Eqs. (22) and (23) should be rearranged and renumbered accordingly. After this is done, it is possible to solve the first r coefficients $k_1{}^j, \cdots, k_r{}^j$ in terms of the remaining $(n'-r)$ coefficients $k_{r+1}{}^j, \cdots, k_{n'}{}^j$ in (22); and similarly, the first r coefficient $k_1{}^i, \cdots, k_r{}^i$ in terms of the remaining $(n-r)$ coefficients $k_{r+1}{}^i, \cdots, k_n{}^i$ in (23). If these are worked out and substituted back into (18), after simplifying, we then have

$$\hat{Z}_{ij} = (I_0, J_0) - [(I_0, J_1) \cdots (I_0, J_r)] \cdot \begin{bmatrix} (I_1, J_1) \cdots (I_1, J_r) \\ \cdots\cdots\cdots \\ (I_r, J_1) \cdots (I_r, J_r) \end{bmatrix}^{-1} \begin{bmatrix} (I_1, J_0) \\ \cdots \\ (I_r, J_0) \end{bmatrix}. \quad (32)$$

It should be noted that (32) is finally independent on the remaining $(n+n'-2r)$ coefficients $k_{r+1}{}^i, \cdots, k_n{}^i$ and $k_{r+1}{}^j, \cdots, k_{n'}{}^j$, and the corresponding trial functions. In actual application, r is generally equal to the smaller one of the two numbers, n and n'. If n is the smaller one of the two, then (32) is identical to (25). But it should also be noted that the additonal $(n'-n)$ trial functions cannot be chosen arbitrarily, because they must satisfy the above necessary and sufficient condition; otherwise there will be no consistent solutions at all for (22) and (23). Furthermore, the condition is a very stringent one. Even if it is satisfied, it does not contribute to any improvement of the solution. Therefore, it is clear that n' should be chosen equal to n in actual applications.

A New Method for Obtaining Maximum Gain from Yagi Antennas*

H. W. EHRENSPECK† AND H. POEHLER†

Summary—**In conventional Yagi design, optimum performance requires separate adjustments in a number of parameters—the array length and the height, diameter, and spacing of the directors and reflectors.**

By introducing the notion of a surface wave traveling along the array, it is possible to demonstrate experimentally the interrelationship between these parameters. With this, the gain then depends only on the phase velocity of the surface wave (which is a function of the height, diameter, and spacing of the directors) and on the choice of the reflector. Thus, maximum gain for a given array length, for any director spacing less than 0.5 λ, can be obtained by suitable variation of the parameters to yield the desired phase velocity.

A design procedure that provides maximum gain for a given array length is presented.

Introduction

A Yagi antenna consists of a number of linear elements parallel to each other along a straight line. Fig. 1 represents (a) a conventional Yagi antenna, and (b) one that consists of a row of monopoles imaged in a ground plane. Only one of the elements—the so-called *feeder*—is excited, all the others being parasitic. The elements in the direction of increased gain are directors, and the one in the opposite direction is the reflector. By choosing the correct dimensions for the different parameters of the Yagi antenna (height, spacing, and diameter of the elements), we can obtain increased gain in the endfire direction of the array.

The simplicity of Yagi antenna construction has invited many applications. One of the advantages of the Yagi is its usefulness as practically all frequency bands.

In designing a Yagi antenna the problem is to find the correct dimensions of the parameters. It is therefore necessary to discover how these parameters are related to each other under conditions of optimum gain.

Some early investigators of this problem, Yagi [1], Uda and Mushiake [2], and Walkinshaw [3], computed the currents in the elements according to the impedance concept but treated only short Yagi antennas because the computation for more than three or four elements becomes too complicated. Others, Reid [4], Fishenden and Wiblin [5], and Vysokovsky [6] [7], incorrectly, as first pointed out by Vysokovsky [6], [7], assumed that the current amplitudes were the same in all the directors. To date, there exists no rigorous theoretical solution of the Yagi problem. The experimental results that have been published are always restricted to special cases, with no attempt made to find a connection between them.

The goal of our investigation was to establish a general design method for Yagi antennas with optimum gain. The investigation was restricted to a consideration of Yagis with a single reflector and directors of equal height, spacing, and diameter. Our design criteria were based on achieving forward gain without respect to the front-to-back ratio and the sidelobe level.

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All gain figures are given in terms of power gain above a reference dipole (the feeder) and they thus include the effect of ohmic losses. The symbols used are (see Fig. 2):

h_F = height of feeder above ground plane
$2\rho_F$ = diameter of feeder
h_R = height of reflector above ground plane
$2\rho_R$ = diameter of reflector
s_R = spacing between reflector and feeder
h_D = height of directors above ground plane
$2\rho_D$ = diameter of directors
s_D = spacing of directors
L = length of the array (measured from feeder to last director)
n = number of directors
λ = wavelength
v_x = phase velocity along the antenna
c = phase velocity in free space
g = power gain over dipole
$g_{\max}$ = maximum power gain of Yagi antenna.

