Polyrod Antennas

By G. E. MUELLER and W. A. TYRRELL

The polyrod, a new form of microwave endfire antenna, is described. This consists of a properly shaped dielectric rod protruding from a metal waveguide. For applications requiring moderate gain, it possesses desirable electrical and mechanical properties. It is useful as a unit antenna in broadside arrays on account of its low crosstalk into adjacent polyrods. This paper describes work done from 1941 to 1944 at the Bell Telephone Laboratories, Holmdel, N. J. Important individual contributions are acknowledged in some of the footnotes. A report of this development has been withheld from earlier publication for reasons of military security.

1. Introduction

A UNIFORM rod (or "wire") of dielectric material without metallic boundaries is a well-known type of single conductor transmission line. In this kind of waveguide, a portion of the energy travels along in the space outside the rod. At discontinuities, including those caused by proximity to other objects, radiation takes place. For this reason, the dielectric waveguide has not become generally useful as a transmission medium, this need having been satisfied by the hollow metal pipe. The tendency toward radiation inherent in the dielectric guide is turned to advantage, however, in a new form of radio antenna. Here the objective is to encourage radiation from all parts of the dielectric rod. In progressing along the rod, therefore, power is gradually transferred from within the dielectric to the space outside. At a point where the transfer has been effectively completed, the rod can be terminated abruptly. By proper design, this radiating structure is an endfire antenna. Since it has been most often fabricated from polystyrene, it has become known as the polyrod antenna. It is especially useful for microwaves.

We must now review and examine certain features of dielectric rod transmission and of endfire antenna theory, for their bearing on polyrod design and performance.

2. Dielectric Wire Transmission[1]

A dielectric rod can be energized with an infinite variety of transmission modes. These are in general hybrid waves[2] possessing transverse and longitudinal components of both E and H. We shall here be concerned only

[1] Hondros and Debye, *Ann. der Phys.*, Vol. 32, pp. 465–476; J. R. Carson, S. P. Mead and S. A. Schelkunoff, *B.S.T.J.*, Vol. 15, pp. 310–333, 1936; G. C. Southworth, *B.S.T.J.*, Vol. 15, pp. 284–309, 1936; S. A. Schelkunoff, "Electromagnetic Waves," pp. 425–428, D. Van Nostrand, New York, 1943.
[2] Except in the case of circular symmetry. Cf. Schelkunoff, *loc. cit.*, pp. 154, 425.

with the lowest mode,[3] that which is the counterpart of the dominant wave[4] in a metal pipe. If a dielectric-filled metal guide is excited at the dominant mode, and if the metal shield is abruptly terminated, the wave energy will continue on in the unsheathed dielectric rod and will be confined almost exclusively to the lowest hybrid mode. This is, indeed, the most common way of exciting the dielectric wire.

The extent to which the power is concentrated within the dielectric is a function of the rod diameter and dielectric constant. This is shown[5] in Fig. 1. If the curves for the two different dielectric constants are replotted against the effective diameter, $\frac{D\sqrt{\epsilon}}{\lambda}$, they become more nearly

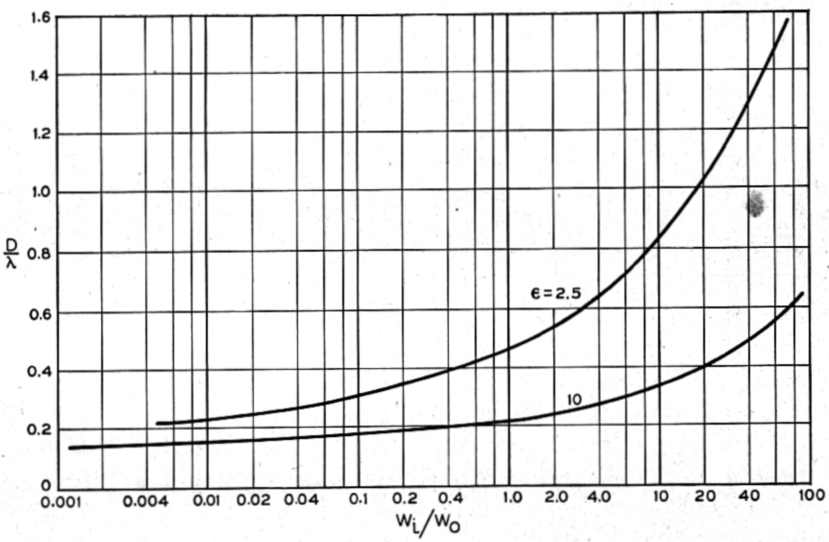

Fig. 1—Ratio of power inside W_i to power outside W_o for a cylindrical dielectric wire.

coincident. A universal curve cannot be given, however, because the field-retaining effect of a dielectric-air interface increases with increasing dielectric constant.

The phase velocity within the rod is also a function of the diameter and dielectric constant, as shown[5] by Fig. 2. When $\frac{D}{\lambda}$ is very small compared with unity, the rod exerts negligible guiding action, and the transmission is close to that in free space. For rods of large diameter, the power is con-

[3] Unlike all other modes in a dielectric wire and all modes in a conducting pipe, the lowest dielectric wire mode theoretically has its cutoff at zero frequency. Cf. Schelkunoff, *loc. cit.*, p. 428.

[4] That is, the TE_{11} mode in circular pipe or the TE_{10} mode in rectangular pipe.

[5] Figs. 1 and 2 are based on calculations by Dr. Marion C. Gray.

fined almost entirely within the rod, and the phase velocity approaches that in an unbounded medium of the same dielectric constant. By choosing intermediate values of $\frac{D}{\lambda}$, $\frac{v}{c}$ can be varied between these limits.

