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VOL. 19, NO. 7 JULY, 1949 Subscription By Application Only

Directional VHF Antennas

By the Engineering Department, Aerovox Corporation

THE design of antenna components for use with radio systems operating in the very high frequency region of the spectrum is of extreme importance. This frequency range, from 30 to 300 megacycles, contains many broadcast and point-to-point services which depend upon effective antenna systems for proper functioning. These services include; FM broadcasting, television, aircraft-to-ground communications, and police and taxicab mobile radio, as well as several popular amateur frequency allocations. Radio wave propagation at these frequencies is largely limited to virtual line-of-sight distances, and signals received from beyond the horizon are usually weak. In addition, the operating efficiency of conventional vacuum tubes and circuitry used for transmitting and receiving begins to decrease considerably at the VHF frequencies. On the other hand, since the deceasing wavelength permits the use of more elaborate antenna systems, appreciable gains may be achieved with directional antennas. Therefore, high-gain antenna arrays may be used to compensate, in part, for the shortcomings of other circuit components in this portion of the radio-frequency spectrum. It is generally the case that improvements in VHF communication system gain can be effected more economically by increasing the antenna directivity than by alterations in other parts of the system if the antenna is not already complex.

This paper will discuss the fundamental properties underlying the operation of such directional antennas. Part II will describe various VHF antenna systems applicable to television, FM, amateur and citizens radio communications. Part III will detail the design and construction of a high-gain, all channel television antenna.

The Half-Wave Dipole

Most VHF antenna designs are evolved from combinations of the elementary half-wave dipole antenna. To understand the operation of the more complex directive antenna systems, it is necessary to examine the characteristics of this basic "antenna building-block" in some detail.

A dipole antenna is a straight wire or other conductor which has an electrical length equal to one-half of its operating wavelength. This free-space half-wavelength, expressed in feet, is equal to the constant 492 divided by the operating frequency in megacycles. As used in the VHF region, the dipole usually consists physically of a metal rod or tube about 5 to 7% shorter than an actual half-wavelength to compensate for "end effects".

When radio-frequency energy of the proper wavelength is coupled to such an antenna, either by a transmission line connected to it or by radiation from another antenna, it exhibits resonance characteristics similar to those of a tuned coil-condenser circuit, and is said to be resonant. Its electrical behavior resembles that of a resonant quarter-wave section of spaced-wire transmission line which has been straightened out to form a linear half-wave conductor. Fig. 1a demonstrates the similarity between the voltage and current standing-wave distributions on a half-wave dipole antenna and a quarter wave section of transmission line when each is excited at its lowest resonant frequency. The voltage is maximum and of opposity polarity at the ends of the conductors, while the current is maximum at the center of the conductor and nearly zero at the ends in both cases. These voltages and currents are oscillatory, however, so that the polarity of the voltage and the direction of the current flow reverse each half r. f. cycle. In the case of the dipole, these alternating charges set up electrostatic and electromagnetic waves which are radiated into the space surrounding it at the speed of light.

Fig. 1b. shows the equivalent lumped-constant circuit of the resonant dipole compared with that of the quarter-wave line section. The resistance which appears at the center of the dipole equivalent circuit represents the loss due to radiation and is called the *radiation resistance*. The power radiated by the dipole is equal to this resistance times the square of the current flowing in the center of the dipole or

$$\text{(1)} \quad \text{RADIATED POWER } (P) = I^2 R_a$$

Where: R_a is the radiation resistance.
I is the current at the center of the dipole.

The transmission line equivalent circuit does not have a radiation resistance since radiation from it is effec-

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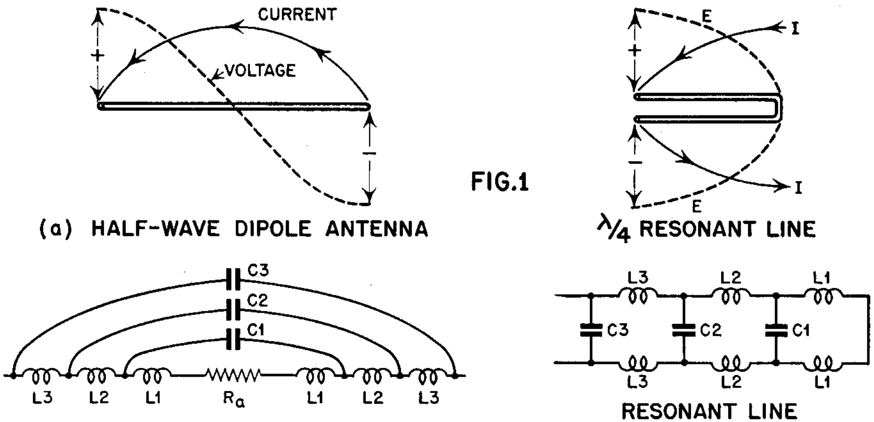