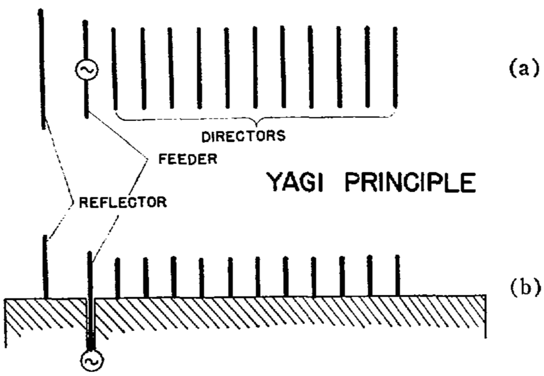

Fig. 1—(a) Conventional Yagi; (b) Yagi consisting of monopoles imaged in a ground plane.

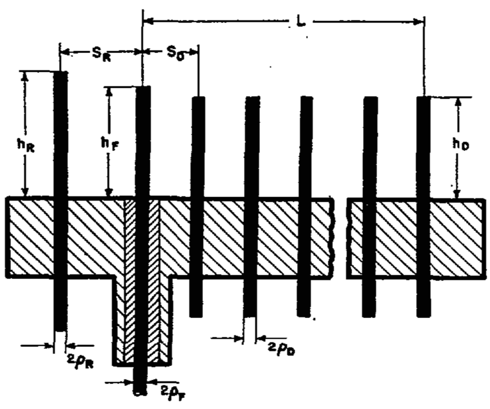

Fig. 2—Yagi parameter symbols.

Treatment of the Problem

Our basic approach was to consider the Yagi antenna as consisting of two parts: the combination feeder-reflector and the row of director elements. Experimental evidence in support of this approach will be presented.

We started by adjusting the combination feeder-reflector for maximum gain in the forward direction, and noted that this adjustment remained optimum (within experimental error) even when the row of directors was added. This result has also been established by the Tinkertoy Antenna Group [8]. It was possible to retain the same adjustment of the feeder-reflector combination in successive experiments involving different rows of directors.

If we consider the wave traveling along the array as a surface wave propagating with a certain phase velocity —an approach first adopted by Stanford Research Institute [9]—we can show that the maximum gain of a Yagi antenna of given length L occurs at a definite value of the phase velocity v_x. This value is a function of element spacing s_D, element height h_D, and element radius ρ_D, and a criterion has thus been found for the optimum combination of these parameters.

The separate effects of the two parts of a Yagi antenna are shown in Figs. 3 and 4. These figures are phase and amplitude plots of the nearfield of a Yagi 6 λ long and are adjusted for maximum gain. The patterns were obtained with the automatic plotter built at the Air Force Cambridge Research Center [10]. In Fig. 3 the reflector has been removed; in Fig. 4 the field of the entire Yagi is plotted. We note that the phase lines lying perpendicular to the row of directors are undisturbed by the addition of the reflector, thus proving that one and the same surface wave is generated. The shift in corresponding amplitude lines A, B, C, D (plotted at 5-db intervals) show that in the vicinity of the feeder, the pattern is omnidirectional in the absence of the reflector, and directive when the reflector has been added.

Experimental Arrangement

Because it was necessary to have a setup in which the different parameters of the Yagi could easily be changed, it was decided to conduct the experiments above a ground plane. Another obvious advantage of using a ground plane was that the feeder element could be excited from below, leaving the antenna unobstructed. The individual radiators were brass rods, and their height was varied by press-fitting the rods in a set of holes drilled in the ground plane. Mechanical support of the elements was furnished by the ground plane. The spacing between elements could easily be changed in multiples of the smallest separation.

To measure the pattern and gain in the farfield of the antenna, the ground plane had to be extended far out. We decided to work at X band (3.3 cm) so that the dimensions could be kept within reasonable limits. It was sufficient to let the ground plane extend to the far zone of the antenna in one direction only. We chose a width of 6 feet and a length of 12 feet (110 wavelengths).

The rods were set in holes drilled in a circular plate which was recessed and free to rotate in the ground plane. To plot the radiation pattern of the Yagi, it was only necessary to rotate this circular plate while the receiving antenna was held fixed. The following appear in Fig. 5, which shows the diagram of the experimental setup used in all measurements.