3. Endfire Antennas

We consider a linear array of isotropic radiators, infinite in number but so closely spaced as to occupy a finite length. We assume that the radiators are uniformly excited from a feed line, a transmission line parallel to the array phasing the various elements according to phase velocity on the line. The radiation pattern is given by[6]

$$r = \left| \frac{\sin \pi(\rho \cos \theta - \beta)}{\pi(\rho \cos \theta - \beta)} \right| \tag{1}$$

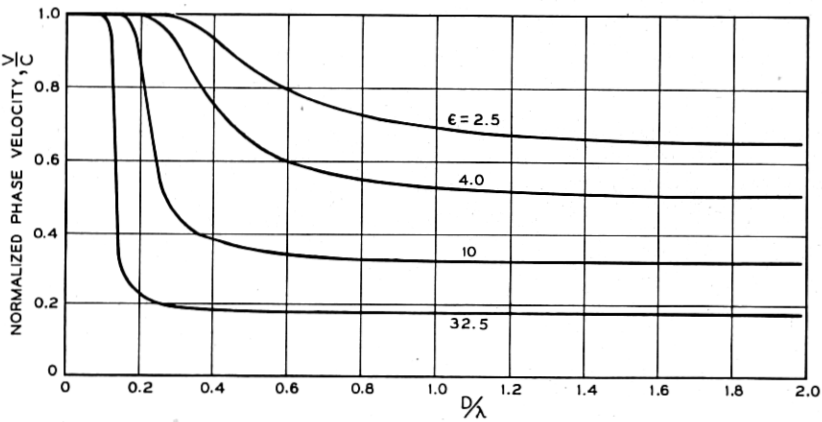

Fig. 2—Normalized phase velocity for a cylindrical dielectric wire.

where r = relative field strength
θ = angle with respect to the array axis
ρ = length of array in free space wavelengths
$2\pi\beta$ = phase shift in radians in the feed line from one end of array to the other end.

The pattern is symmetrical about the array axis.

Plotted from (1), Fig. 3 shows the pattern of a six wavelength radiator, $\rho = 6$, for selected values of β. When $\beta = \rho$ (= 6 in this case), phase velocity along the feed line is equal to free space velocity, and the resulting pattern is endfire. With $\beta = \rho + 0.5$ (= 6.5) the pattern remains endfire and the major lobe becomes sharper. For $\beta < \rho$ and $\beta > \rho + 0.5$ (as shown by β = 5.0, 5.5, 7.0) the pattern deteriorates into a forward conical beam.

[6] R. M. Foster, *B. S. T. J.*, Vol. 5, p. 307, 1926.

The gain of a uniformly excited endfire antenna[7] with $\beta = \rho$ is 4ρ. For $\beta \neq \rho$, the gain can be written

$$g = 4A\rho. \tag{2}$$

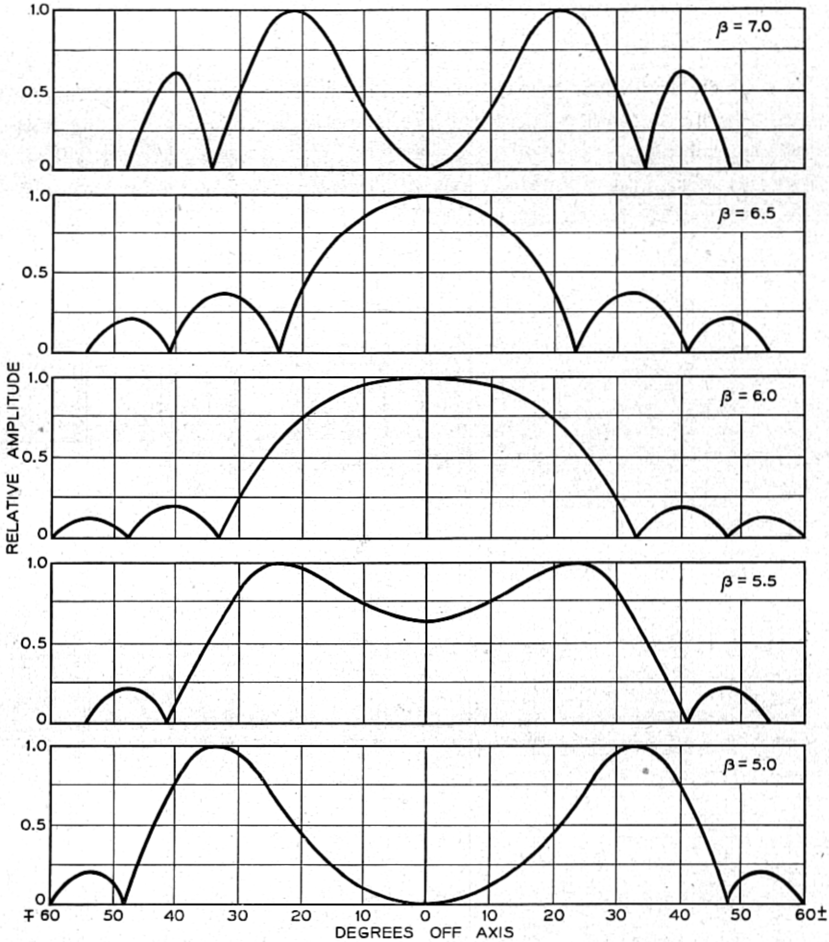

Fig. 3—Directional patterns of a six wavelength ($\rho = 6$) continuous array.