FIG.1

(a) HALF-WAVE DIPOLE ANTENNA

$\lambda/4$ RESONANT LINE

(b) DIPOLE EQUIVALENT CIRCUIT

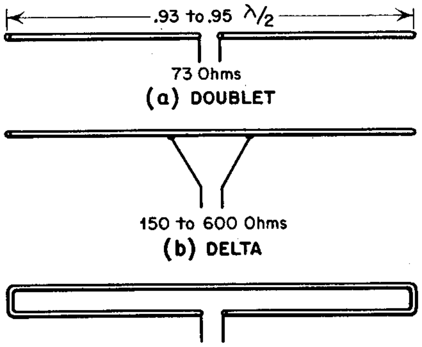
RESONANT LINE EQUIVALENT CIRCUIT

tively cancelled by the close spacing of its two halves, which have equal r. f. currents flowing in opposite directions at any given instant. Thus, the fields set up about it are 180 degrees out-of-phase and cancel out.

When the dipole is sufficiently removed from the earth and other objects to be considered in "free space", it has a radiation resistance which is usually taken as a pure resistance of about 73 ohms at resonance. In practice, this value varies through wide limits as a function of antenna height above ground and the ratio of conductor length to diameter. The manner in which the radiation resistance of a dipole antenna varies with height above perfectly reflecting earth is shown graphically in most engineering tests and will not be reproduced here. In most applications, VHF dipole antennas are used many wavelengths above ground, so that the radiation resistance is close to 73 ohms. The proximity of other elements in an antenna array also alters the dipole radiation resistance.

A dipole which is fed in the center as a doublet antenna (Fig. 2a) has an input or feeding impedance which is equal to the radiation resistance, and the transmission line to the transmitter or receiver must match this value. If the dipole is slightly shorter than the correct length for resonance, a capacitative reactance is added to the radiation resistance; if it is somewhat longer than an electrical half-wave, an inductive reactance is added. The extent of this reactive component limits the width of the frequency band over which the antenna may be used.

When the dipole is fed at a point other than the center, the input impedance increases with the distance from the center. The input impedance is a pure resistance only at the center or at the extreme ends of the antenna where its value may exceed 2400 ohms, depending upon the same factors as the radiation resistance. The variation of feeding impedance with distance from the center is a property of the dipole which is useful when matching transmission lines of various characteristic impedances to the antenna. Such a matching system is the "delta" match illustrated in Fig. 2b. The "folded dipole" shown in Fig. 2c is a special form of broadband dipole in which the radiation resistance and the feeding impedance are equal to the radiation resistance of the simple dipole multiplied by the square of the number of parallel elements in the folded dipole. Thus, if the folded dipole is made up of two elements, as in 2c, the feeding impedance is about four times the impedance of a single dipole, or about 292 ohms. If three "folds" are used in the dipole, the impedance is nine times the single dipole impedance, or about 657 ohms. The above rule-of-thumb assumes equal conductor size of all elements.



(a) DOUBLET

(b) DELTA

(c) FOLDED DIPOLE

DIPOLE COUPLING SYSTEMS

FIG.2

In addition to the radiation resistance and the feeding impedance mentioned above, a third impedance is defined in connection with the dipole antenna. This is the characteristic or "surge" impedance, which is of importance in considering certain properties of the dipole, especially its operating bandwidth. This impedance must be considered an *average* surge impedance, since it is not constant over the length of the dipole. The *average* surge impedance of a cylindrical dipole antenna is given by Schelkunoff* as approximately;

$$Z_0 = 276 \log_{10} \frac{L}{r} - 120 \quad \text{(ohms)} \tag{2}$$

Where: L is the total length of the dipole.
r is the radius of the conductor in like units.

This expression indicates that the characteristic impedance of a dipole antenna varies inversely with the radius of the conductor.

