A Survey of the Very Wide Band and Frequency Independent Antennas—1945 to the Present

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The last few years have witnessed major developments in the field of antennas which are suitable for use over a range of frequencies. Operating bandwidths that were considered an impossibility as little as seven years ago are now readily available.

To trace these developments, a brief historical survey of the literature in this field since the Second World War, is presented.

1. Introduction

The past two decades have witnessed a rapid extension of that portion of the electromagnetic frequency spectrum that is useable for communication purposes. With this portion of the spectrum expanded to a range of over 10⁷ to one, and with present applications requiring continuous coverage of large portions of this spectrum, it is not surprising that a great deal of time and effort have been directed toward the development of the physical equipment to provide this coverage. One of the serious drawbacks to any simplified solution has been the extremly limited bandwidths obtainable with both the receiving and transmitting equipment and the antennas required to successfully launch and receive the electromagnetic radiation. Recent developments, of which the traveling wave tubes are of note, have somewhat alleviated the first portion of this problem. This survey is concerned with the latter portion of the problem, the development of antennas which are capable of being operated over a very wide range of frequencies.

As World War II came to a close, the general status of research and development in the field of antennas had led to a few structures that were capable of being operated over a 2 to 1 or slightly greater range of frequencies with acceptable radiation and impedance characteristics. In a majority of cases, it was the radical changes in the radiation pattern with changes in operating frequency, which limited the usefulness of antennas to somewhat less than this range. Antennas had been developed with an input impedance that remained relatively constant with a change in frequency.

In a discussion of antennas intended to be used over a range of frequencies one is immediately faced with a problem in terminology. Such antennas have been referred to as "broadband antennas." The term broadband, however, is a rather nebulous term. It has been and is still being very loosely applied. In the usual sense it has been applied to antennas whose radiation and input impedance characteristics were acceptable, although not necessarily constant, over a frequency range that may be anything from $1\frac{1}{2}$ to 2 to 1.

In contrast to these antennas, this survey has been limited to antennas which are useful over at least a 4 or 5 to 1 range of frequencies. Thus, although this is certainly a broad band of frequencies it might be preferrable to refer to them as "very wide band" antennas.

2. Discone

Probably one of the first of the very wide band antennas was the discone antenna proposed by Kandoian [1946]. It was a departure from prior antennas in that it could be used over approximately a 4 or 5 to 1 range of frequencies. However, advances in the field during the next 7 or 8 years, were, in the main, limited to increasing the bandwidth of existing types of antennas by a few percent. The one exception during this period was a modified helical antenna investigated by Springer [1949] and later by Chatterjee [1953, 1955]. These unbalanced conical helical structures fed against a ground plane had acceptable pattern bandwidths of 4 or 5 to 1.

3. Archimedes Spiral

In 1953 a major step forward was taken when Turner [1955] proposed the first spiral antenna. This antenna consisted of two flat, rather narrow, constant width metallic arms, wound in the form of an Archimedes spiral. Fed at the center in a balanced manner it radiates a broad circularly polarized lobe on each side of the plane of the antenna. Subsequent investigations and development of this antenna produced forms that had stable pattern and impedance characteristics over bandwidths up to 10 to 1 [Burdine and McElvery, 1955; Burdine and Zimmerman, 1955: Jones and Turner, 1959; Curtis, 1960; Kaiser, 1960; Bawer and Wolfe, 1960; Donnellan, 1960, 1961; Donnellan and Close, 1961].

4. ''Frequency Independent'' Antennas— Equiangular Spiral

In 1954, Rumsey, applying a theory that an antenna specified entirely by angles would have characteristics which are independent of frequency, suggested that an infinite length structure based upon the equiangular or logarithmic spiral could be specified completely in terms of angles. He proposed that a finite structure be studied. Subsequent investigation of a balanced planar antenna based upon these curves disclosed the equiangular spiral antenna to be the first antenna to have, in a practical size, the characteristics which could be associated with an infinite structure [Dyson, 1955, 1957]. Thus it became the first of a class which might be called "frequency independent antennas" [Rumsey, 1957].

"frequency independent antennas" [Rumsey, 1957]. The introduction of the term "frequency independent" adds to the terminology problem. It is being used, however, by the author and others, in the sense that, since the upper and lower frequencies at which these antennas imay be operated are determined by independent parameters, the bandwidth over which the radiation pattern and input impedance characteristics are essentially contstant is theoretically unlimited. In actuality it is limited only by practical considerations of construction, and antennas have been constructed to operate over a bandwidth of more than 42 to 1. There is no fundamental reason why this could not be extended.

The general philosophy behind the equiangular spiral antenna is to design a radiating structure such that successive applications of a scaling factor results in structures which are identical with the original, or which at most, differ by some rotation about an



FIGURE 1. Balanced planar equiangular or logarithmic spiral slot antenna.

axis through the origin of the original structure. Although the structure must be infinite in size to fulfill the scaling condition of exact equivalence, it has been found that forms based upon the equiangular (or logarithmic) spiral curve may be truncated to a finite size and still retain, over an extremely wide range of frequencies, the characteristics that would be associated with the infinite structure.