The factor A is given graphically in Fig. 4 as a function of $2\pi(\beta - \rho)$, the phase lag.[8] The highest gain occurs for a phase lag of approximately π radians relative to free space transmission, that is, for $\beta = \rho + 0.5$, in conformity with the patterns of Fig. 3. For a short radiator, A is about 2; with increasing antenna length, A approaches 1.8.

[7] Schelkunoff, *loc. cit.* p. 347.
[8] Fig. 4 and equation (5) were supplied by Dr. H. T. Friis.

The width of the major lobe is given by

$$\text{Beam Width} = \frac{B}{\sqrt{\rho}}. \tag{3}$$

The constant B depends on $\beta - \rho$ and on the manner in which beam width is defined. For width in degrees between half power points, and with $\beta - \rho = 0.5$ for maximum gain, B is computed from (1) to be about 60.

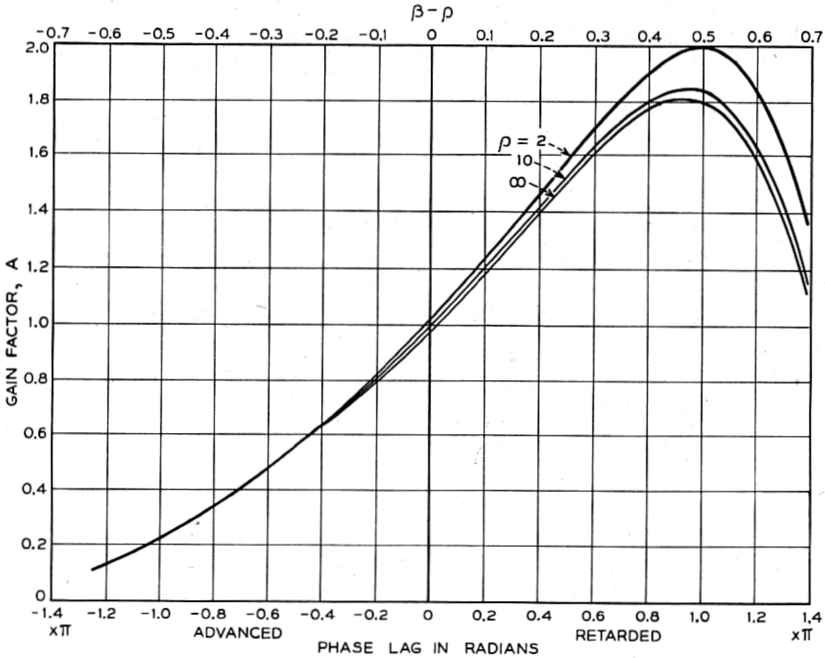

Fig. 4—Gain factor A as a function of phase lag in endfire arrays.

If a sinusoidal variation in excitation voltage along the radiator is superposed on the constant amplitude assumed for (1), we get

$$r = \left| a \frac{\sin \pi(\rho \cos \theta - \beta)}{\pi(\rho \cos \theta - \beta)} + (1 - a) \frac{\cos \pi(\rho \cos \theta - \beta)}{1 - 4(\rho \cos \theta - \beta)^2} \right| \tag{4}$$

where a is defined in Fig. 5. This figure gives patterns of a six wavelength radiator according to (4) for various values of a. Here β is fixed at 6.5 for maximum gain. Tapering symmetrically away from the center decreases the minor lobes. The gain is also decreased, but to a lesser extent.

Exponential tapering comes about from heat losses and radiation losses in the feed line. With attenuation α per wavelength, (1) becomes[8]

$$r = \sqrt{\frac{2 \cosh \alpha\rho - 2 \cos 2\pi(\cos\theta - \beta)}{\alpha^2\rho^2 + 4\pi^2(\rho\cos\theta - \beta)^2}} \tag{5}$$

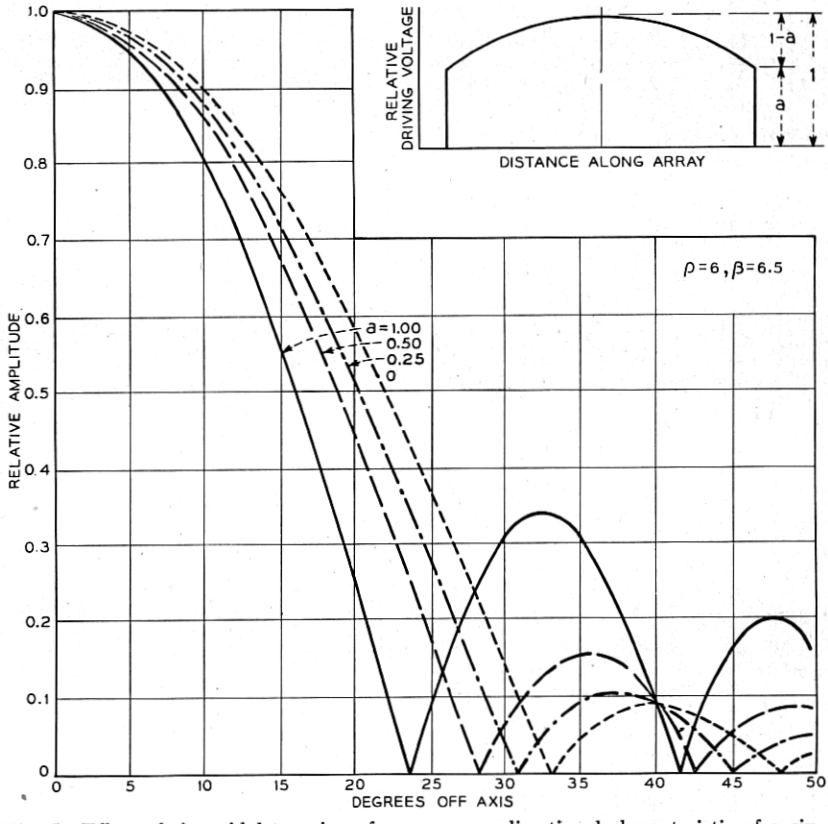

Fig. 5—Effect of sinusoidal tapering of power upon directional characteristic of a six wavelength continuous array.