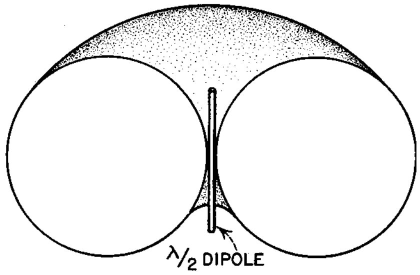
In television and other services where the antenna is required to give uniform response over large bandwidths, it is important to use elements of large radius, (low Zo) since the Q of the antenna is given roughly by;

$$Q = \frac{\pi}{4} \frac{Z_0}{R_a + R_L} \quad \text{or} \quad \frac{.78 Z_0}{R_a + R_L} \tag{3}$$

Where: R_a is the radiation resistance of the antenna.
R_L is the load resistance coupled to the antenna.

and the bandwidth of the antenna at the 3 db. points is equal to the operating frequency divided by the antenna Q. Thus, a dipole with a Q value of 6 and resonant at 300 Mc. would have a bandwidth of 300/6 or 50 megacycles.

Fig. 3 shows the field distribution around a half-wave dipole antenna in free space. It will be seen that maximum radiation occurs in a plane perpendicular to the axis of the dipole and through its center. Thus, when the dipole antenna is used with its axis perpendicular to the surface of the earth, i. e., vertically polarized, it radiates equally in all compass directions and is said to be *omnidirec-*



"DONUT"-SHAPED DIPOLE RADIATION PATTERN (HALF VIEW)

FIG.3

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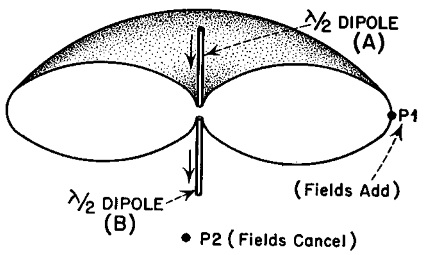
*S. A. Schelkunoff, "Theory of antennas of arbitrary size and shape." Proc. I. R. E. Sept. 41.

tional. Very little radiation occurs in the direction of the axis, however, and deep "nulls" appear in the radiation pattern at each end. The radiation pattern of the simple half-wave dipole is used frequently as a comparison standard in evaluating the performance of directional antennas.

Collinear Dipoles

An antenna which has dimensions which are comparable to the operating wavelength will radiate more energy in some directions than in others. This property of antenna directivity is based upon wave interference. If waves radiated from different parts of the same antenna array reach a point in space in the same phase, the fields will add and considerable energy will be received at that point. Conversely, if waves from different parts of the antenna reach a point in space out-of-phase, and of comparable magnitude, the waves will cancel and little energy will be received. An excellent example of this principle is the *collinear array,* which consists of a number of half-wave dipoles on the same axis, fed in-phase and usually spaced one-half wavelength between centers. Fig. 4 illustrates a simple collinear array made up of two dipoles spaced and fed as above. The directional properties of this combination of elements can be understood by considering the effects of radiation from these dipoles (A and B in Fig. 4) upon two points in space, designated P1 and P2. Waves radiated in-phase from A and B travel essentially the same distance to P1 and so are additive. At point P2, however, the radiations from A and B arrive in *phase opposition* since the wave from any given part of A must travel one-half wavelength farther than the wave from the corresponding part of B. Thus, the waves are 180 degrees out-of-phase at any instant and cancel any effect upon a receiving device placed at P2.

The collinear array is useful in applications where the omnidirectional radiation of the vertical dipole is desired. It exhibits appreciable gain over a single dipole by confining more of the radiated energy to the low angles of radiation which are the most useful in VHF propagation. The power gain in db. of a collinear dipole array having between two and eight elements is roughly numerically equal to the number of dipole elements used.

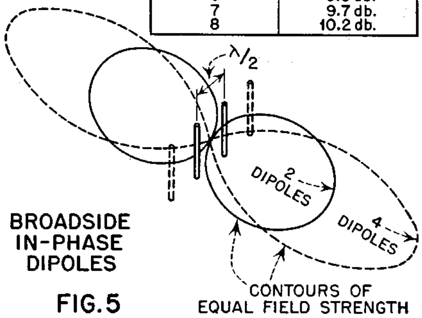


COLLINEAR DIPOLES
FIG.4

Broadside Dipole Arrays

Another combination of dipoles which has important directional properties is the broadside array. If two half-wave elements are spaced one-half wavelength apart as is shown in Fig. 5, and are excited in-phase, the radiation is concentrated in two directions perpendicular to the plane of the elements. This *bidirectional* pattern is easily understood by applying the reasoning used above. The waves from the dipoles cancel in the plane of the array because of the spacing, which makes them arrive at a point in space 180 degrees out-of-phase, while in the favored directions the radiations add. The width of the radiation lobes is decreased, and the gain in the two directions is increased by the addition of more elements spaced similarly and fed in-phase. Approximate power gains for half-wave spaced, in-phase, broadside arrays containing up to eight elements are tabulated in Fig. 5.