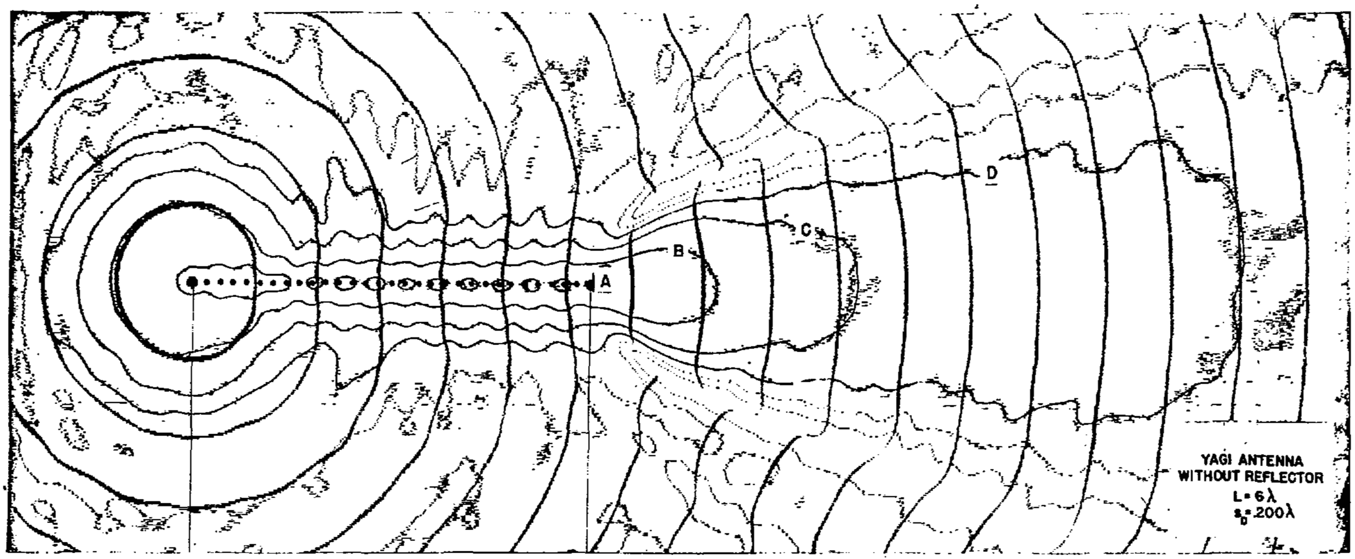

Fig. 3—Nearfield amplitude and phase plot of Yagi antenna without reflector.

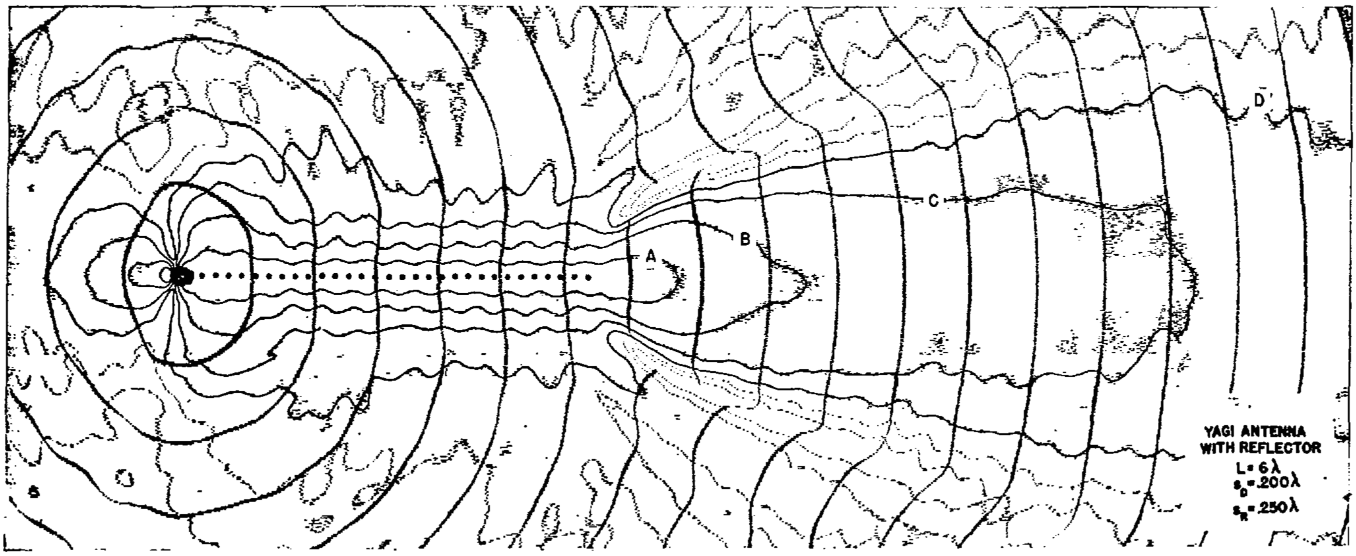

Fig. 4—Nearfield amplitude and phase plot of complete Yagi antenna.