Feed line attenuation increases slightly the minor lobe amplitudes and fills in the nulls. Exponential tapering caused by radiation can be reduced or eliminated if the coupling of the radiating elements to the feed line is gradually increased along the line.

4. The Polyrod Antenna

It has been found experimentally that a suitably proportioned dielectric rod can act as an efficient endfire radiator. A complete understanding of

[8] Loc. cit.

its operation involves the solution of Maxwell's equations subject to the boundary conditions appropriate to the configuration. An analysis of this sort is not available because of its mathematical complexity. However, a satisfactory explanation of polyrod operation, especially for engineering purposes, can be obtained by establishing analogies with array theory, coupled with existing knowledge about transmission in uniform dielectric wires. In this treatment by analogy, we remain essentially ignorant of the local fields in the vicinity of the dielectric, the role played by the discontinuities at both ends of the antenna, and other detailed features. We do have, however, a working theory which predicts closely the features of the radiation as observed at a distance. Under these circumstances, insistence upon a rigorous field solution has not so far appeared necessary.

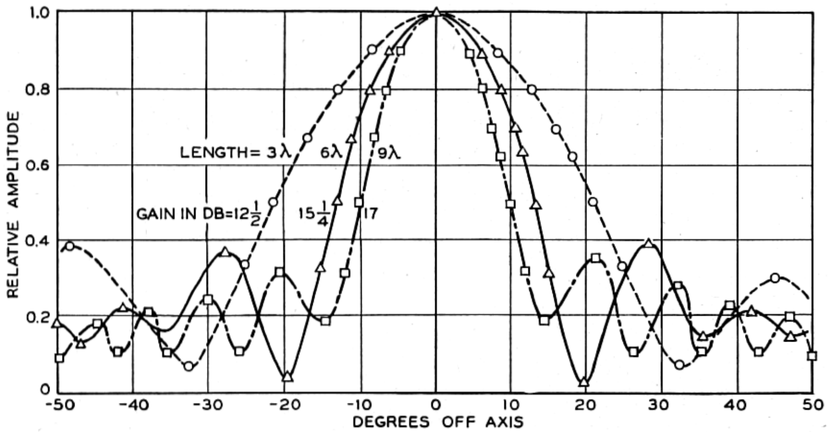

Fig. 6—Data on polyrods of uniform rectangular cross-section $\frac{1}{3}\lambda$ by $\frac{1}{2}\lambda$.

Experimental data have been obtained at frequencies in the vicinity of 3000 megacycles except for Fig. 9, representing work at 9000 megacycles. For the sake of generality, these results are presented in dimensions of λ, the free space wavelength. In all cases, polyrods have been energized from a dielectric filled metal guide whose conducting sheath is abruptly terminated, the dielectric continuing on as the radiator.

The earliest form of polyrod[9] was a polystyrene rod of uniform rectangular cross-section, about $\frac{1}{3}\lambda$ by $\frac{1}{2}\lambda$. Figure 6 shows the gains and directional patterns measured for such rods in three different lengths. In a plane normal to the axis, the radiation is approximately isotropic. The observed gains are proportional to length. They are greater than 4ρ by a factor of

[9] The earliest work on polyrods was done in 1941 by Dr. G. C. Southworth. Cf. his *U. S. Patent* 2,206,923 issued in 1940.

about 1.4. Phase velocity in these rods was not measured and is not available from theory. Referring to Fig. 4, however, we must assume at least 0.4π radians of phase retardation to explain the increased gain. When the pattern for the 6λ rod is compared with the sharpest pattern ($\beta = 6.5$) in Fig. 3, the observed characteristic is sharper than expected even with a phase retardation of π. The amplitudes of minor lobes are in good agreement. Attenuation, as revealed by the amplitudes at minima in the patterns, is apparently appreciable but not serious.

The principal defect of the uniform polyrod is the strong minor lobes. This is remedied by tapering the amplitude of radiation symmetrically about the midpoint, as suggested in Fig. 5. To obtain such tapering let us start at the waveguide end with a relatively thick rod. From Fig. 1, this tends to retain a larger fraction of the power and should therefore not radiate so strongly. Let us decrease the cross-section gradually in progressing along the rod, thus increasing the power radiated. Upon reaching a point near the center, we find the power in the rod already considerably diminished by the radiation which has already taken place. Beyond this point, gradually decreasing radiation is automatically secured with a uniform cross-section as a result of previous radiation.

This line of reasoning, calling for a polyrod tapered down in cross-section only in the first half of its length, is verified experimentally. Since detailed field analysis is not available for the polyrod, the most favorable proportions have been found empirically. Three examples will be described.

Figure 7 shows a 6λ rectangular polyrod linearly tapered for a little more than half its length from a base $\frac{1}{2}\lambda$ square to a rectangular section $\frac{1}{4}\lambda$ by $\frac{1}{2}\lambda$. the remainder being uniform. The tapering is confined to the magnetic plane. Measured phase velocity and directional pattern are included in Fig. 7. By reference to Fig. 5, the observed minor lobe amplitudes correspond to a value of a somewhat less than 0.5. The gain, considerably improved over the uniform rod, implies from (2) a value of 1.86 for A in remarkable agreement with Fig. 4.