5. Logarithmic-Periodic Antenna

Shortly after the investigation of the equiangular spiral geometry was initiated, DuHamel proposed that it should also be possible to force radiation from otherwise angular structures by the use of periodic discontinuities [DuHamel and Isbell, 1957; DuHamel, U.S. Patent No. 2,985,879]. This led to a form of linearly polarized antenna which had pattern and impedance characteristics which would repeat periodically with the logarithm of frequency. Thus although these "logarithmic-periodic" antennas scale exactly at only certain discrete frequencies, they can be designed so that the radiation characteristics do not change appreciably over the period between these frequencies. Hence they also exhibit nearly frequency independent characteristics.

6. Versions of the Equiangular Spiral

Many versions of these log-spiral 1 and log-periodic antennas have been developed in the last few years. The planar log-spiral antenna shown in figure 1, is a bidirectional antenna, radiating a broad circularly polarized beam on each side of, and perpendicular to, the plane of the antenna. The antenna may be made unidirectional by an orthogonal projection of the balanced spiral arms upon the surface of a cone as shown in figure 2 [Dyson, 1958a, 1958b, 1959; Dyson, U.S. Patent No. 2,958,081]. For included cone angles less than about 45 deg, radiation is confined to one broad circularly polarized lobe with maximum radiation off the apex of the cone. The antenna is a balanced structure with the feed voltage applied between the two arms at the apex of the cone. This feed voltage may be supplied by a conventional balanced line carried along the axis of the cone or by a coaxial line and balun. The characteristics of these antennas permit a third method. The feed line, a coaxial cable, may be carried along and soldered in contact with one of the arms. Because the amplitude of the antenna currents on the arms (and also on the outside of the cable) fall off rapidly with distance from the apex, the ends of the arms where the cable enters carry negligible antenna current. This optional feed conveniently and automatically provides a frequency-independent balun, permitting feeding the balanced antenna by means of an unbalanced line.

Conical log-spiral antennas have been constructed to operate over more than 40 to 1 bandwidths. Again this bandwidth is at the discretion of the designer. The upper useable frequency being determined by the truncated region at the apex which

¹ A convenient abbreviation for logarithmic spiral, a synonym for equiangular spiral.



FIGURE 2. Balanced conical logarithmic spiral antenna with feed cable carried along one arm.

must remain small in terms of wavelengths (less than ¼ wavelength). The lowest useable frequency by the base diameter of the cone which must be on the order of 0.4 wavelength at the lowest frequency of operation.

A highly practical version of the conical log-spiral antenna can be constructed by allowing the exponentially expanding arms to degenerate into rather narrow constant width structures following the logarithmic spiral curve as shown in figure 3. For fairly tightly wrapped spirals this version has characteristics which are very similar to those of the original antenna. This "wire" version is simple to construct and if the "infinite balun" feed referred to above is desired, the feed cable itself can become one of the arms with a dummy cable becoming the second arm of a balanced structure.

It is interesting to note that Nussbaum [1958] and Barsky [1959] proceeding from Chatterjee's work in an independent investigation developed a different version of an unbalanced conical helix antenna. This antenna consists of a single helical conductor formed into a cone and fed against a small disk at the apex of the cone. It radiates a broad circularly polarized lobe directed off the apex of the cone. This projection of a cylindrical helix, with a judiciously chosen variable pitch angle, onto a coaxially oriented conical surface, resulted in an antenna which is constructed in a logarithmic spiral curve and thus the antenna is usable over very wide bandwidths.² The



FIGURE 3. Wire version of balanced conical logarithmic spiral antenna fed with coaxial line and balun along axis of cone.

unbalanced antenna however has a slight pattern tilt and does not have the excellent circular polarization off the axis of the antenna, or the stable input impedance that is characteristic of the balanced two arm conical log-spiral antenna.

Multiarm versions of the balanced conical logspiral antenna can be constructed to provide operation in several distinct modes [Dyson and Mayes, 1960a, 1960b, 1960c; Dyson, 1961a]. Thus a four arm symmetrical structure may be exicted to radiate an axial beam with an $e^{\pm j\phi}$ variation. i.e., the phase of the far field varies linearly with the azimuthal angle ϕ , around the antenna. It may also be exicted to produce a conical beam with an $e^{\pm j2\phi}$ and a conical beam with an $e^{\pm j3\phi}$ variation. Since the orientation of the maximum of the conical beam may be controlled by a variation in the rate of spiral of the antenna arms, it may be positioned perpendicular to the axis of the antenna to provide a simple very wide band circularly polarized omnidirectional source.

The complex coefficient of coupling and characteristics of the conical log-spiral antennas in simple arrays have been investigated [Dyson, 1961b].

