Book Company, Inc., 1961, and in U. S. Pat. No. 3,257,661, issued June 21, 1966 to the present Applicant. Basically, the major advantage of the log-periodic antenna is that it is frequency independent over a chosen frequency range for which the antenna is designed.

Typically, a true log-periodic antenna comprises an array of elements in which each element is dimensioned and positioned such that the antenna's electrical properties repeat periodically with the logarithm of the frequency of the applied signals, which is within the frequency range for which the antenna is designed. The dimensions of the different elements of the antenna are related to one another by a factor or ratio, often designated as τ. Also, the distances of adjacent elements along the antenna's feed line or feed axis from an antenna vertex, which lies on said axis, are related to one another by the same factor τ.

While the frequency independence property of a log-periodic antenna is probably the main reason for using such an antenna, significant disadvantages of prior art log-periodic antennas prevent them from being used more extensively. Primary among these disadvantages, is the limited gain of the log-periodic antenna.

The main reason for the limited gain becomes apparent when considering the physical dimensions of a prior art log-periodic antenna, dimensions which herebefore were directly related only to the antenna's operating frequency range. Herebefore, the widest antenna dimension in the broadside direction has been fixed by the lowest frequency in the frequency range. Typically, in a prior art balanced log-periodic antenna, incorporating a plurality of pairs of elements which form dipoles, the widest antenna dimension in the broadside direction is generally equal to somewhat less than ½ free space wavelength of the input signals of the lowest frequency. The ½ free space wavelength represents the physical length of the longest dipole, in which each element is somewhat less, but not longer, than ¼ free space wavelength of the lowest frequency. Since the physical width of the antenna's radiating aperture is limited by the dipole's length, the antenna's overall broadside gain is quite limited.

Furthermore, in a prior art log-periodic antenna, the elements have high Q's so that few elements tend to be active at any frequency within the antenna's frequency range. Consequently, the antenna's active region is generally quite short, resulting in relatively poor end-fire gain. Another major disadvantage of a conventional log-periodic antenna is the relatively large number of elements, needed to produce a reasonable operating frequency range. The large number of elements, when properly arrayed, form a curtain of significant physical size and weight, which produces many significant structural problems. Thus, a need exists for an improved antenna which, though retaining the frequency independence characteristics of a conventional log-periodic antenna, by retaining the log periodicity property of a log-periodic antenna, has increased gain. It is further desired that the physical size of such an improved log-periodic antenna be significantly smaller than a comparable conventional log-periodic antenna.

Another most significant disadvantage of prior art log-periodic antennas is their limited use in antenna arraying applications. As is appreciated, in many applications of antennas it is desired to form many simple elements of antennas into antenna arrays, in order to increase the total radiating aperture to obtain higher gain and sharper beams, then can be obtained with a single antenna. Another advantage realized with an antenna array is the ability to steer the beam of the array from one side of the antenna broadside direction to the other. Clearly, it would be highly advantageous if the array could be operated over a relatively large frequency range.

From a cursory analysis, it would seem that since log-periodic antennas are designable to operate over significantly large frequency ranges, such antennas would be ideally suited for arraying purposes. However, this is not the case. The main reason for their limited use in arraying is the appearance of grating lobes in the array pattern as the frequency of the input signals is increased significantly above the lowest frequency of operation. The grating lobe problem is greatly aggravated and grating lobes appear at lower frequencies when an attempt is made to steer the beam of the array. Consequently, arrays, incorporating conventional log-periodic antennas, are operable only over very limited frequency ranges. A need therefore exists for an antenna array which has broadband characteristics, similar to a log-periodic antenna, but one which can be operated over a much broader frequency range than herebefore realizable, and can be steered without producing grating lobes.

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a new improved log-periodic antenna.

Another object of the invention is to provide a new, true log-periodic antenna with increased gain.

Yet another object of the invention is to provide a true log-periodic antenna whose overall size is considerably smaller than a conventional log-periodic antenna, designed to operate over the same frequency range.

A further object of the invention is the provision of an antenna which possesses many of the features of a log-periodic antenna but in addition yields increased beam sharpness, or broadside gain, at nearly all frequencies within its operating frequency range, which is commensurate with the overall broadside dimension of the antenna.

A further object of the invention is to provide a novel antenna array with log-periodic type features.

Still a further object is to provide a new broadband antenna array in which beam sharpness is commensurate with the broadside dimension of the array, and one which does not exhibit grating lobes even when the frequency of the input signals is much greater than the array's lowest frequency of operation, and even when the beam of the array is steered to angles markedly different from the broadside direction.

Yet, another object of the invention is to provide a new circular-like antenna array comprising a plurality of antennas which exhibit beam sharpness at nearly all frequencies in their operating ranges that is commensurate with their individual overall broadside dimensions.

These and other objects of the invention which are directed to providing a true log-periodic antenna are achieved by providing an antenna in which each element is capacitively loaded in such a way that series resonance occurs at an element whose individual physical length exceeds a quarter free space wavelength of the applied signals, at which the element is designed to resonate. Consequently, at any frequency, within the antenna's operating range, energy radiates from one or more elements which are physically longer than one or more comparable elements in a prior art log-periodic antenna, designed to radiate at the same frequency. The enhanced length of the element from which energy radiates accounts for the electrical and mechanical advantages of the new log-periodic antenna of the present invention. Due to the fact that in the novel antenna energy radiates from longer elements, resulting in a larger radiating aperture, it will hereafter be referred to as the Extended Aperture Log-Periodic Antenna, or EALPA.

Briefly, the electrical advantages of the EALPA are enhanced broadside gain due to the increased lengths of the radiating elements. The Q's of the longer elements are lower than the Q's of the elements of prior art log-periodic antennas which resonate at the same frequencies. This causes more elements to be active at any one frequency, thereby lengthening the active region of the antenna when signals at frequencies within the antenna's frequency range are applied. The increased length of the active region results in a significant increase in the antenna's endfire gain. Thus, the EALPA exhibits significantly higher gain than a conventional log-periodic antenna, designed for the same frequency range.

The mechanical or structural advantages of the EALPA are primarily due to the fact that the EALPA requires a number of elements which is significantly smaller than that required in a prior art log-periodic antenna, designed for comparable gain and for operation over a corresponding frequency range. Thus, in the EALPA, the array of elements or curtain is much shorter than a curtain in a comparable conventional log-periodic antenna. The reduced curtain size tends to reduce structural loads, thereby simplifying the structure needed to support the antenna curtain. Also, since the Q's of the elements are reduced, compared with the Q's of corresponding elements in a conventional log-periodic antenna, a given deviation in the position of an element in the EALPA causes a much smaller change in the current flow therein. Consequently, the problems of positioning and securing elements in the curtain of the EALPA are much less critical than those encountered in a prior art log-periodic antenna.

While in the EALPA each element is capacitively loaded so that the antenna retains true log periodicity in all respects, in another embodiment of the invention, only selected elements of selected lengths are capacitively loaded. This results in an increase in beam sharpness which is not in a true log-periodic relationship but, rather, one in which the beam sharpness increases as the frequency increases. At the same time, however, the impedance of the antenna remains nearly constant over the entire operating frequency range, just as in a log-periodic antenna designed according to the prior art. Since such an antenna does not have log-periodic characteristics in all respects, it will hereafter be referred to as an Extended Aperture Quasi-Log-Periodic Antenna, or EAQLPA.

The EAQLPA has advantages which are particularly useful for producing broadband linear or circular antenna arrays without producing undesired grating lobes.