Figure 8 shows data on a 6λ cylindrical polyrod linearly tapered for about half its length from a diameter of 0.5λ to 0.3λ with the remainder uniform. The pattern is very similar to that of the preceding example; the gain is slightly reduced, and $A = 1.66$. From Fig. 1, $\epsilon = 2.5$, about half the power is internal for $\frac{D}{\lambda} = 0.5$, while less than one-tenth is internal for 0.3. Agreement between Figs. 2 and 8 for phase velocity is fairly good.

Figure 9 gives information[10] about an 8.65λ radiator which resembles the

[10] Supplied by Mr. C. B. H. Feldman.

conical-cylindrical design of Fig. 8, but which is longer and is tapered for slightly less than half its length. The minor lobes (solid curve) are all lower than 0.125, a marked improvement over Fig. 8. From the measured gain, A is 1.82.

Regardless of whether the cross-section is square, rectangular, or round, radiation is nearly isotropic about the axis of the polyrod. For the patterns

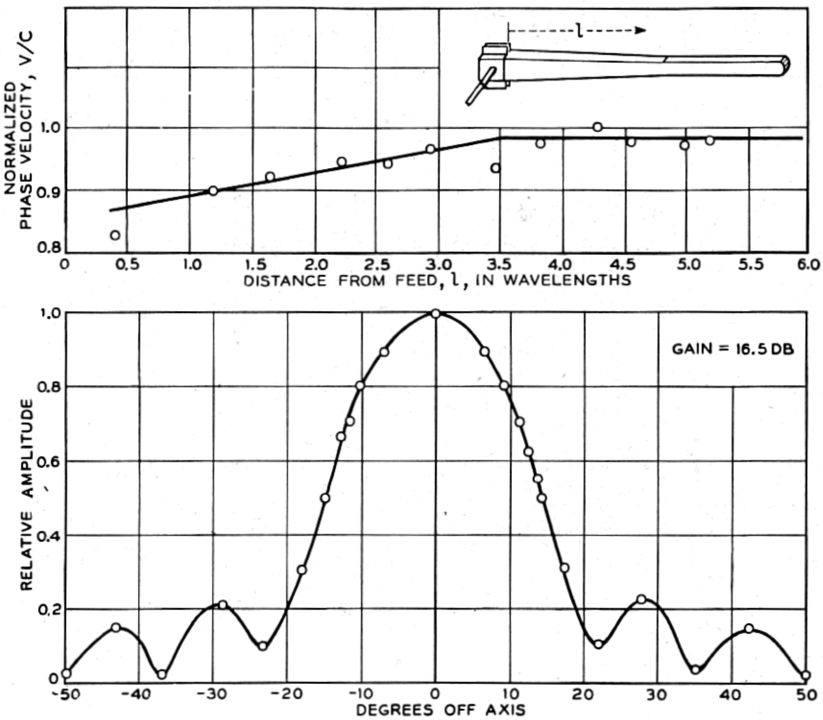

Fig. 7—Data on a 6λ tapered rectangular polyrod.

in Fig. 6–9, beam widths in degrees between half-power points correspond to values of B in (3) between about 50 and 60.

The characteristics of polyrods can thus be correlated with array theory for isotropic radiators continuously distributed along an axis. There are, to be sure, minor discrepancies which might become more serious in a different range of polyrod proportions. For the lengths and cross-sections tested, however, equations (1) to (5) describe polyrod performance very satisfactorily for engineering purposes.

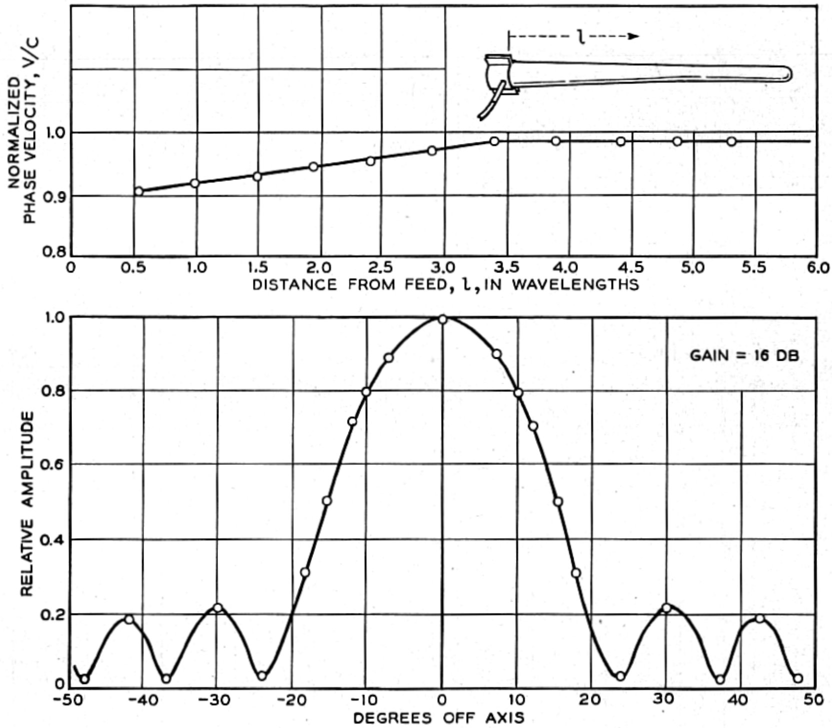

Fig. 8—Data on a 6λ tapered cylindrical polyrod.

