The magnitudes of the sideband components would be much smaller when the output cavity is loaded down in order to increase the bandwidth than they were in the experimental work which was performed for this paper. In an actual case, a bandwidth of about a hundred megacycles would probably be desired, which would require loading the output cavity until its equivalent Q is about sixty,[6] as compared with the Q of about a thousand in the cavity configuration used for this paper. This would mean that the magnitudes of the various sidebands would be approximately 7 to 10 per cent of the values obtained in the experimental work of this paper. The tube used in this work was a very poor one; a large share of this decrease in magnitude could be regained by using a good klystron and higher voltages.

CONCLUSION

It is believed that this preliminary investigation has shown that this method will produce a frequency spectrum that is admirably suited for use for a microwave frequency standard. It has been shown that this scheme will produce a wide band of microwave voltages of reasonable magnitude and accurately determinable frequencies. With a single carrier frequency, an operating range of ten or fifteen times the lowest modulating frequency may be easily obtained on each side of the carrier frequency.

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[6] Massachusetts Institute of Technology Staff, *op. cit.*, p. 509.

A Turnstile Polarizer for Rain Cancellation

PAUL A. CRANDELL*

***Summary*—This paper describes a rain canceller using a turnstile junction to provide the necessary polarization of the fields. It discusses the system from the point of view of adapting an existing radar feed system to one that will permit the reduction of rain return. The turnstile junction is described, and it is shown to have properties that meet the requirements for obtaining circular or elliptical polarizations. Along with this description, the theory behind the effect of elliptical and circular polarization on rain return is discussed in detail as well as the practical limits such a theory can be put to. Other considerations such as aspect ratio of antennas and screening for the antenna surfaces are touched upon.**

THE DELETERIOUS effect of rain on radar systems has long been a troublesome condition. This effect is well known and has been the object of much study. The energy lost to a target is lost in two ways:

1. The rain absorbs the rf and converts it to heat,
2. The spherical drops reflect the energy and cause it to appear as scintillating high-level noise.

The first condition is a function of wavelength:

$WaSf(a, \lambda) =$ energy lost,
$S =$ pointing vector,
$a =$ radius of a spherical drop,
$\lambda =$ wavelength in air.

The loss is directly proportional to frequency. At 10 cm and above, the attenuation is negligible, and even down to 3 cm it is not too serious; but for $\lambda < 3$ cm the attenuation goes from 0.01 db/km for a drizzle to 1 db/km for excessive rain. For our case, this attenuation is unavoidable and must be accepted as reduction in system performance. However, the second case of rain scattering the incident signal can be remedied to some extent. This "rain clutter" can be extremely troublesome for targets of small cross section when the beam is pencil or fan shaped.

There is one saving feature to this entire problem, and that is the unique property of the rain target itself, namely, its shape. Since rain drops tend to be spherical, the intensity and phase of the reflection from the target do not depend on the direction in which the incident beam is polarized. When these spheres are struck by a circularly polarized plane wave, the scattered wave which is returned is also circularly polarized and just the sense of rotation of the vector is changed (see Fig. 1).

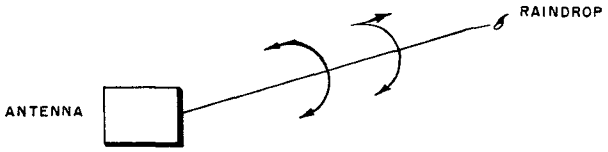

Fig. 1—Principle of rain cancellation.