The novel features of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simple diagram of one embodiment of an EALPA:

FIGS. **2***a* and **2***b* are diagrams of extended length elements, capacitively loaded by one and two line sections respectively;

FIG. **3** is a view of an embodiment of an EALPA actually reduced to practice;

FIG. **4** is a side view of the longest element in the dipole **51**, shown in FIG. **3**;

FIG. **5** is a simplified diagram of an unbalanced EALPA;

FIG. **6** is a simplified diagram of one embodiment of a EAQLPA;

FIG. **7** is a diagram of a linear antenna array employing the teachings of the EAQLPA;

FIG. **8** is a side view of two linear phased arrays of EAQLPA's;

FIG. **9** is a simplified top view of a circular array of EAQLPA's;

FIG. **10** is a detailed diagram of antennas **A4**, **A5** and **A6**, shown in FIG. **9**;

FIG. **11** is a side cross-sectional view along lines **11—11** in FIG. **9**; and

FIG. **12** is a simple diagram useful in explaining phasing problems as related to beam steering in the array of FIG. **10**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Before proceeding to analyze the principles on which the present invention is based, one specific embodiment of an EALPA will first be described in connection with FIG. **1**, to which reference is made herein. Therein, reference number **10** designates an antenna comprising a two-wire transposed transmission or feed line **12**, connectable at a feed end **12***x* to a source of radio frequency (RF) signals **14**. The two wires of the feed line are designated by **12***a* and **12***b*. Directly connected to the feed line **12** are dipoles **21–32**. Dipole **21** which is the shortest is connected near the feed end **12***x*, while the longest dipole **32** is connected to the feed line's opposite end **12***y*. The two elements of each dipole, such as **32**, are designated by the dipole's refer-

ence numeral, followed by the letters *a* and *b*, such as **32***a* and **32***b*.

As seen, alternate ones of the dipoles (such as **30** and **31**) are connected electrically in opposite senses to the feed line **12**, due to the line transportation between them. Though the elements of each dipole are of equal length, elements of different adjacent dipoles differ (lengthwise) from each other, by a constant ratio, designated τ. Designating the length of element **32***a*, **31***a* and **30***a*, L_{32a}, L_{31a} and L_{30a}, respectively,

$$\tau = L_{31a}/L_{32a} = L_{30a}/L_{31a}.$$

Likewise, the distances R_{32a}, R_{31a} and R_{30a}, which are assumed to represent the distances of the points on the feed line, at which elements **32***a*, **31***a* and **30***a* are directly connected, from a common antenna vertex point **20**, are related by the same constant. That is

$$\tau = R_{31a}/R_{32a} = R_{30a}/R_{31a}.$$

It is appreciated that such an array of elements forms an antenna having true log-periodic characteristics. Thus, the antenna **10** is a true log-periodic antenna and, since the elements of each dipole are assumed to be equal and the feed line is transposed between adjacent dipoles, the antenna is actually a balanced, log-periodic antenna with a transposed feed line.

If the various elements, shown in FIG. **1**, were straight simple elements, the antenna **10** would not be different from many known log-periodic antennas, described in the prior art. Antenna **10**, however, is significantly distinguishable from any prior art log-periodic antenna by the unique feature which comprises a separate capacitive component **34**, which is serially connected to each element of the antenna, at a point intermediate one element end, which is directly coupled to the feed line **12**, and an opposite free end of the element. As will be appreciated from subsequent explanations, the capacitive component **34** which, in practice may assume more than one form, is not connected at a midpoint of each element, neither at either of its ends. Rather, it is connected at a chosen point between the element's ends. Thus, the expression "intermediate the element's ends" as will be used herein tends to imply a point along the element, other than at its ends.

It will also be appreciated from the following discussion that the number of capacitive components which are serially connected to each element is not limited to one, as shown in FIG. **1**. Two or more capacitive components may be serially connected to each element. As will be discussed hereafter in detail, the function of these capacitive components is to tune out at least some of the inductive reactance of the element to which they are connected, so that a capacitively loaded element of a physical length greater than one quarter free space wavelength of a given frequency resonates when excited by signals of that frequency substantially the same as a true quarter wavelength element. Stated differently the physical length of a capacitively loaded element is greater than one quarter of free space wavelength of its resonant frequency. The number and spacing of the capacitive components are chosen so that the current distribution over the entire length of the capacitively loaded element is substantially similar to the current distribution of an unloaded quarter wavelength element at the same resonant frequency.

In theory it is preferable to distribute the capacitive loading over the entire length of each element. However since such loading would greatly complicate the antenna structure and may not be practical, loading is done at discrete locations along each element. Loading may be done with lumped capacitors or any other means which provide capacitive loading. It has been discovered that the use of line sections to provide capacitive loading is very advantageous. Though line sections are discrete locations they provide some distributed capacitance thereby providing a more desirable distribution of capacitance along the element's length. Hereafter the line sections may be referred to as such or simply as capacitors, since they provide capacitance loading and since they can be replaced by lumped capacitors.

FIG. **2***a* is a simple diagram of a generalized element, loaded with a single line section. Therein, the element **35** is shown comprising an inner portion **35***a* extending from one end of the element which is connected to the feed line **12** to an overlapping line section **36**. The element also includes an outer portion **35***b* which extends from the element's free end to the line section. In practice the length of the inner portion **35***a* including the length of section **36** definable as L_l is less than one quarter free space wavelength ($\frac{1}{4}\lambda$) of the resonant frequency. While the length of outer portion **35***b* with the line section defined as L_o is less than $\frac{1}{2}\lambda$, an element loaded with a single line section (or other capacitive component) has a maximum total length which is always less than $\frac{5}{8}\lambda$ of its resonant frequency.

FIG. **2**b is a simple diagram of a generalized element loaded with two line sections. The element designated by numeral **37** consists of an inner portion **37***a*, an outer portion **37***b* and a center portion **37***c* which is connected to the inner and outer portions by line section **38***a* and **38***b* respectively. In FIG. **2***b* three lengths of the various element portions with the sections adjacent thereto are designated L_l, L_c and L_o. In practice $L_l < \frac{1}{4}\lambda$, $L_c < \frac{1}{2}\lambda$ and $L_o < \frac{1}{2}\lambda$ of the resonant frequency. The total element length is always less than one full wavelength. This is true even when more than two capacitive components are used to load a single element.

One of the basic advantages which is realized by serially connecting to each element in the antenna one or more line sections, intermediate the element's ends, is to enable the incorporation in the antenna of elements which are physically and significantly longer than corresponding elements in a prior art log-periodic antenna designed for the same frequency. As is well known, in a conventional prior art log-periodic antenna, the antenna's active region occurs at a frequency where the impedances of the individual elements are approaching series resonance, and where the length of each element is just short of a quarter free space wavelength. Thus, the physical width of the radiating aperture is less than one half of a free space wavelength.

In the log-periodic antenna of the present invention, the active region of the antenna also occurs where the impedances of the individual elements are approaching series resonance. However, the lengths of the individual elements are significantly greater than one quarter free space wavelength, yet the current phase is substantially constant over the entire element length, similar to that over a conventional quarter wavelength element. Consequently, in the present antenna, the physical width of the radiating aperture, at any given frequency of operation, within the antenna's operating frequency range, is greater than the physical width of a conven-

tional log-periodic antenna which is operated at a corresponding frequency. Since the radiating aperture in the antenna of the present invention is greater than in a prior art antenna, the present antenna is defined as an Extended Aperture Log-Periodic Antenna or EALPA. Typically, the elements in the EALPA are significantly longer than corresponding elements in a prior art log-periodic antenna. Thus, the physical width of the radiating aperture in the EALPA is significantly greater than the aperture in a conventional log-periodic antenna. The exact ratio of element length to the length of corresponding prior art elements can be adjusted over a rather wide range to meet particular design goals. This adjustment is accomplished by adjusting the number, placement and size of the serially connected capacitive components. As previously pointed out when one capacitive component is used with each element, the length is less than $\frac{5}{8}\lambda$ and when more than two capacitors are employed, the maximum element length may approach one wavelength though always being less than a full wavelength.