7. Versions of the Log-Periodic Structure

The log-periodic antennas have been extensively investigated [Mayes, Isbell, and Carrel, 1958]. Isbell [1958] demonstrated that the planar antenna could

 $^{^2}$ If this antenna were constructed as a bifilar structure with one arm fed against the other it would be identical to the wire version of the antennas as referred to by Dyson.

be modified to provide unidirectional patterns by forming the two elements of the antenna into a "V." DuHamel and his associates developed a wire version of the log-periodic antennas and demonstrated their capabilities in arrays and as feeds for reflectors [DuHamel and Berry, 1958, 1959; DuHamel and Ore, 1958, 1959]. Isbell [1959a] constructed a log-periodic feed for a 28-ft parabola. The near fields on the log-periodic structure were studied by Bell, Elfving, and Franks [1960]. Elfving [1961] has considered the design of these structures.

A simple form of log-periodic structure is the logperiodic dipole array proposed by Isbell [1959b]. In this array shown in figure 4, the length of each element bears a fixed ratio to the length of the preceding element and the adjacent element spacings bear the same ratio one to another. From the principle of scaling, the pattern and impedance characteristics of the array at frequency f_n , such that the *n*th element is resonant, will be repeated at a higher frequency f_{n+1} , which makes the (n+1)th element resonant. The characteristics repeat periodically at all frequencies given by $\tau^n f$, where *n* is an integer and τ the ratio of the lengths of adjacent elements. When excited with a 180° phase shift between elements it radiates a single-lobe linearly polarized beam directed toward the apex of the array. An analysis and design information for this array has been presented by Carrel [1960, 1961].

In an extension of this work, Berry and Ore [1961] investigated a log-periodic monopole array in which they have used simple reactive networks to produce the proper monopole current, amplitude, and phase



FIGURE 4. Logarithmic periodic dipole array.

distribution for unidirectional frequency-independent operation.

The log-periodic resonant-V array shown in figure 5, developed by Mayes and Carrel [1960a], was designed to operate in several different modes. In the lowest order mode the performance is approximately that of the log-periodic array. The active portion of the antenna centers around those elements whose lengths are near a half-wave-length at the frequency of operation. As the frequency of operation is increased this active region moves toward the apex. The antenna may be designed such that as the $\lambda/2$ region moves off the apex of the antenna the large elements on the other end are approaching a $3\lambda/2$ resonance. Thus as the frequency of operation is increased still further the active region moves through the array in the $3\lambda/2$ wave mode, then in the $5\lambda/2$ mode, etc. This scheme permits useable bandwidths up to 20 to 1 or more with only relatively small unstable intervals interspaced throughout this range about the mode-transition frequencies. The forward tilting of the individual elements insures a unidirectional beam and provides increased directivity.

It has been demonstrated that many of the logperiodic designs may be optimized to operate over a moderate bandwidth of 2 or 3 to 1 with a significant increase in directive gain [Mayes and Carrel, 1960b]. Directive gains in excess of 10 db over isotropic can



FIGURE 5. Log-periodic resonant-V array.



FIGURE 6. Vertically polarized log-periodic zigzag antenna.

be achieved over broad bandwidths using a small logperiodic zigzag structure over a ground plane, and on the order of 18 db over isotropic in the higher order modes of the log-periodic resonant V antennas. The zigzag structure was also considered by Carr [1961]. Greiser and Mayes [1961] have investigated a vertically polarized log-periodic zigzag structure over a ground plane as shown in figure 6.

8. On the Theoretical Analysis

The new class of antennas which have been termed "frequency independent" have opened up a new era in wide band antennas. Operating bandwidths that were considered to be an impossibility as little as seven years ago are now readily available. However, in view of the complex geometery involved it is perhaps not surprising that the experimental and empirical development of these antennas has far outstripped the theoretical analysis. The theoretical problem of the log-spiral antenna has been attacked by Mast [1958] who calculated the fields due to a logarithmic spiral filament and by Rumsey [1959] who considered the fields produced by an infinite number of planar logarithmic spiral filaments. Copeland [1960] has obtained an approximate analysis for the radiation patterns of the log-spiral antenna with an assumed current distribution and Wheeler [1961] has considered a semicircular geometry to approximate the spiral curve. The impedance of multiterminal antennas was studied by Deschamps [1959] and that of the log-periodic dipole arrays by Carrel [1961].

A new approach which holds promise is to consider the log-periodic antenna as a locally periodic structure whose period varies slowly, increasing linearly with distance to the origin or apex [Mayes, Deschamps, and Patton, 1961]. Such an approach indicates that the basic ingredients for a frequencyindependent antenna are a slow-wave transmission medium and a series of radiating elements satisfying the similarity condition, and which are coupled to the transmission medium at points spaced in geometric progression. Proper design of such a structure can produce a wave substantially radiated toward the feed point with characteristics which vary little as the frequency of operation is varied over extremely wide bandwidths.

9. Conclusions

In considerably less than a decade major changes have been wrought in accepted concepts concerning the usable bandwidth of antennas. There is a great deal yet to be learned about these new antennas, but it can be said that the path has been opened for future investigation.

Figures 4 and 5 are reproduced with the kind permission of R. L. Carrel and figure 6 with the permission of J. W. Greiser.

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