- Y1 the audio oscillator (1000 cps) used with MOD.
- Y2 the frequency-stabilized source operating at 9084 Mcps.
- MOD the ferrite-type modulator for amplitude modulation of the signal source.
- AT1 the attenuator that measures the antenna gain. [The power input to the antenna was attenuated until the field strength in the farfield was the same as obtained from the reference monopole (the feeder).]
- ST1 the standing-wave indicator.
- TR1 the impedance transformer.
- MT1 the mode transducer from waveguide to coaxial line.
- ANI the receiving antenna in the farfield. (The detector monitors the signal strength.)

Fig. 5 also shows the method used for measuring the phase velocity along the row of directors. A probe was

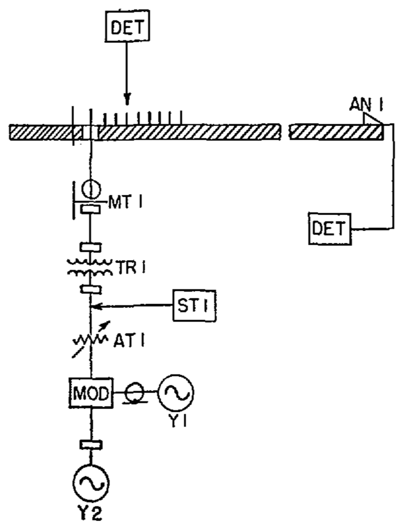

Fig. 5—Block diagram of experimental setup.

carried along a line parallel to the array, at a small distance from the tip of the brass rods. The phase velocity was then determined by measuring the distance between minima. The standing wave along the array was enhanced by placing a metal reflector plate at the end of the Yagi.

The results of the measurements are described in the following section. All experiments were conducted in a reflectionless room, the ground plane also surrounded with absorbing material to reduce reflections to a minimum. All mechanical parts were machined to a tolerance of less than 0.001 inch. Measurements taken on different days could be repeated with a relative error of no more than ±0.1 db.

Experiments on the Properties of Yagi Antennas

Optimum Adjustment of the Combination Feeder-Reflector

To obtain optimum design criteria for reflector height and spacing, the power in the farfield of the combination feeder-reflector was measured as a function of reflector height and spacing. The height of the feeder, adjusted for resonance, and the input power were kept constant.

Fig. 6 shows the result of these measurements for reflector spacings between 0.083 λ and 0.313 λ, with $\rho_R/\lambda = 0.024$. The maxima of these curves, plotted as a function of reflector spacing (see Fig. 7), show that the adjustment of the combination feeder-reflector for maximum gain is not too critical, although there is an optimum value for the spacing 0.250 λ. With this spacing, and with a reflector height of 0.226 λ, the gain of the combination feeder-reflector is 3.85 db above the feeder alone.

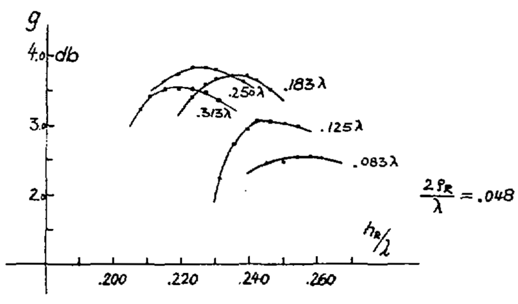

Fig. 6—Gain of feeder-reflector combination as a function of reflector height for various reflector spacings.

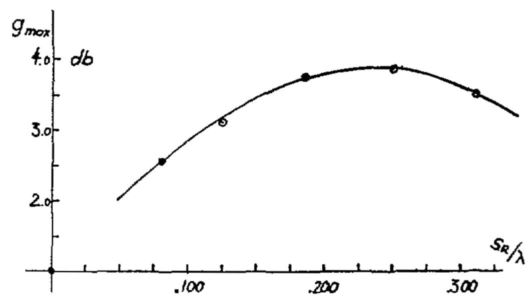

Fig. 7—Maximum gain of feeder-reflector combination as a function of reflector spacing.

Optimum Adjustment of the Directors

Just as in the feeder-reflector case, it is possible to determine the maximum gain as a function of the director parameters but more difficult to obtain a general picture since at least four parameters are involved (s_D, h_D, ρ_D and L). In displaying our experimental results we are restricting ourselves to the more interesting examples, bearing in mind that we are chiefly interested in showing the effect of the parameters on one characteristic, the phase velocity along the row of directors.

In Fig. 8 gain was plotted against director height for several different spacings, for two different spacings, and for two different lengths ($L = 1.2$ λ and $L = 6.0$ λ). The radius ρ_D was held constant throughout. The maximum obtained from these curves was plotted against director spacing in Fig. 9. We note that up to spacings of 0.3 λ, the maximum gain is independent of spacing and, thus, depends only on the array length and on ρ_D. We are omitting experimental data indicating the further conclusion that within certain limits the maximum