The enhanced element length in the EALPA has several most important beneficial effects on antenna performance. Since the phase of the current is approximately constant over the element of increased length, the individual element has much enhanced broadside gain and correspondingly, increased beam sharpness or narrowed E-plane beamwidth. Also, due to the increased lengths of the elements, their Q's are reduced significantly, for reasons to be explained hereafter. The elements with reduced Q's tend to be active over a broader frequency band than corresponding elements in a conventional log-periodic antenna. This has the effect of increasing the number of active elements thereby greatly lengthening the antenna's active region. The lengthened active region, in turn, results in a considerable increase in the endfire gain and reduced beamwidth in the H plane.

The increased number of reduced Q elements in the antenna's active region has the effect of signi-ficantly reducing the number of elements which are needed to provide the antenna with the capability of proper operation over the desired frequency range. Thus, the overall size of the EALPA of the present invention is greatly reduced from that of a prior art log-periodic antenna, operable over the same frequency range. Since fewer elements are required, the EALPA curtain is much smaller. Consequently, a much simpler and lighter structure is needed to support the smaller size curtain.

The reduced overall size of the EALPA of the present invention may better be appreciated by comparing the size of an EALPA designed for a specific frequency range with a conventional log-periodic antenna for the same bandwidth. Typically, a prior art log-periodic antenna designed to operate from about 5mHz to 30mHz and to provide a gain of 13db relative to an isotrope may require as many as 53 dipoles. Each of the two elements of the longest dipole, for operation at the low end of the frequency range (5mHz), would be about (but not more than) 50 ft. in length, while each of the elements of the shortest dipole would be about 8 ft. in length. The 53 dipoles would generally form a relatively heavy and long curtain, of the order to 750 ft. in length. Such a curtain would require an even longer support structure.

Unlike such a large size log-periodic antenna, the teachings of the present invention may be employed to provide an EALPA comprising 18 dipoles, which may be arranged in a curtain only 200 ft. long. It should be pointed out that the broadside dimension of the EALPA would be significantly greater than that of the conventional log-periodic antenna. However, the overall EALPA size, due to its relatively short curtain would be greatly less than that of the conventional antenna. Also, since fewer elements would be needed in the EALPA, a much simpler and lighter support structure would suffice. The following Table includes specific lengths of the various elements in an EALPA designed to operate between 5mHz and 30mHz. One complete embodiment of such an antenna is diagrammed in FIG. **3.** Each element is capacitively loaded by a serially connected capacitive line section designated **51***a*, **52***a*, etc., similar to the two line sections shown in FIG. **2.** The values of the various components of each element are also listed in the table. In FIG. **3,** numeral **50** designates the feed line, the separate wires of which would be **50** *a* and **50***b*. Numerals **51–68** designate the 18 dipoles.

TABLE I

Dipole number	Horizontal distance to antenna vertex (40) in feet	Length of capacitive line section (51a, etc.) in feet	Length of base section (51b, etc.) in feet	Length of end section (51c, etc.) in feet	Overall length of element from feed end to tip in feet
51	220	21.0	19.5	59.5	100
52	192.5	18.4	17.1	52.0	87.5
53	168.5	16.1	15.0	45.5	76.6
54	147.5	14.1	13.1	39.8	67.0
55	129.0	12.3	11.5	34.8	58.6
56	113.0	10.8	10.0	30.5	51.3
57	99.0	9.4	8.8	26.7	44.9
58	86.6	8.2	7.7	23.4	39.3
59	75.8	7.2	6.8	20.4	34.4
60	66.3	6.3	5.9	17.9	30.1
61	58.0	5.5	5.2	15.6	26.3
62	50.8	4.9	4.5	13.6	23.0
63	44.4	4.3	4.0	11.9	20.2
64	38.8	3.7	3.5	10.4	17.6
65	34.0	3.2	3.1	9.1	15.4
66	29.8	2.9	2.7	7.9	13.5
67	22	2.5	2.3	7.0	11.8

1. All wires composing capacitive line sections, base sections and end sections of all elements have diameter = 0.16 in.
2. Spacing between wires composing capacitive line sections in all elements = 4.0 in.

The dimensions of one of the elements in the longest dipole **15** and the capacitive line section, serially connected thereto, are shown in FIG. **4,** to which reference is made herein. It should be pointed out that the aforelisted elements' lengths and capacitance values are presented for explanatory purposes only, in connection with one specific embodiment, presented to highlight the teachings of the invention, rather than to act as a limitation thereof.

From FIG. **4,** it is seen that in the particular EALPA, the capacitively loaded element of the dipole **51,** designed to be activated at the low end of the frequency range, i.e., at 5mHz, is 100 ft. long which is about one-half of one free space wavelength at 5mHz. Such an element is about twice as long as a conventional element,

activated at the same frequency. For reasons to be explained hereafter, it is the serially connected capacitive line section, which capacitively loads the longer element in such a way that its impedance approaches series resonance at the low end of the frequency range, considered in the example to be 5mHz, even though the element is considerably longer than a quarter wavelength conventional element, designed to resonate at such a frequency.

There are a number of different approaches which may be taken in analyzing the effect of the capacitors in increasing the physical length of a resonant element. One of the simplest approaches is to view the capacitance of one or more capacitors which are connected to an element as tuning out part of the series inductance which is associated with a conventional simple element.

The current distribution on a simple dipole element may best be viewed in terms of a standing wave. A wave emanating from the driving generator travels out the element until it reaches the open end. There, it is reflected with a reversal of phase of the current, and the reflected wave travels back toward the generator. Interference between the incident and reflected waves produces the standing wave which exists on a resonant element.

The speed with which both the incident and reflected waves travel is given by the known relation

$$v = 1/\sqrt{LC} \tag{1}$$

where L is the series inductance per meter of the element and C is the shunt capacitance to ground (or to the neutral plane) per meter. It is well known, also, that C and L have values in the case of simple slender dipoles such that v is equal approximately to the velocity of light in free space. Formula (1) applies to simple dipole antennas, uniform transmission lines, etc. A more general expression is

$$v = \omega/\sqrt{Z_{series}\, Y_{shunt}} \tag{2}$$

The phase velocity of the wave on the antenna is greatly affected when capacitors are connected in series with the antenna wire at relatively small intervals. By providing series capacitors having values such that they tune out a substantial portion of the series inductance of the antenna wire, it is found that Z_{series} in (2) is much reduced because the reactance of the series capacitors cancels in substantial part the inductive reactance of the antenna wire. Y_{shunt}, however, is not greatly altered.

The reduction of Z_{series} results in an increase in the phase velocity of the wave on the wire to a value which can be considerably greater than the velocity of light. As a consequence of this increased phase velocity, the wavelength of the element with series capacitance can be made greater than the free space wavelength of the wave by the same factor by which the velocity is increased. The increased phase wavelength means that the length of the resonant element, where the impedance is observed to go through its first resonance, is greater than for a simple element. When used as an antenna, such an element will radiate much more strongly than a simple unloaded element. In the present example, increased element length is achieved by capacitively loading it with one or more capacitors.