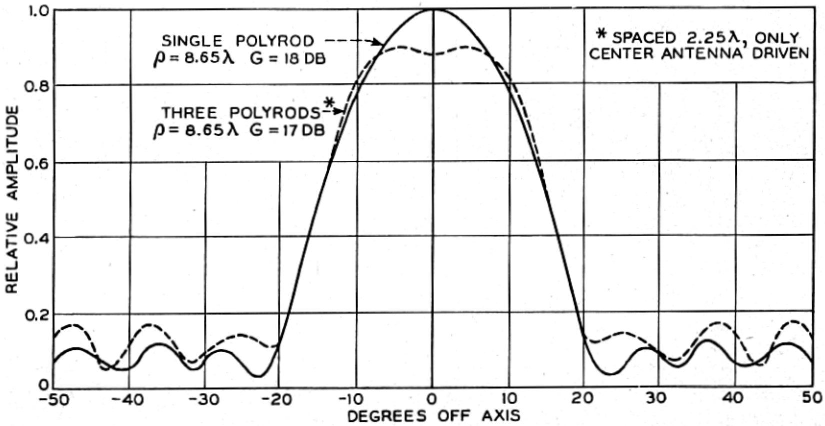

Fig. 9—Data on an 8.65λ tapered cylindrical polyrod, including effect of adjacent similar polyrods.

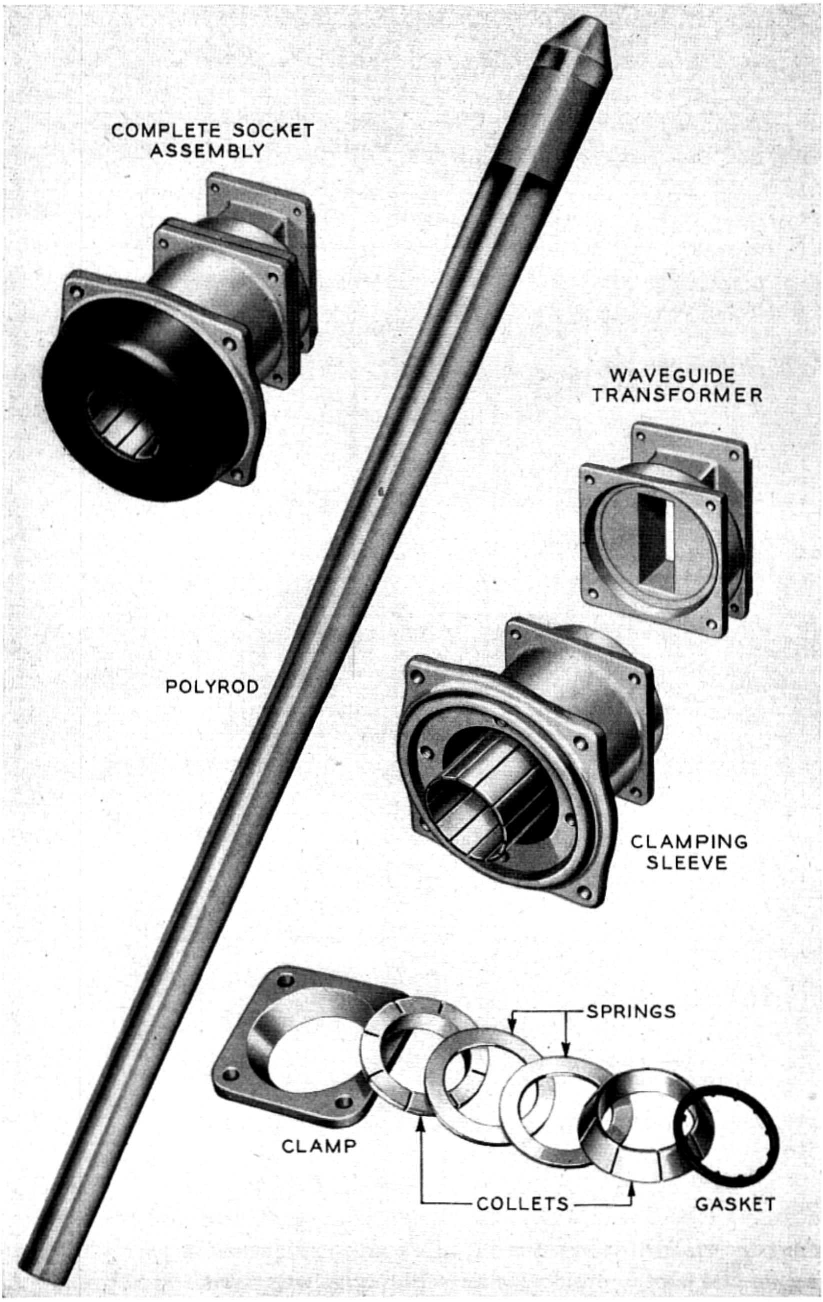

Fig. 10—Polyrod and waveguide feed details.

5. Construction and Operational Details

Figure 10 shows a production model of a polyrod for 3000 megacycles, with means for matching it to a rectangular waveguide.[11] A two-iris transformer is used with a resulting width of 4% between the 1 *db* standing wave points. The clamping illustrated is designed to maintain a firm grip on the rod despite tendencies of the polystyrene to cold flow.