The sense is defined as the direction of rotation as seen by an observer watching an oncoming signal. Circular polarizers are so designed that this return, which is in the opposite sense from the impinging signal, will not be accepted by the feed system. A simple device which will manufacture circular polarization in one sense and

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reject or absorb circular polarization in the opposite sense is a circular waveguide capable of supporting the TE_{11} mode. The E vector in the circular guide is considered as two vectors at right angles. That is space quadrature, but in time phase. In order to circularly polarize this vector, it must be in both space and time quadrature. Therefore, to convert the linear mode in the circular guide into this condition, a dielectric septum of the correct electrical length is placed parallel to one vector component, delaying it by the 90 degrees needed to accomplish the time delay. Since the return signal of the opposite sense must be absorbed completely so that the receiver never sees it, a septum of absorbing material is placed 90 degrees to the E vector of the transmitted TE_{11} mode absorbing the received signal, which has passed through the polarizer in the opposite direction and is now parallel to this absorbing material. The proof of this may be seen from the following equations:

β = phase angle

δ = phase difference

$$E_y = C \cos(\omega t - \beta x + \delta) \text{ vector in one plane} \quad (1)$$

$$E_x = A \cos(\omega t - \beta x) \text{ vector at right angles.} \quad (2)$$

Substituting $u = \omega t - \beta x$ in (1) and (2),

$$E_x = A \cos u \quad (3)$$

$$E_y = C \cos(u + \delta) = C(\cos u \cdot \cos \delta - \sin u \cdot \sin \delta). \quad (4)$$

Since

$$\cos u = E_x/A,$$

$$\sin u = \sqrt{1 - (E_x/A)^2}.$$

Substitute for cos u and sin u

$$E_x \cos \delta/A - E_y/C = \sqrt{1 - (E_x/A)^2} \sin \delta. \quad (5)$$

Squaring both sides and simplifying,

$$E_x^2/A^2 + E_y^2/C^2 - 2E_xE_y \cos \delta/AC$$
$$= \sin^2 \delta \text{ equation of an ellipse} \quad (6)$$

if $\delta = \pi/2$ and $A = C$

$$E_x^2 + E_y^2 = A^2 \text{ equation of a circle} \quad (7)$$

if $\delta = 0$ or 2π

$$E_x = AE_y/C \text{ equation of a straight line.} \quad (8)$$

Rain cancellation up to 30 db has been achieved by this and similar systems, the only limitation on the cancellation being the degree of ellipticity of the secondary beam. This is a simple enough system, but, as always, there are other considerations.

One of these is the type of antenna being used with the polarizer. A circular waveguide will require a circular feed horn, and here is where the real problem begins.

For shaped beams, a dish with special beam forming properties must be used. One of these properties is an aspect ratio of other than unity. A circular horn will not illumine such a surface properly, and a pyramidal or sectoral horn is essential to the task. The problem has now resolved itself down to one of designing a circular polarizer that can utilize a conventional horn, or at least a horn that can give the proper illumination of the surface for a doubly curved beam-forming antenna.

Our system uses a turnstile junction and incorporates a pyramidal horn at the output of the turnstile to manufacture the circularity. A turnstile is a waveguide device consisting of four guides meeting at a common H-plane junction. The common E-plane of this junction has a circular waveguide capable of supporting energy received from any one of the four guides. In the symmetry plane of these five guides there are two concentric matching posts which may be adjusted so that looking into any arm with a matched termination in the other four, there will always be a match. When energy from one of the guides arrives at the junction, it divides, with one-half of the power going up the circular guide and one-quarter going down each of the side arms. Nothing goes down the guide which is directly opposite the transmission arm due to the fact that, since the signals are 180 degrees out of phase at this point, they cancel. If the short circuits are placed in the two side arms such that one arm is $\frac{1}{4}$ wavelength longer than the other, the energy that is sent up the circular arm from these arms will lag the energy from the transmission arm by 90 degrees in both space and time, and circular polarization will result. By varying the positions of the two shorts in the side arms, thus changing the electrical length, the polarization can be changed from linear, through circular to elliptical. Fig. 2 shows