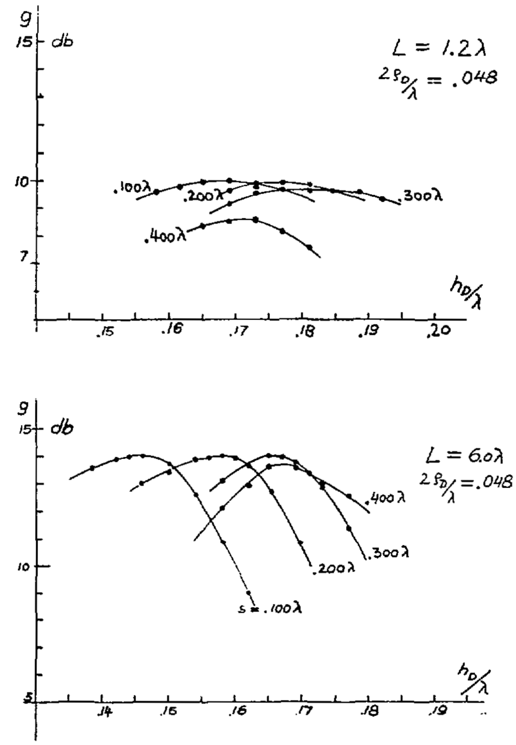

Fig. 8—Gain of Yagi array as a function of director height and spacing for array length.

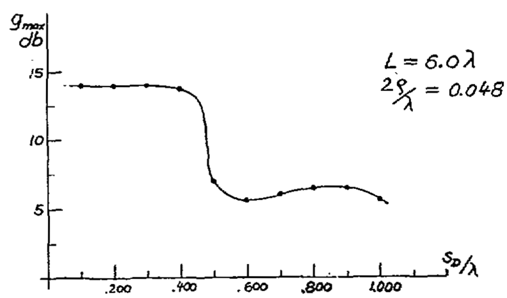

Fig. 9—Maximum gain of Yagi array as a function of director spacing.

gain is also independent of ρ_D, at least up to values of $\rho_D/\lambda = 0.024$.

We noticed that the slight drop in gain for spacings larger than 0.3 λ could be compensated for by inserting an additional director spaced 0.1 λ from the feeder. This director increased the coupling between the feeder and the row of directors. From curves such as those of Fig. 9, but for a sequence of different lengths L, we plotted the solid curve in Fig. 10, showing maximum gain as a function of array length. The broken curve in Fig. 10, showing the relation between maximum gain and L for improved endfire arrays, was taken from Hansen and Woodyard [11]. The difference between the two curves in discussed in the following section.

From the relationship between maximum gain and array length, Hansen and Woodyard deduced the value of the phase velocity traveling along the array and discovered that it was slower than the freespace-propagation velocity by an amount that decreased with increasing length of the array. Since the Yagi antenna differs from an improved endfire array of the Hansen and Woodyard type in its amplitude distribution, we did not know whether we would be able to measure a unique phase velocity. Our experimental results show that such a phase velocity does exist and that it is constant along the row of directors, with small perturbations in the vicinity of each element. Fig. 11 gives the phase velocity, under conditions of maximum gain, as a function of the array length L. Since this phase velocity depends on the parameters s_D, h_D, and ρ_D, it is easier to consider maximum gain as a function of phase velocity than as a function of three individual parameters. Once we know how the phase velocity depends on s_D, h_D, and ρ_D, we can design Yagi antennas by focusing attention on the single parameter instead of on the three constituent parameters. The method by which the optimum phase velocity is obtained is quite unimportant since infinitely many combinations of director spacing, height, and diameter yield the same phase velocity. Fig. 12 shows the measured phase velocity as a function of director height, with the spacing as parameter and the diameter held constant. The measurement of phase velocity for short Yagis being difficult, it is advisable to proceed by first determining the director height for maximum gain, and then taking the phase velocity from the values plotted in Fig. 12.

We have already remarked that different array lengths require different phase velocities for optimum gain. It is possible to show the dependence of phase velocity, array length, and maximum gain upon director height, with director spacing and diameter as parameters. We can limit ourselves to spacings of 0.100 λ, 0.200 λ, 0.300 λ and 0.400 λ, and draw four charts that give all the information required for designing a Yagi antenna. Interpolation takes care of intermediate values of spacing. Fig. 13 contains two such charts, for $s_D = 0.200$ λ and $s_D = 0.400$ λ.

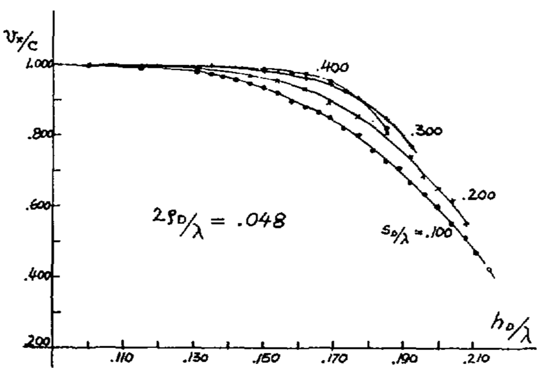

Fig. 12—Phase velocity as a function of director height.