Another type of coupling is indicated in Fig. 11. Here the polyrod is still fed from a waveguide but this is in turn transformed to a coaxial line. The composite can thus be regarded as a coaxial to polyrod coupling. The coaxial line taps at point *b* onto the short-circuited antenna *a-b-c* at a point

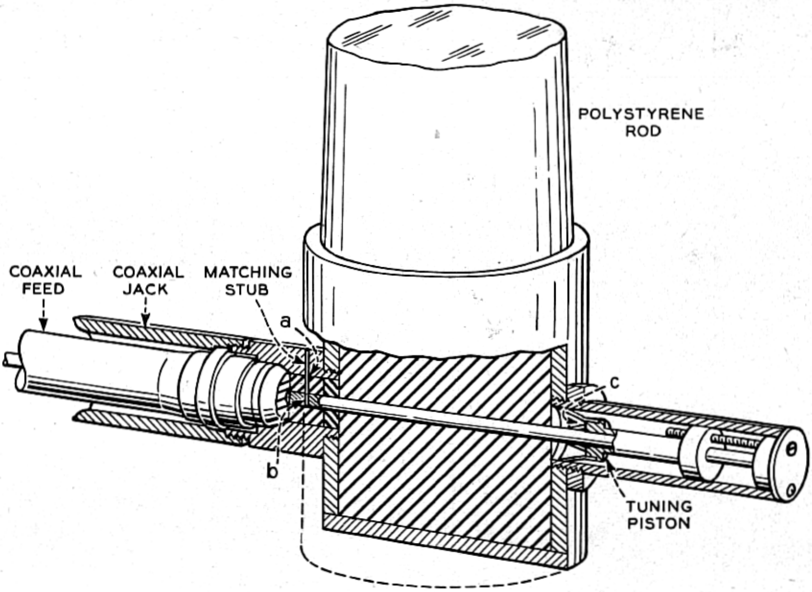

Fig. 11—Coaxial feed for polyrod.

chosen to match the characteristic impedance of the coaxial line. The back end of the waveguide is short circuited by a metal cap a quarter wavelength behind the transverse wire antenna. A movable coaxial plunger provides tuning. This arrangement has a bandwidth of 1% to the 1 *db* standing wave points.

The frequency response of a polyrod is inherently broad. The directive pattern varies slowly with both phase velocity and amplitude distribution along the axis. As shown in Figs. 1 and 2, these quantities are slowly varying functions of λ over a considerable range of polyrod proportions. At

[11] Developed by Mr. D. H. Ring.

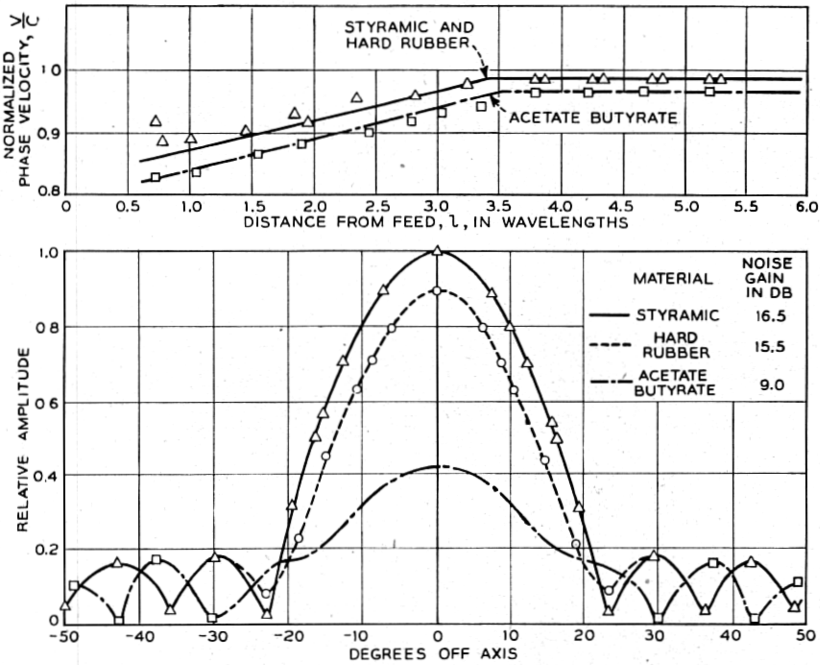

Fig. 12—Effect of dielectric loss on polyrod performance.

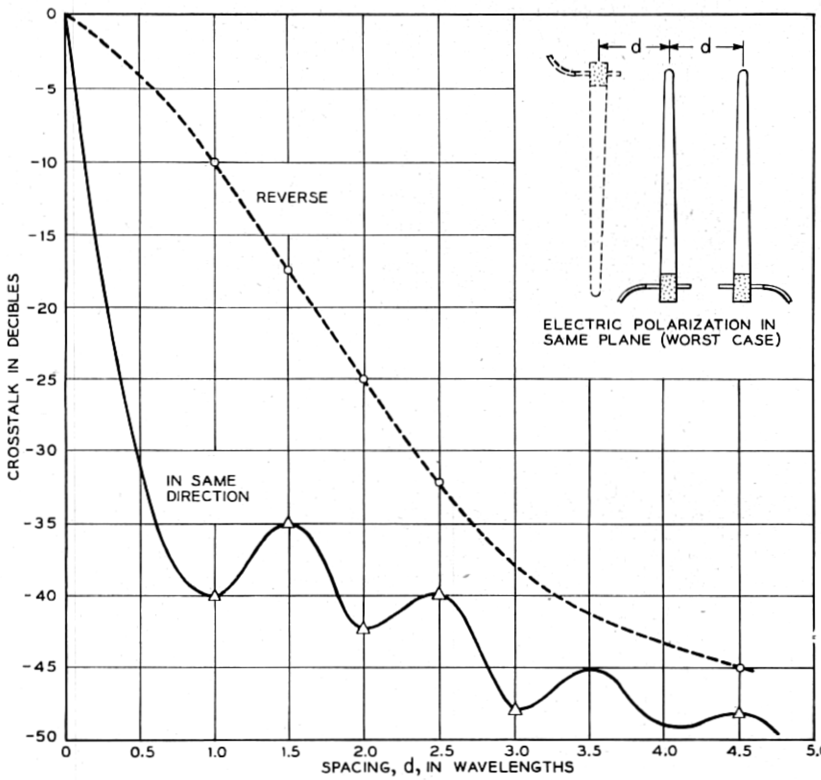

Fig. 13—Crosstalk between polyrods.