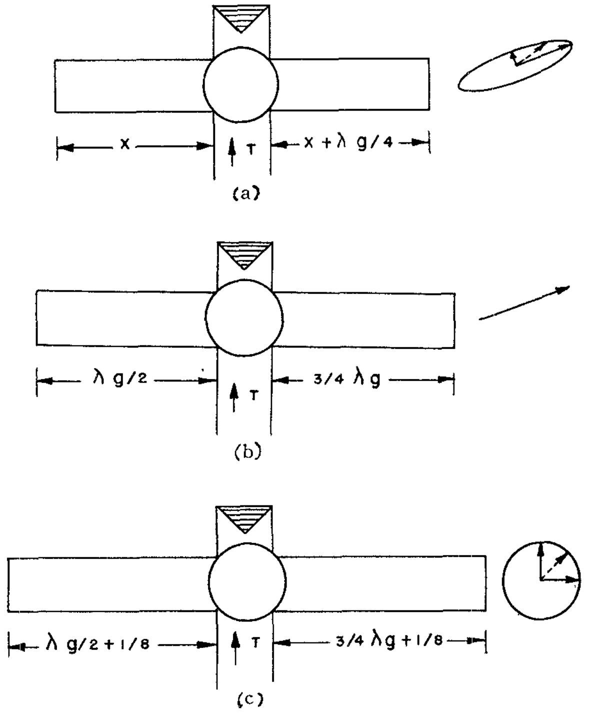


Fig. 2—Physical conditions for various polarities.

the short position for various polarizations. In the case of (a) as X varies, so also does the major and minor axis of the ellipse. Thus the resultant passes through an ellipse from a straight line to a circle back to a straight line in the opposite direction. Any one of these forms may be considered as an ellipse as proven by equations above. When X is $\lambda g/2$, as in (b), a straight line results and the condition is known as crossed linear polarization. The 45-degree angle will be preserved if the horn is symmetrical around the symmetry plane. If a pyramidal horn is used, the fields will be shifted in phase as they pass through, and thus an unwanted ellipse will result. This condition can be corrected by phasing the shorts so that an ellipse is generated at the start, which will be transformed into a straight line due to the phase shifting of the horn itself. Fig. 2(c) shows the condition for circular polarization. The waves are in quadrature in both time and space. In crossed linear the waves are in time phase, but are in space quadrature. While an ellipse still retains the space quadrature of the vectors, the time phase is some in-between value.

It is evident that illumination may be provided by a symmetrically patterned circularly mouthed feed-horn, but not without objectionable loss of antenna gain resulting from either over- or under-illumination of the reflecting surface.

In order to keep the maximum antenna gain and still use circular polarization, we developed the device this paper describes. Since our antenna surface has an aspect ratio of approximately 4:1, we know that we must have a pyramidal horn with a Gaussian feed differing in the two planes of the antenna surface. However, to keep this horn for proper surface illumination and still to generate circular polarization in the primary feed was the problem. We solved it by the following scheme. The properties of the turnstile are well known and have been long used as a polarizing device. The usual procedure is to terminate the output of the turnstile with a circular horn and assume equal phase shifting in the two planes of the horn. Therefore, by generating circular polarization in the turnstile, the horn will serve only to generate it into space without changing the degree of circularity. A pyramidal horn will not do this, and any circularity at the input will be shifted to elliptical at the orifice. This is true since a pyramidal horn may be considered as a waveguide tapering in two planes, each above cutoff but propagating energy with different phase velocities. Our system makes use of this phase shift, and the shorts in the turnstile are so positioned as to give circular polarization at the orifice of the horn when some elliptical polarization is generated at the turnstile to horn junction, as shown in Fig. 3.

$$\delta = \theta_x + \int_0^1 \beta_x(1)dl - \theta_y - \int_0^1 \beta_y(1)dl$$

$= $ phase difference,

where θ_x and θ_y are the initial time phase shifts which the two space quadrature vectors undergo in the turnstile due to the positioning of the shorts, the $\int_0^1 \beta_{x,y}(1)dl$ is the phase shift which the horn gives the vectors due to the changing phase velocity,

$$\beta_{x,y} = \frac{2\pi}{\lambda g} = \frac{2\pi}{\lambda_0\sqrt{1-\left(\frac{\lambda_0}{2b_{x,y}}\right)^2}}$$

$b_{x,y}$ is the changing waveguide dimension $= 21 \tan \alpha_{x,y}$.