Although the foregoing analysis applies to an element loaded with series capacitors at intervals frequent enough that the series capacitance is assumed to be distributed, closely related performance occurs when the series capacitance is lumped, at one or more points along the element's length. The points at which the series capacitors are positioned are selected so that the phase of the current along the entire length of the increased length element is substantially constant. As previously indicated the use of line sections may be advantageous since they can be viewed as providing distributed capacitance, particularly at their ends.

As pointed out herebefore, in the EALPA, one or more capacitors are serially connected to each extended length element. The number and sizes of the capacitors and their locations along the increased length element are chosen as a function of how much longer the element is than a conventional element of one quarter free space wavelength. Generally, the length of each of the elements of the EALPA is chosen to be not less than one quarter free space wavelength and less than one free space wavelength. Superior performance is achievable with elements, each one of which is between ⅓ and ¾ free space wavelength in length and is capacitively loaded by one or two capacitors. For elements shorter than ½ free space wavelength one capacitor or capacitive line section will usually suffice. For elements greater than ½ free space wavelength, two or more capacitors are needed.

When the element is capacitively loaded by two serially connected capacitors, or line sections as shown thereby defining inner, center and outer element portions, the inner portion should be the shortest, generally not more than one half of the center portion. The latter's length should not exceed that of the outer portion. Satisfactory length ranges for the three portions are listed below:

1. Inner Portion 1/12λ to ⅛λ, maximum less than ¼λ
2. Center Portion 1/6λ to ¼λ, maximum less than ½λ
3. Outer Portion ¼λ to ⅜λ, maximum less than ½λ

These length ranges are presented as preferred, rather than as limiting the invention thereto. Clearly, if more than two capacitors are serially connected to each element, the element would include more than one center portion. The basic consideration in selecting the relative lengths of each element portion and the sizes of the capacitors is to produce an element so that the phase of the current is substantially the same over the entire element length, at the frequency where the element exhibits its first resonance and for a reasonable range of frequencies above this resonance frequency.

As previously stated, the Q's of the extended length elements are considerably lower than those of corresponding simple elements in conventional log-periodic antennas. The reasons for their reduced Q's will now be explained. It is well known that the radiation Q of an antenna can be expressed in terms of the ratio of the maximum reactive energy stored in the induction fields about the antenna to the energy radiated per RF cycle. The reactive stored energy is principally in the concentrated electric and magnetic fields, closely surrounding the antenna wire, and if the current in the antenna is maintained at a constant value, the reactive energy will increase in direct proportion to the length of the element. On the other hand, the energy radiated by the an-

tenna, again assuming the current is held at a constant value, increases as the square of the dipole moment and, thus, increases as the square of the element length. Thus, since the energy radiated tends to increase as the square of the length, while the energy stored tends to increase only in proportion to the length, it is evident that the Q of the element tends to drop off in inverse proportion to the length. Thus, to a first approximation, the element Q's for the elements of an extended aperture antenna where resonant length of the elements is assumed to be increased by a factor of two, tend to be only half as great as the Q's of the corresponding elements in a simple transposed dipole. In fact, the Q reduction factor, because of a number of second order effects which will not be detailed here, in somewhat greater than two.

Herebefore, the EALPA has been described in connection with a balanced element array and a transposed feed line. It should, however, be appreciated that since the primary novel feature of the invention is directed to extended length elements, for use in a log-periodic antenna, this feature is not limited to a balanced transposed feed line log-periodic antenna. If desired, it may be incorporated in a log-periodic antenna which includes a straight feed line and/or one which is unbalanced, provided proper phase retardation is provided. The need for phase retardation is well appreciated by those familiar with the art.

An example of an unbalanced EALPA, which is fed against ground is diagrammed in FIG. **5** to which reference is made herein. Therein, elements like those previously described in conjunction with FIG. **1** are designated by like numerals. In FIG. **5**, numerals **70** represent phase retardation units which may be emboided in any one of a plurality of ways. For example, each unit **70** may assume the form of a shunt capacitor between wire **12***a* of the feed line **12** and ground, or a shunting inductive-capacitive series resonant circuit, or an inductor in series with wires **12***a* (as shown). Also, it may take the form of a series inductor and shunt capacitor or a simple delay line, formed by extending the length of wire **12***a* between adjacent elements, as shown by dashed lines in unit **70** between the two longest elements on the right hand side.

Although in FIGS. **1, 3** and **5**, herebefore described, the elements are shown as perpendicular to the feed line, in practice it is sometimes preferred to tilt the elements toward the small end of the antenna which is in the direction of antenna radiation, as shown in FIG. **6.** The reasons for tilting the elements are well known in the art. Briefly explained, the current in a given element of the antenna is not precisely in phase at all points as it should be if the element is to radiate with maximum broadside gain. Rather, there is a phase retardation in the current as the observation point moves outward from the driven end to the free end of the element. This retardation results from radiation which alters the wave propagating on the element so that the incoming reflected wave is smaller than the outgoing wave and the net phase of the current tends to exhibit the retardation of the outgoing wave. This retardation effect becomes more pronounced as the element length is extended according to the principles described herebefore further beyond the length of the simple resonant element.

A consequence of this retardation is that a wave, radiation from the element, tends to be tilted in the direction of the element axis, broadening the radiation patterns of the individual elements of the array. However, by tilting the element this retardation effect is compensated for. When tilted, radiation from the different parts of an individual element tends to add in phase in the direction of principal radiation from the antenna which is the small end of the antenna and tends to cancel in the opposite direction thereby enhancing the overall gain of the antenna.

Summarizing the foregoing description, in accordance with the teachings of the present invention, different embodiments of a true log-periodic antenna with increased gain as compared with the gain of a prior art log-periodic antenna are provided. The increased gain is achieved by incorporating capacitively-loaded extended-length elements which provide increased radiation in the antenna's broadside dimension. The extended-length elements have lower Q's than corresponding elements in a conventional log-periodic antenna. Consequently, more elements are active over a larger frequency bandwidth, thereby increasing the length of the antenna's active region which in turn results in an increase in endfire gain. Also, the reduced Q's of the elements make it possible to use fewer elements, resulting in a much smaller antenna as compared with the size of a conventional log-periodic antenna, designed for the same gain and frequency range. The overall reduction of the antenna size simplifies the antenna support structure design. Since the overall antenna size is reduced, the antenna's overall aperture efficiency is increased.

All these advantages are realized by capacitively loading each element to tune out a substantial portion of the element's series inductance, thereby increasing the phase velocity of the wave on the element to a value greater than free space wave phase velocity. Such an increased length element radiates more strongly than a simple unloaded element. Alternately defined, the advantages of the antenna are realized by incorporating extended length elements which are individually, capacitively loaded so that the phase of the current is substantially constant over each extended length element at the frequency at which the element is designed to go through its first series resonance.

Although each embodiment of the foregoing described EALPA of the present invention possesses advantageous properties which are not present in a corresponding prior art log-periodic antenna, the EALPA, like a conventional log-periodic antenna has a radiating aperture whose physical length decreases in a logarithmic fashion as the frequency increases. This limitation can be eliminated by providing an antenna which is like an EALPA, except that the physical width of its radiating aperture does not decrease with increased frequency, but rather, is commensurate with the antenna's physical dimension in the broadside direction. Since such an antenna is like an EALPA in some, but not all respects, it will hereafter be defined as an Extended Aperture Quasi-Log-Periodic Antenna or EAQLPA.