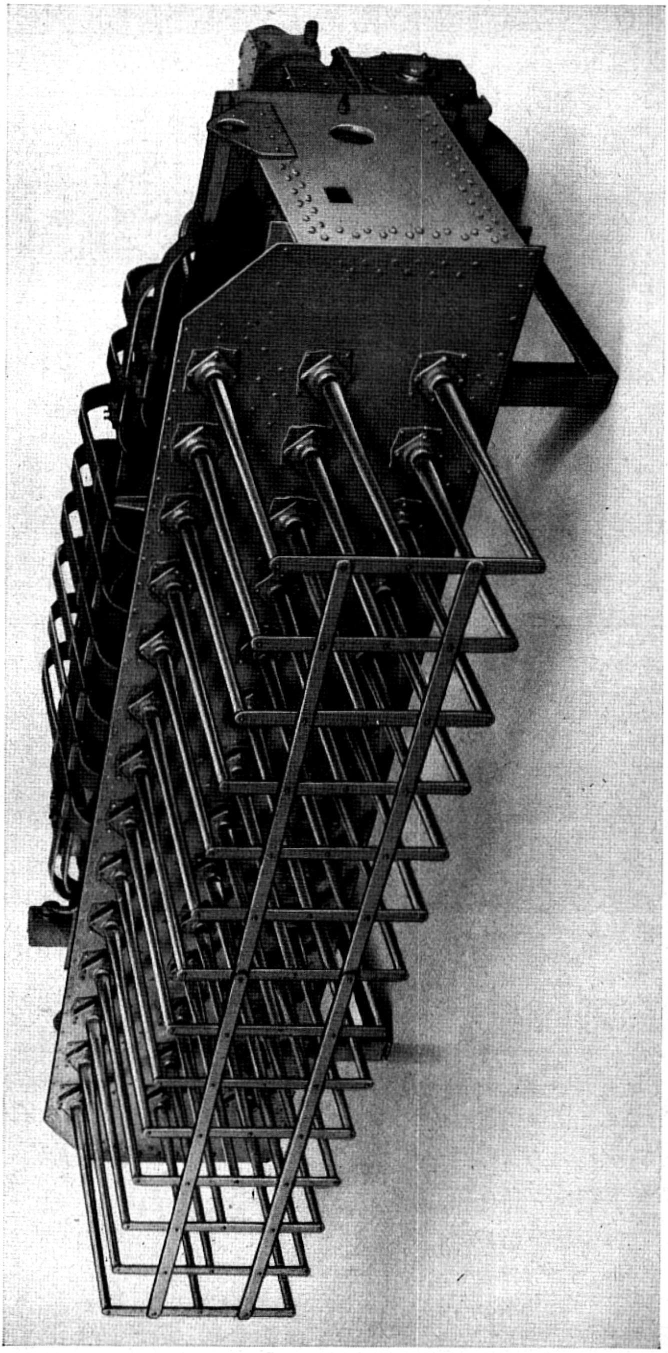

Fig. 14—Broadside array of polyrods.

present, the usable bandwidth is therefore limited primarily by the frequency response of the coupling arrangements from polyrod to waveguide or coaxial line.

We have been exclusively concerned so far with plane polarized radiation. A circularly symmetrical polyrod such as in Fig. 8 can be used equally well to radiate circularly polarized waves. To do this, the polyrod is fed from a waveguide in which circulary polarized dominant waves are generated by means of a 90° phase shift section.[12]

The effect of dielectric loss upon polyrod performance is shown in Fig. 12, to be compared with Fig. 7. The power factors are: Styramic, 0.0005; hard rubber, 0.003; acetate butyrate, 0.020; polystyrene, 0.0002. Materials having power factors less than 0.001 are satisfactory for polyrod antennas.

Figure 13 shows the crosstalk between adjacent polyrods, that is, the power received in one radiator when the other is energized. For polyrods pointing in the same direction, separations greater than a wavelength insure low mutual coupling. This makes the polyrod attractive as the element in broadside arrays. Proximity to other undriven polyrods affects the gain and directional pattern to a greater extent, as shown in Fig. 9.

More generally, the performance of a polyrod is affected by proximity to any metallic or dielectric objects. The gain and pattern must be determined empirically for each new configuration. It has been found that a metal rod can be placed parallel to a polyrod without seriously affecting its behavior so long as a separation of a wavelength or more is maintained. Sheets of dielectric material can be brought even closer without adverse effect so long as large surfaces are not in direct contact with the polyrod. These and other experiences suggest that the polyrod is relatively unaffected by nearby objects.

Tests have been made of the effect of fresh and salt water in the form of a spray or solid stream playing on a polyrod. Provided that puddles do not form on the surface, as can happen with rectangular polyrods, the effect is a decrease of 1 to 2 *db* in gain under the worst conditions.

In conclusion, for microwave applications involving moderate gains of 15 to 20 *db*, the polyrod assumes a convenient physical form and displays high electrical efficiency. It is less subject to disturbance by nearby objects than might be expected. It is especially useful as an element in broadside arrays. As an example of such arrays, Fig. 14 shows a 42 rod steerable beam antenna used in an important type of Navy fire control radar.

[12] For a discussion of this subject, cf. A. G. Fox, "An Adjustable Waveguide Phase Changer," to be published in *Proc. I. R. E.*