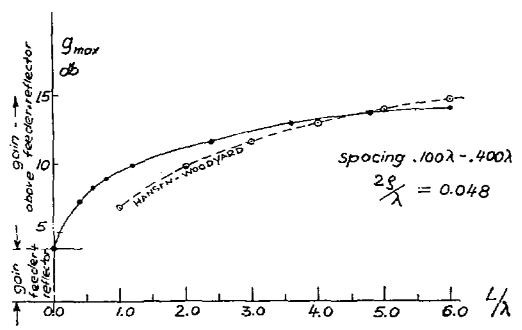

Fig. 10—Maximum gain of Yagi array as a function of array length.

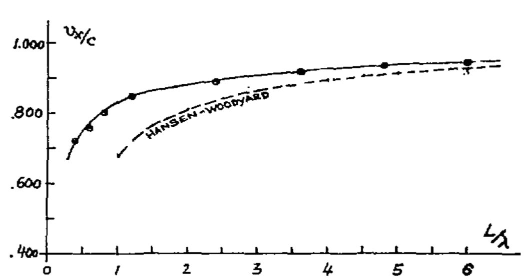

Fig. 11—Phase velocity for obtaining maximum gain as a function of array length.

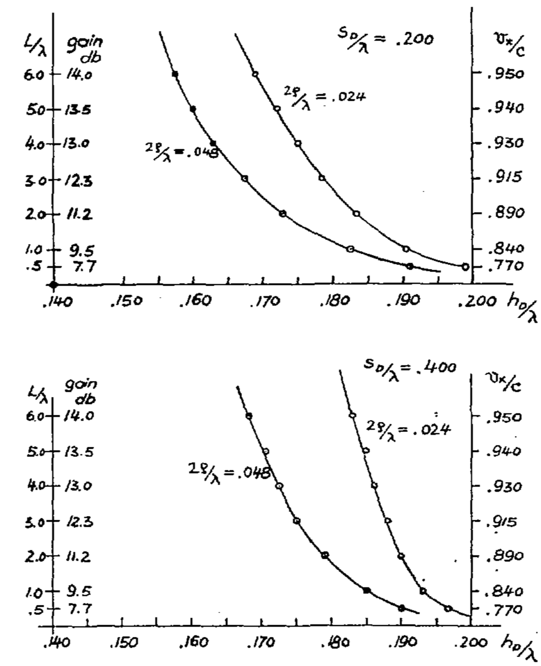

Fig. 13—Gain, phase velocity and array length of an optimized Yagi array as a function of director height.

Comparison with the Hansen-Woodyard Condition

The introduction of phase velocity as the criterion for the design of a maximum-gain Yagi antenna invites a comparison with the Hansen-Woodyard condition. In Fig. 11 we have already shown the experimental discrepancy between our case and theirs. In their case, Hansen and Woodyard [11] assumed that the current distribution along the array is constant, that the element spacing is infinitesimal, and that the array is long compared with the wavelength. In the case of the Yagi antenna, their first assumption is clearly not applicable, as can be seen from our Fig. 14, which gives the current distribution measured along a Yagi array of length 3 λ, adjusted for maximum gain.

Let us consider the field strength in the farfield as a superposition of the field strengths produced by the individual array elements. The vector diagrams of an endfire array whose current distribution is constant along the array and of a Yagi antenna whose current distribution varies as shown in Fig. 14 are, respectively, shown in Figs. 15 and 16 for the endfire direction. In both figures the array length is taken as 3 λ. With an element spacing of 0.3 λ, there are consequently eleven elements in each array.

To fulfill the condition for maximum gain in the Hansen-Woodyard case (see Fig. 15), we need to adjust the director height such that the resulting phase velocity is given by

$$\frac{v_x}{c} = \frac{L/\lambda}{L/\lambda + 0.468}.$$

This implies that the phase delay from element to element has a constant value of 16.8°. The vector diagram of this array is nearly a semicircle, the total phase delay being close to 180°.

The vector diagram in Fig. 16 is for a Yagi with the same phase delay of 16.8° but with the current amplitudes obtained from the measured curve in Fig. 14. We note that the vector sum of the eleven elements is smaller than the maximum obtainable from this array. The vector reaches its maximum length at a point along the curve that corresponds to a total phase delay considerably smaller than the value given by Hansen-Woodyard. This phase delay, which totals 118°, is reached after the contributions of only eight elements have been added. If we wish to obtain the maximum length of the total field vector after eleven elements, we would have to impose a smaller phase delay from one element to the next. Fig. 17, a vector diagram for such an eleven-element Yagi, shows the difference between this case and the ordinary constant amplitude case of Fig. 15. From Figs. 16 and 17 it follows that to obtain maximum gain on this Yagi array the phase velocity must be adjusted to a value of 0.902 times the freespace velocity. The experimental value obtained from Fig. 11

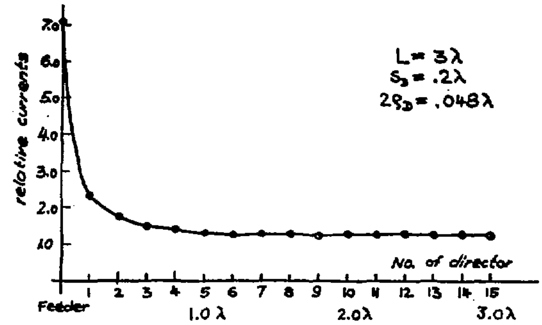

Fig. 14—Current distribution in optimized Yagi array of length 3λ.