Reference is now made to FIG. **5** which is a diagram of one embodiment of such an antenna. Therein numeral **80** represents a feed line to which a plurality, such as **12,** dipoles **81–92** are directly connected. The elements of each of the dipoles are shown tilted toward the antenna vertex **95.** Unlike a conventional log-periodic antenna, or an EALPA in which true log periodicity is retained in all respects by controlling the relative lengths of the elements so that the ratio of the

lengths of adjacent elements equals the fixed ratio τ, in the EAQLPA, as shown in FIG. **6**, the ratio τ is not fixed throughout the antenna. Instead, the lengths of the elements and those which are capacitively loaded are selected so that the physical width of the radiating aperture in the broadwide direction is commensurate with the largest dimension of the antenna in this direction, and is nearly constant for nearly all frequencies in the antenna's frequency range, except the highest frequencies.

In FIG. **6** the nearly constant physical width of the radiating aperture is represented by the nearly constant distance between dashed lines **97.** As seen from FIG. **6,** this nearly constant aperture physical width is commensurate with the largest dimension of the antenna in the broadside direction, which is represented by the distance between the tips of the elements of the longest dipole **81.** In contrast, in a conventional log-periodic antenna or in an EALPA as herebefore described, the physical width of the aperture decreases as the frequency increases. This is represented by the decreasing distance between dash-dot lines **98.**

The nearly constant physical width of the aperture is achieved by selecting the lengths of the elements as well as the elements which are capacitively loaded so that at any frequency within the antenna's frequency range, the active region of the antenna includes resonating elements whose combined radiating effect produces a radiating aperture of nearly constant physical width. In FIG. **6,** the EAQLPA is shown including three dipoles **81, 82** and **83** which consist of simple elements which are active at the lower operating frequencies of the antenna. At a position corresponding to a higher frequency is a dipole **84,** which consists of two, capacitively loaded elements, each loaded by one series capacitor **100.** Similar dipoles **85** and **86** are fixed at positions corresponding to yet higher frequencies. The capacitive loading, provided by the capacitors **100** to the elements of dipoles **84, 85** and **86,** is chosen so that even through the elements of these dipoles are longer than simple elements, the first resonance of these extended length elements occurs at the same frequencies as they would for simple elements if such elements were located at the same portions on the feed line.

It should be pointed out that whereas the lengths of the simple elements of dipoles **81, 82** and **83** decrease in a log-periodic fashion, this does not hold true for the loaded elements of dipoles **84, 85** and **86.** Indeed, the element lengths of these three dipoles exceed by progressively greater amounts the lengths of simple log-periodic elements which would have occupied the same positions in a conventional log-periodic antenna. Consequently, the capacitors **100** connected to the elements of these dipoles decrease in value more rapidly than in a true log-periodic ratio. Assuming a τ ratio of 0.85, if the element length relation were truly log-periodic, the capacitor **100** in each of the elements of dipole **86** would be 72 percent of the capacitor **100** in each element of dipole **84.** However, since the length of each element of dipole **86** is not 72 percent of the length of each element of dipole **84** but rather is considerably longer, closer to 90 percent, the capacitor in each element of dipole **86** is much smaller than 72 percent of the capacitance serially connected to each element of dipole **84.** The capacitors in dipole **86** may be only **36** percent of the value of the capacitors in dipole **84.**

In the antenna shown in FIG. **6** it is assumed that the elements of dipoles **87, 88** and **89,** connected at positions corresponding to higher frequencies, have become so much longer relative to the lengths of simple elements which would occupy the same positions in a conventional log-periodic antenna so that one capacitor in each of them is not sufficient for proper stability of the currents on them. Proper stability may be achieved by serially loading each of them with two capacitors **100.** Consequently, for elements **87, 88** and **89,** elements with two series capacitive sections are used in place of elements with one series capacitance. It should be stressed that even though in FIG. **6** all capacitors are designated by the same numeral, the capacitors would be of different values. It should further be pointed out that since in the antenna diagrammed in FIG. **6,** the length of the elements in dipoles **87, 88** and **89** do not decrease log-periodically but, rather, exceed the lengths of simple elements in a corresponding log-periodic antenna by progressively greater amounts, the capacitors coupled to the elements of these dipoles decrease by more than the true log-periodic ratio τ.

Beyond element **89,** the lengths of the antenna sections between and adjacent to the capacitors has again become too long in terms of a free space wavelength at the frequency where the elements are active. It would be possible to continue forward with longer elements by introducing three capacitors per element. However, it has been found that when approaching the higher end of the frequency range, phasing problems are encountered when attempting to extend the lengths of the elements too far beyond the normal resonant length of one fourth of a free space wavelength. Consequently, in accordance with the teachings of this invention, the elements of dipoles **90–92,** which are connected at positions corresponding to frequencies near the high end of the frequency range, comprise extended length apertures which vary in a true log-periodic relationship as is the case in each of the EALPHA's herebefore described. At such high frequencies, the physical width of the radiating aperture decreases in a log-periodic relationship as represented in FIG. **6** by the decreasing distance between lines **99.**

From the foregoing description of the EAQLPA it should be appreciated that such an antenna, while retaining some of the properites characteristic of a log-periodic antenna, possesses the unique property of providing a radiating aperture whose physical width in the antenna broadside direction is controlled to vary at a selected rate over at least a selected portion of the frequency range. In the particular example of FIG. **6,** the lengths of selected elements such as those of dipoles **84–89,** and their capacitive loadings are controlled to provide an antenna with a radiating aperture whose physical width is substantially constant over most of the antenna's frequency range, except near its higher end.

For many applications of antennas it is desired to form many simple antennas into larger arrays. One purpose of arraying antennas is that by increasing the total aperture it is possible to obtain higher gains and sharper beams that can be obtained with simple antennas. Another purpose is that by applying voltages of progressively retarded or advanced phases to the successive elements of the array, it is possible to steer the beam of the array to one side or the other of the broadside position. The angular deviation of the beam from broadside is proportional to the phase delay or advance

of the voltages applied to the successive antennas of the array.

Heretofore, broadside arrays and steerable phased arrays have operated only over relatively limited frequency ranges, partly because of the limited bandwidths of the individual elements, used in the array. The use of conventional log-periodic antennas in place of other types of antennas has extended the bandwidths over which such arrays can be operated, but not very much. This is true even though the log-periodic antennas making up the array are very broadband. The reason for the limitation in this case is the appearance of grating lobes in the pattern of the array. Such lobes appear if the spacing between elements in an array exceeds significantly one half of a free space wavelength.

The appearance of grating lobes may be better appreciated by considering a specific example, such as conventional horizontally polarized log-periodic antennas, arranged in a linear array. If the antennas composing the array are placed as close together as possible they will be approximately one half wavelength apart at the lowest operating frequency, since the elements in each antenna are one quarter wavelength long. At the lowest operating frequency, no grating lobe will be present. At a frequency twice this high, however, the feed lines of the antennas are one wavelength apart, and the space between the tips of elements in adjacent antennas is one half wavelength. In such a case, a lobe, in line with the array, would be present except for the fact that it is suppressed by the radiation pattern of the individual elements.

The condition just described above applies when the array is phased so that the beam is broadside. However, if at a frequency equal to twice the lowest operating frequency, the array is phased to steer the beam 30° to the right of broadside, a grating lobe equal in magnitude to the main beam is present 30° to the left of broadside, which in most cases represents an unacceptable situation. If an attempt is made to steer the beam further than 30°, the grating lobe approaches the broadside direction and becomes larger than the ostensible main beam. Thus, it is clear that conventional log-periodic antennas cannot be used in linear phased arrays operating over a frequency range larger than about 1.5 to 1.