ELEMENTS	POWER GAIN
2	4 db.
3	5.5 db.
4	6.8 db.
5	8.0 db.
6	9.0 db.
7	9.7 db.
8	10.2 db.



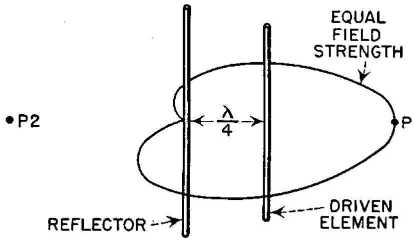
BROADSIDE IN-PHASE DIPOLES

FIG.5

End-Fire Arrays

A third type of dipole directivity occurs when parallel elements, as shown in Fig. 5, are excited out-of-phase. If the spacing is one-half wavelength and the dipoles are fed 180 degrees out-of-phase, the radiation pattern of Fig. 5 is rotated 90 degrees. The result is again a bidirectional pattern but with maxima in the plane of the dipoles. Such an arrangement of dipoles is called an end-fire array.

A special form of end-fire directivity, which is used extensively in amateur practice and other point-to-point communication where *unidirectional* characteristics are required, makes use of "parasitic" dipoles. In beam antennas of this type, frequently called "Yagi" arrays, one or more of the dipole elements are parasitically excited by the radiation or induction fields from the driven elements and are not directly connected to the transmission line. By proper phasing of such parasitic elements, which is controlled by adjusting the length and spacing with respect to the driven elements, back radiation is cancelled and most of the energy is confined to a narrow beam. The power radiated in the favored direction may be multiplied many times by the use of several such parasitic elements, which are classed as either *directors* or *reflectors* according to whether they act to aid or oppose radiation from the driven element in their direction. A simple parasitic array consisting of a driven element and a single *reflector* spaced one-quarter wavelength (90 electrical degrees) is shown in Fig. 6. The reflector is made slightly longer than the resonant length and so is inductive. Its induced current lags the electromagnetic field which produced it by 180 degrees, in addition to the 90 degree lag caused by the quarter-wave spacing. Therefore, the currents in the reflector are 270 degrees out-of-phase with those of the driven element. At point P1 in Fig. 6, however, the waves from both elements are in-phase since the radiation from the reflector is retarded an additional 90 degrees due to spacing, for a total of 360 degrees. At point P2, on the other hand, the reflector waves are advanced by 90 degrees since it is closer, making the phase difference 270 minus 90 or 180 degrees. The radiation at P2 therefore is small.



RADIATION PATTERN OF DIPOLE AND PARASITIC REFLECTOR
FIG.6

A similar line of reasoning may be followed for the director, which is cut shorter than resonance and is therefore capacitative. The addition of either a director or a reflector to a dipole antenna approximately doubles the power radiation in the favored direction.

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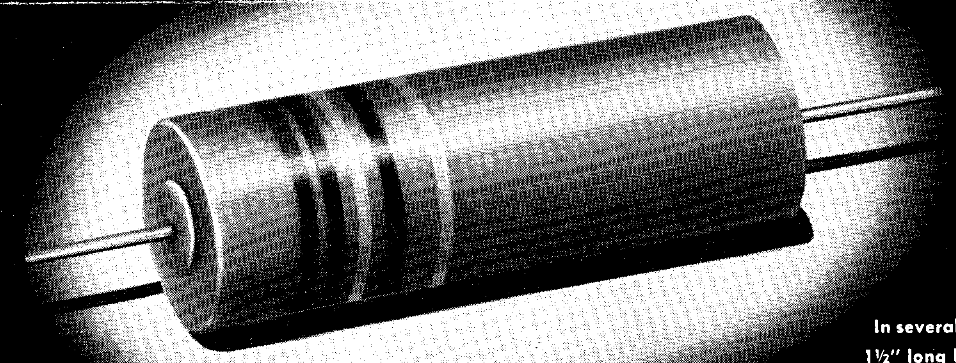

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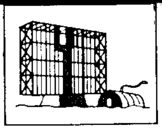

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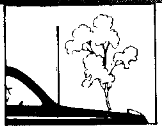

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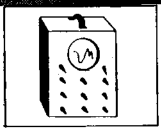

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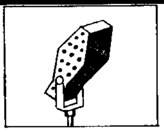

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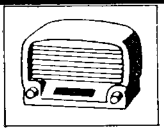

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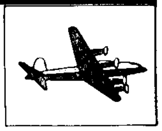

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