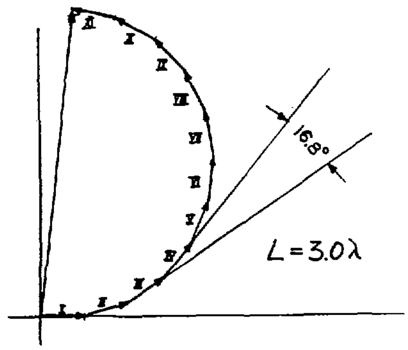

Fig. 15—Vector diagram of field strength in the endfire direction of an array having a constant current distribution.

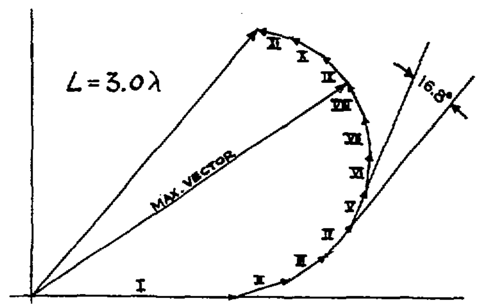

Fig. 16—Vector diagram of field strength in the endfire direction of a Yagi array whose current distribution varies as shown in Fig. 14.

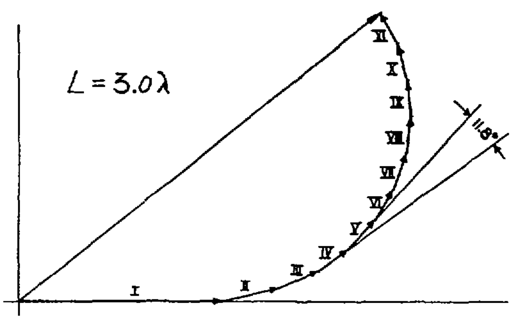

Fig. 17—Vector diagram of field strength in the endfire direction of a Yagi array whose current distribution varies as shown in Fig. 14, with the array adjusted so that the endfire field strength is maximized.

is 0.905 times the freespace velocity, and thus within three per cent of the value given by the graphical method.

The assumption made by Fishenden and Wiblin [5] that the vector diagram of a Yagi should be nearly a semicircle is manifestly incorrect because the current distribution along the array is not, as they supposed, constant. For the same reason, Reid's theoretical results [4] are not applicable either.

To avoid confusion, it should be pointed out that the graphical representation of the farfield intensity enables us to locate the vector position for maximum gain within a given diagram but does not allow comparison between resultant vector magnitudes of different diagrams since the scale vector of each diagram is left undetermined.

Design Method for Yagi Antennas

The optimum design procedure for a Yagi antenna depends on the conditions that must be met. In the most usual situation, the requirement is either for a Yagi with a certain gain in the forward direction or for a Yagi of fixed length and maximum gain.

Let us assume that we wish to design a Yagi over a ground plane such as the fuselage of an airplane. Fig. 13 gives all the information we need. We find in this figure the maximum gain that can be obtained, and also the height of the director elements that must be chosen for a specified spacing. If the element diameter differs from those assumed in Fig. 13, then additional curves must be plotted in, obtained either by interpolation or through experiment.

If the director elements have some shape other than cylindric or if the Yagi is of the conventional type, with a row of dipoles supported on a boom rather than a row of monopoles over a ground plane, then the design procedure is as follows. We again refer to Fig. 13 but ignore the curves and fix attention only on the relation between maximum gain, array length, and phase velocity as read directly from the three scales along the ordinate. Given the gain or given the fixed length of the array, we immediately determine the phase velocity that is required. We must now perform the experimental work of adjusting the director cross section, spacing, and height, so as to obtain the required phase velocity. Mechanical considerations will usually fix one or two of these parameters and so no more than one or two series of data need be taken. (Note that our design method for maximum gain requires no farfield measurements.) It is not necessary to test the phase velocity on the full length array; if the array is at least 3 λ long, the phase velocity will remain unchanged as further elements are added.