Such frequency range limitations are overcome in an array in which the principle underlying the foregoing described embodiments of the invention is employed. The basic underlying principle is the capacitive loading of radiators to tune out at least part of the radiators' series inductances in order to increase the phase velocity of the wave above free space velocity.

The manner in which these teachings are employed in an array may best be explained in connection with FIG. 7. Therein the array, designated by numeral **120**, is shown consisting of three transposed feed lines **121**, **122** and **123**, which are assumed to be connected at their drive ports to generators (or receivers) **121X**, **122X** and **123X**, respectively. Feed lines **121** and **123** are shown connected at their outboard sides to conventional quarter wavelength elements arranged in a log periodic fashion. On their inboard sides the feed lines are connected by capacitively loaded elements or radiators **131–137**, from the back end of the array to the array front end in a log periodic fashion. The capacitors are designated by the letter C.

The feed lines in this particular embodiment are shown to be parallel to one another and consequently elements **131–137** are of equal length, D. The element length D is chosen as a function of the highest frequency of operation. In practice D is always less than one wavelength and generally not more than three-fourths of a wavelength of the highest operating frequency. Thus for a 3:1 frequency range D is generally not more than one-fourth wavelength of the lowest operating frequency. For a range of 10:1, D and therefore the length of element **131** is of the order of one-tenth wavelength of the lowest frequency.

Briefly the elements **131–137** are capacitively loaded in such a manner that over the desired operating frequency range of the array and the desired scan angle, the array formed by these elements has an active region in which some elements radiate at the desired frequency to produce a main beam at the desired scan angle. As is appreciated, for broadside radiation all the generators are excited in phase. The elements are loaded so that an active region exists in which at least one element supports a current phase velocity of infinity which is needed for broadside radiation, and the current distribution is uniform over the entire length of the array. In the particular embodiment the elements at the front of the array are loaded so that when the generators drive the feedlines with signals at the highest frequency in the operating range, the phase velocity of the current is infinite on one of the elements at the front of the array and therefore the element radiates broadside. As the frequency is decreased (while all the generators are in phase), another loaded element is present toward the back of the array which carries a current at infinite phase velocity at the lower frequency, with uniform current distribution.

As is appreciated, beam scanning is achieved by phasing the generators and thereby exciting radiators which carry a current at a phase velocity which is related to the velocity of light as a function of the sine of the angle between the beam at broadside and the desired scan angle. This may be expressed as

$$V_L/V_{ST} = \sin\theta,$$

where V_L is the velocity of light, V_{ST} is the phase velocity of the current on the radiators at the active region of the structure, and θ is the angle off broadside. Clearly when V_{ST} is infinite, $\sin\theta=0$ and therefore the radiation is broadside. However, as V_{ST} decreases from infinity, e.g., $V_{ST}=2V_L$, then $\sin\theta=\frac{1}{2}$ and therefore $\theta=30°$.

In the structure shown in FIG. 7, the elements are loaded so that when all generators are in phase, the structure includes a region with at least one element which supports a current of infinite phase velocity. When the generators are phased for a particular scan angle, the same structure includes a region with at least one element which carries a current at a phase velocity appropriate for the desired scan angle.

From the foregoing it is thus seen that in accordance with the present invention, an antenna array is provided in which capacitively loaded elements are connected at their two opposite ends to feed lines which in the embodiment of FIG. 7 are spaced apart a distance D, equal to the elements' lengths. The elements are connected to the lines in a log-periodic or quasi log-periodic fashion from the front end of the array to the back end. The elements are loaded so that the structure

includes an active region with elements which carry a current at a phase velocity which is a function of the phasing of the voltages provided by generators coupled to the feed lines and at a frequency of these voltages which may vary over a selected operating range.

The elements are loaded so that when the voltages are in phase and at the highest frequency, an element at the front of the array carries a current at infinite velocity for broadside radiation. Assuming that steering is desired at the highest frequency, the voltages are phased for the desired steering or scan angle. For this angle a phase velocity is needed which is less than infinite. Thus, the active region moves back on the array until a loaded element is encountered which supports a current at the phase velocity which matches the voltage phasing to thereby radiate in the desired direction off broadside. That is, the region move back until an element is found with larger capacitors which do not tune out all the inductive reactance so that the phase velocity of the current is less than infinite and matches the voltage phasing.

It should be stressed that regardless of the scan angle, the current distribution over the array is substantially uniform as represented by dashed line **140**, which shows the current distribution on a rear radiator at a low frequency and at broadside scan. Since the elements are connected to the feed lines in a log-periodic or quasi log-periodic fashion, the array is capable of providing broadside radiation at any frequency in the design range as well as at any desired angle off broadside within the design steering range, which is generally not more than ±45°.

As previously stated, the length D of each element **137**, the most forward element in the array, is less than one and generally not more than three-fourth wavelength of the highest operating frequency. The length D of each of elements **131** in terms of wavelength of the lowest frequency depends on the frequency range. For a frequency range of at least 2:1, the length of element **131** is less than one-half wavelength of the lowest frequency and it may be as small as one-sixteenth of a wavelength at the lowest frequency.

It is thus seen that in array **120**, the feedlines are spaced apart by a distance which is less than half a wavelength at the lowest frequency, and less than one wavelength at the highest frequency and that regardless of the excitation frequency, uniform current distribution is produced over the array distance between adjacent feedlines. This is unlike any prior art array of log-periodic antennas in which conventional quarter wavelength elements are employed. Therein the minimum spacing between feedlines is never less than one half wavelength at the lowest frequency and for a frequency range of at least 2:1, the spacing is at least one wavelength at the highest frequency. Also therein, the elements between feedlines are never interconnected to fill the space between adjacent feedlines. Therefore such arrays are incapable of providing a uniform current distribution over the array length, nor are they capable of any significant beam steering without producing severe grating lobe problems.

The array **120** shown in FIG. **7** may also be viewed as comprising a plurality of quasi log-periodic antennas **120***a*, **120***b* and **120***c*, with antennas **120***a*, **120***c* having outboard conventional quarter wavelength elements **141–147**. The inboard elements of each antenna **120***a* and **120***c* are connected at their tips to elements of the center antenna **120***b*. Thus element **131**, between feedlines **121** and **122** of antennas **120***a* and **120***b*, can be viewed as consisting of the two inboard most rearward elements **131***a* **131***b* of antennas **120***a* and **120***b*, while element **137** consists of the two inboard most forward elements **137***a* and **137***b* of the two antennas. Since the length of element **131** is assumed to be less than one-half the wavelength at the lowest frequency, the length of each of elements **131***a* and **131***b* is less than one quarter wavelength. They are therefore end loaded by the single capacitor C to compensate for their reduced size below one quarter wavelength. On the other hand, element **137** is assumed to be longer than one-half wavelength and not more than 1 wavelength at the highest frequency. Therefore each of elements **137***a* and **137***b* has a length greater than one-fourth wavelength. Thus, each of these elements is loaded to tune out part of its inductive reactance to compensate for its greater length than one-fourth wavelength. Each of the other elements **132** and **136** is likewise coupled by one or more capacitors so that the two halves of each element resonate at the same frequency as corresponding unloaded one-fourth wavelength elements. Thus each of the antennas in the array can be thought of as a modified log periodic antenna in that it includes a capacitively loaded element such as **131***a* at the back end of the array which is less than one-fourth wavelength long and a capacitively loaded element such as **137***a* at the front end of the array which is more than one-fourth wavelength long.

Ideally each element should be capacitively loaded uniformly over its entire length. However, for practical reasons this is not feasible. Therefore the element is loaded only at discrete or periodic locations. However, the intervals between capacitors are made small enough so that the loading seems approximately uniform for the range of frequencies for which the elements are intended to become active.

It is appreciated that the actual lengths of the elements i.e., the length D, and the number and sizes of capacitors depend on the particular array frequency range. In a particular embodiment designed for a range of frequencies from 5mHz to 40mHz, elements with lengths and capacitors are listed in the following table were employed:

TABLE II

Element Number	Distance from vertex in feet	Length of Element	Number of Capacitors	Size of Capacitors in pf
1	429.4	15	1	196.0
2	400.6	15	1	176.5
3	373.7	15	1	147.0
4	348.7	15	1	132.5
5	325.3	15	1	114.0
6	303.5	15	1	98.0
7	283.2	15	1	84.0
8	264.2	15	1	72.5
9	246.5	15	1	61.0
10	230.0	15	1	52.0
11	214.6	15	1	43.8
12	200.2	15	1	39.0
13	186.8	15	1	34.5
14	174.3	15	1	30.5
15	162.6	15	1	27.0
16	151.7	15	1	23.5
17	141.5	15	1	20.6
18	132.0	15	1	18.0
19	123.2	15	1	15.6
20	114.9	15	1	13.5
21	107.2	15	2	26.0
22	100.0	15	2	23.0
23	93.3	15	2	20.5
24	87.1	15	2	18.1
25	81.3	15	2	16.0

26	75.0	15	2	14.0
27	70.7	15	2	12.2
28	66.0	15	2	10.7
29	61.6	15	2	9.4
30	57.4	15	2	8.1
31	53.6	15	2	6.9
32	50.0	15	2	5.8
33	46.7	15	3	8.7
34	43.5	15	3	7.7
35	40.6	15	3	6.9
36	37.9	15	3	6.1
37	35.3	15	3	5.4
38	33.0	15	3	4.8
39	30.8	15	3	4.2
40	28.7	15	3	3.7

In practice the spacing of the capaciitors should be such that the element length from a feedline to a capacitor should be in the range of 0.03 to 0.13 wavelength and the element length between capacitors when more than two are coupled to each element should be in the range of 0.1 to 0.3 wavelength of the expected frequency of resonance.

With reference to FIG. **7**, the figure shows the radiators as directly coupled to transposed two-wire feedlines. It should be appreciated that other types of coupling might be useful and desirable. For example, the coupling between radiators and feedline can be effected by transformers, by various types of L-C coupling networks, or by coupled transmission line sections.

Arrays of the type shown in FIG. **7** can be further arrayed vertically, as shown by the elevation view in FIG. **8**. The object of such vertical arraying would be to increase the beam sharpness in the vertical direction and also to permit steering of the beam in the vertical direction. Such vertical beam steering would require that the arrays of voltage sources, feeding the separate curtains of the total array, be independently phased. This is represented in FIG. **8** by the two separate voltage sources **171** and **172**, shown connected to sub-arrays **173** and **174**, respectively, which are vertically arrayed. The sub-arrays are shown supported by a support tower **175** and guys **176**. Each sub-array may be similar to the linear array of FIG. **7**, and each of sources **171** and **172** is assumed to represent a plurality of voltage sources, such as sources **121***x*, **122***x* and **123***x* in FIG. **7** which can be phased to produce the desired beam steering of each sub-array. It is obvious that even though in FIG. **8** only two sub-arrays are shown, more than two sub-arrays can be arrayed vertically.

As shown in FIG. **8**, the two sub-arrays converge to a common vertex, designated **180**, that makes them truly log-periodic in the elevation plane. This leads to an elevation plane pattern that is essentially independent of frequency. If it is desired to have an elevation plane pattern, where at the high frequencies the beam is narrower and closer to the horizontal than is obtained at lower frequencies by having the arrays converge to the true log-periodic vertex at ground level, this can be accomplished by spreading the vertex points of the two sub-arrays and elevating them above the ground.

Antennas of the type described previously can be arrayed in circular arrays, as well as in linear arrays. FIG. **9** shows a schematic plan view of such an array composed of **18** individual antennas, designated A1–A18. The typical details of three of the antennas A4, A5 and A6 with their elements and the loading capacitors are shown in FIG. **10**. FIG. **11** shows a typical section through such an array along lines **11—11** in FIG. **9**. In FIG. **10** numerals **181, 182** and **183** designate the feedlines of the antennas A4, A5 and A6 respectively. Numerals **190** designate antenna support towers and numerals **191, 192** and **193** and the voltage sources coupled to feedlines **181, 182** and **183**, respectively.

As can be seen from FIG. **9**, the array occupies an annulus so that the array closes up on itself. Therefore the conventional outboard elements of the array shown in FIG. **7** are not needed. The annular array has significant desirable properties. One of these is related to the phasing of the driving voltages to obtain a sharp beam.

Typically to obtain a sharp beam withh an **18** antenna array, such as that shown in FIGS. **9, 4, 5** and **6** of the antennas, occupying an angular sector of 80° to 120°, would be simultaneously excited. The remainder of the antennas would be terminated in an impedance, usually a matched load, although a suitably chosen reactance might in some circumstances be used. If the array is composed of more or fewer antennas than **18**, more or fewer antennas would be included in the excited sector, but the angular size of the sector would be approximately the same.

To obtain maximum beam sharpness or gain, the field, radiated by the different antennas in the excited sector, must arrive at a distant point with the same phase. Since the energy leaving the center antennas of the sector travels further in reaching a distant point than the energy leaving the edge antennas, these antennas must be excited with a phase that leads that of the voltage applied to the edge antennas of the sector. Ordinarily, the proper phase voltages for thhe different antennas are obtained by connecting the different antennas of the excited sector to a common voltage source through different lengths of transmission line. If the transmission lines connected to the edge elements are made longer than those connected to the center elements, the energy from the source will arrive at the center element earlier and will consequently have a phase that leads the phase of the edge elements. The amount of phase lead can be adjusted by the difference in transmission line length.

It can be shown that maximum gain is obtained when the difference in phase delay in the lines exactly compensates for the difference in free space distance travelled by the waves radiated from the several antennas of the excited sector. The proper lengths of the phasing lines can be readily obtained from a simple geometrical construction as shown in FIG. **12**. Therein, numerals **201–205** designate the phase centers of five antennas of an excited sector. Line **210** represents a line parallel to a phase front of a radiated wave and arrows **211–215** represent the lengths of delay lines required to collimate a beam in the direction of arrow **220** from such a circular sector array of five antennas.

Since the phase center of log-periodic antennas moves toward the large or low frequency end of the antenna as frequency is reduced, it requires a different set of phasing lines at every frequency to obtain a collimated beam. With true log-periodic antennas the vertex of all antennas comprising the circular array is a common point **200** at the center of the circle and the lengths of the phasing lines required is inversely proportional to frequency. This fact has precluded the use of true log-periodic antennas in circular sector arrays if the excited sector is larger than 20° or 30°. However, because of the annular form of the circular array, the relative motion of the phase centers of the several antennas of the excited sector is much smaller and one set

of phasing lines is adequate for use at all operating frequencies of the array. Usually, the lengths of the phasing lines would be chosen for collimation of the beam at the high frequencies. Then, typically, if the ratio of the outer radius to inner radius of the annulus is two to one, the phase delay provided at the low frequencies would be only half as great as necessary to obtain perfect collimation. However, this error, in electrical degrees, is relatively small because of the large wavelength at the low frequency. Furthermore, the broadside dimension of the aperture, in wavelengths, is much less than it is at the higher frequency so that the deleterious effect of the phasing error is small. The penalty in terms of increased beamwidth beyond the best that can be obtained in the space encompassed by the array, is negligible.