As already mentioned, we can choose any spacing less than 0.5 λ and still obtain the maximum gain. If, for example, we are designing a Yagi in the microwave region, we might decide to insert rods at fixed distances along a metal strip. For mechanical stability we would choose very close spacing. If, on the other hand, we are designing a Yagi for lower frequencies—for example, to launch a ground wave—then the number of elements would have to be as small as possible to conserve material costs, and a suitable spacing would be between 0.40 λ and 0.50 λ. Figs. 18 and 19 show these two examples of Yagi antennas. The first director in Fig. 19 is an element that increases the coupling between the feeder and the rest of the directors, as described previously.

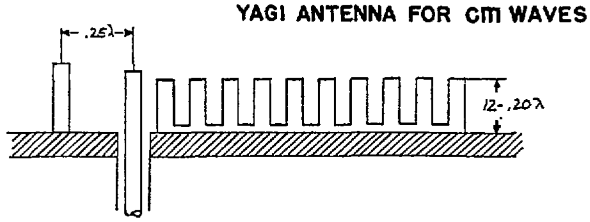

Fig. 18—Yagi array for very high frequencies.

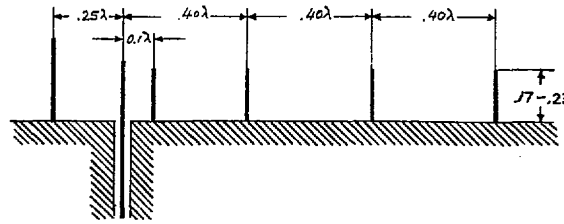

Fig. 19—Yagi array for low frequencies.

Conclusion

We have shown in this report that the phase velocity of the surface wave traveling along the row of directors in a Yagi antenna can be used as the design criterion for maximum gain.

We have also shown that the Hansen-Woodyard condition is inapplicable to the Yagi antenna because the amplitude distribution is not constant along the array. Figs. 10 and 11 give the values of the maximum obtainable gain and the corresponding optimum phase velocity on the Yagi antenna.

To date, very long arrays of the Yagi type have been successfully designed only by J. C. Simon [12], who uses periodic variations in the spacing and height of elements. This procedure has not yet been explained theoretically, and no optimum design procedures are available. It is clear, however, that the explanation will again have to come from a consideration of the spectrum of surface waves propagating along the array.

Acknowledgments

This work was done under the general direction of F. J. Zucker, chief of the Airborne Antenna Section, and R. E. Hiatt, chief of the Antenna Laboratory. The authors are indebted to Dr. W. Gerbes and F. J. Zucker for many stimulating discussions, and to W. J. Kearns for assistance in making the measurements.

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A Dipole Antenna Coupled Electromagnetically to a Two-Wire Transmission Line*

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Summary—**The properties of a dipole antenna coupled electromagnetically to a two-wire transmission line are studied experimentally. It is found that the coupling of the antenna to the transmission line can be maximized by a proper choice of 1) the angular position of the antenna with respect to the transmission line, 2) the length of the antenna, and 3) the separation of the antenna from the transmission line. The effect of the spacing between the wires of the transmission line on the optimum parameters is investigated. It is found that the optimum angular position of the antenna is not noticeably altered if, instead of a single antenna, an array of properly located antennas is used as the load. The advantage of an antenna array built on this coupling principle is discussed.**

Introduction

For some high-power VHF-UHF communications purposes, it is desirable to have a high-gain linear array whose elements are driven by voltages of proper amplitude and phase. This arrangement involves several transmission lines which cannot all be in the neutral planes of all the others. The unavoidable coupling between the lines and between the antennas and the lines makes the realization of a predetermined pattern difficult, if not impossible. Therefore, it is desirable to reduce the number of transmission lines.

In the region of very short wavelengths, arrays consisting of several slots on a waveguide wall are in common use. An analog of the slot array driven by a single waveguide is an array of dipoles driven by a single transmission line. Such an arrangement was first proposed by Sletten.[1] It consists of several dipoles situated in a plane parallel to that of a two-wire transmission line with their centers adjacent to the positions of voltage maxima on the line. When the axis of the dipole is parallel to the direction of the line the antenna is not excited, since it is in the neutral plane. However, when the antenna is rotated, it is excited in an amount that depends, among other factors, on its angular position. Consequently, the several antennas of the array may be excited with currents that differ from one another. Note that the elements of this array can all be driven from a single two-wire line with currents of predetermined amplitudes. As compared to the waveguide slot array, greater power can be obtained from this dipole array. Also, this array of dipoles coupled electromagnetically to a two-wire line has a desirable radiation pattern that is useful for communications purposes.

In order to understand and design a practical array of dipoles, it is first necessary to know the properties of a single antenna coupled to a two-wire line. It is therefore the purpose of this research to investigate the circuit properties of a dipole antenna coupled electromagnetically to a two-wire transmission line. The field properties are reserved for a later study.

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[1] C. J. Sletten and G. R. Forbes, "A New Type of Antenna for VHF-UHF Communications," Air Froce Cambridge Res. Center, Bedford, Mass., Tech. Rept. ERD-CRRD-TM-56-103; January, 1956.