It is obvious that it is not necessary to construct a circular array of antennas in a complete circle as shown in FIG. **9.** Depending upon the azimuthal coverage required and the angular size of the sector to be excited, the antennas can be arrayed in a sector of a circle. The central antennas of the sector would have capacitively loaded extended aperture elements as shown in FIG. **10.** The antennas at the edges of the sector would have on the outboard sides simple quarter-wave log-periodically arranged elements like the outboard elements of the array of FIG. **7.**

Although particular embodiments of the invention has been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and, consequently, it is intended that the claims be interpreted to cover such modifivations and equivalents.

What is claimed is:

1. In a log-periodic type antenna responsive to signals of frequencies in a selected frequency range in the ½ wavelength mode, the antenna including feed means extending along a feed axis and a plurality of radiating elements, each having first and second ends, coupled to said feed means at the first ends thereof at log-periodically related points along said axis to form a log-periodic like array, each element having an electrical length between its opposite ends which is substantially equal to ¼ free space wavelength of the element's resonant frequency, the improvement comprising:

capacitive means comprising an overlapping line section serially connected to at least one of said elements intermediate its first and second ends to provide distributed capacitive loading for the element to tune out at least a part of its inductive reactance, so that the current distribution over the entire length of the capacitively loaded element whose physical length is greater than one-fourth wavelength of its resonant frequency is substantially similar to the current distribution on an element whose physical length is equal to the one-fourth wavelength of the resonant frequency, the physical length of said capacitively loaded element being less than ⅝ free space wavelength of its resonant frequency, the length of the element from said first end including said line section being definable as L_I, and the length of the element from said second end and including said line section being definable as L_o, L_I and L_o being not more than one-fourth and one-half of a free space wavelength respectively, of the element's resonant frequency.

2. The arrangement as recited in claim **1** wherein each of said elements is capacitively loaded by at least one line section at a point intermediate said first and second ends thereof.

3. The arrangement as recited in claim **1** wherein $L_o/L_I \geq 1.5$.

4. The arrangement as recited in claim **3** wherein each of said elements is capacitively loaded by at least one line section at a point intermediate said first and second ends thereof.

5. In a log-periodic type antenna responsive to signals of frequencies in a selected frequency range in the ½ wavelength mode, the antenna including feed means extending along a feed axis and a plurality of radiating elements, each having first and second ends, coupled to said feed means at the first ends thereof at log-periodically related points along said axis to form a log-periodic like array, each element having an electrical length between its opposite ends which is substantially equal to ½ free space wavelength of the element's resonant frequency, the improvement comprising:

at least first and second capacitive means coupled to at least one element for providing capacitive loading therefor so as to tune out part of the inductive reactance thereof, so that the phase velocity of the current thereon at the resonant frequency is substantially constant along its entire length comparable to the constant phase velocity on an unloaded one-fourth wavelength long element at the same resonant frequency, said at least one element defining an inner portion, a center portion and an outer portion, said first capacitive means being connected to said inner and center portions, and said second capacitive means being connected to said center and outer portions, the total length of said at least one element between its first and second ends, being less than 1 wavelength of its resonant frequency, the center portion being not longer than the outer portion and not less than the inner portion.

6. The arrangement as recited in claim **5** wherein the length of said one element is not less than one-half wavelength of its resonant frequency.

7. The arrangement as recited in claim **5** wherein said first and second capacitive means are first and second line sections, the total length of said inner portion with said first line section, and the total length of said outer portion with said second line section being less than one-fourth and one-half wavelength respectively of the element's resonant frequency.

8. The arrangement as recited in claim **7** wherein said center portion with said first and second line sections is less than one-half wavelength of the element's resonant frequency.

9. The arrangement as recited in claim **8** wherein the length of said one element is not less than one-half wavelength of its resonant frequency.

10. An antenna comprising:

feed means extending in a feed axis from a first end to a second end; and

a plurality of radiating elementss each having first and second ends, said first ends being coupled to said feed means between the first and second ends thereof at substantially log-periodically related points to form an antenna array, at least one of said elements comprising inner and outer element portions, said inner portion having one end corre-

sponding to the element first end directly coupled to said feed means and an opposite end overlapping one end of said outer portion, which extends to the second element end, to form a line section which provides distributed capactive loading for said element to tune out at least part of its inductive reactance, the respective length of said inner and outer element portions being less than one-fourth and one-half of a wavelength at the element's resonant frequency, with its total length being less than five-eighths wavelength of its resonant frequency, with the current distribution over the entire length of the capacitively loaded element being substantially similar to a ¼ wavelength element at said resonant frequency which is not capacitively loaded.

11. A broadband antenna array comprising:

a plurality of feed means;

a plurality of capacitively loaded radiating elements, each element having first and second opposite ends connected to adjacent feed means, the elements being connected at points on said feed means spaced substantially log periodically from an array front end to an array back end, whereby when said feed means are energized in phase at a frequency within the design band the array includes an element for the supporting wave propagation at inifinite phase velocity, the elements about the array front end including an element, whose total length between said first and second ends is less than 1 wavelength of the highest frequency in said band and the elements about the array back end include an element whose total length between its first and second ends is less than ½ free space wavelength of the lowest frequency in said band.

12. The arrangement as recited in claim **11** wherein each capacitively loaded element is loaded by at least one capacitive means, the spacings between capacitive means on the same element and between capacitive means on corresponding elements within said array being substantially equal.

13. The arrangement as recited in claim **12** wherein the spacings between capacitive means on the same element and between capacitive means on corresponding elements being less than one-half wavelength of the element's resonant frequency.

14. The arrangement as recited in claim **11** wherein said plurality of feed means comprising at least first and second substantially parallel feed means, with each of the elements between said first and second feed means being connected at said first end to said first feed means and at said second end to said second feed means, with all elements being substantially of equal length, and further including outboard elements coupled to said first feed means in a direction away from said second feed means and to said second feed means in a direction away from said first feed means, the lengths of said outboard elements decreasing substantially log periodically from the array back end to the array front end.

15. The arrangement as recited in claim **11** wherein the element at the back end of said array is capacitively coupled by at least one line section at the center thereof and the element at the front end of said array is capacitively coupled by at least two line sections, the spacing between line sections in the same element and in corresponding elements being less than ½ free space wavelength of the element's resonant frequency.

16. A broadband antenna array comprising:

a plurality of feed lines;

a plurality of radiator means connected to extending between adjacent feed lines in said array, from an array front end to the array back end, with all radiator means substantially parallel and spaced substantially log-periodically from said array front end to the array back end; and

capacitive means coupled to each of said radiator means to control the reactances of said radiator means whereby when said feed lines are excited in phase at the highest or lowest frequencies in said band, the radiator means at the front end and back end respectively of said array include radiator means which support a current at infinite phase velocity, the length of the radiator means at the back end of said array being less than one-half wavelength of the lowest frequency in said band, and the spacing between feed lines being less than 1 full wavelength of the highest frequency in said band.

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