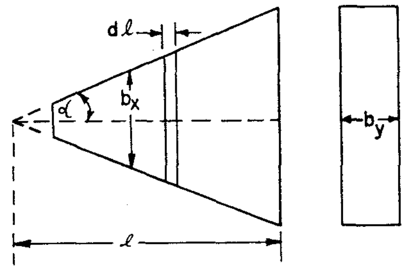


Fig. 3—Phasing properties of a pyramidal horn.

The horn which was used with the turnstile feed system was a little different from the linear horn feed. This horn (Fig. 4) was designed as a compromise so that the E- and H-fields exist only in the same plane will be approximately matched to the antenna. The primary patterns from this horn show that the edges of the reflector will be illuminated within the 8–12 db points as is conventional to most antenna surfaces of this kind.

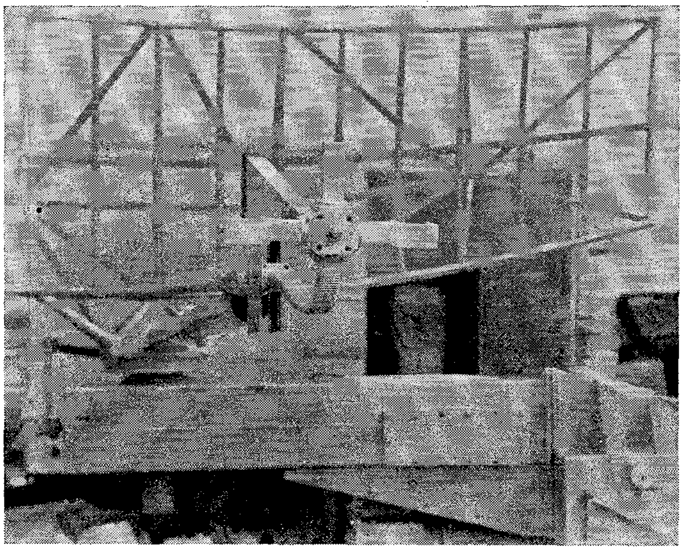


Fig. 4—Polarizing horn substituted for conventional linear horn.

Also the distributions are approximately Gaussian, which was one of the design prerequisites. Figs. 5–8 (opposite) are typical primary patterns of the four fields which will make up the circular polarization.

This then gives us a source of a circular polarization, and also a primary feed system with the proper field distribution in the two planes for the beam shaping antenna with an aspect ratio of other than unity.

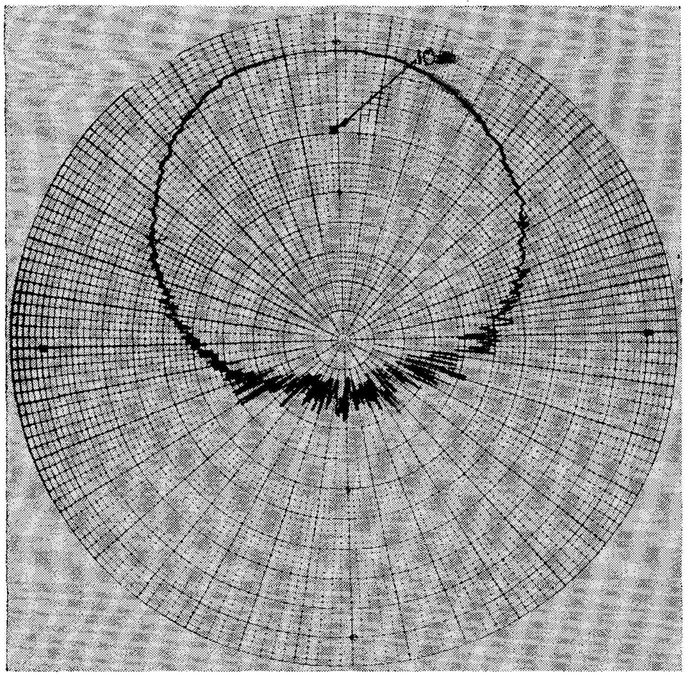


Fig. 5—E_1 plane.

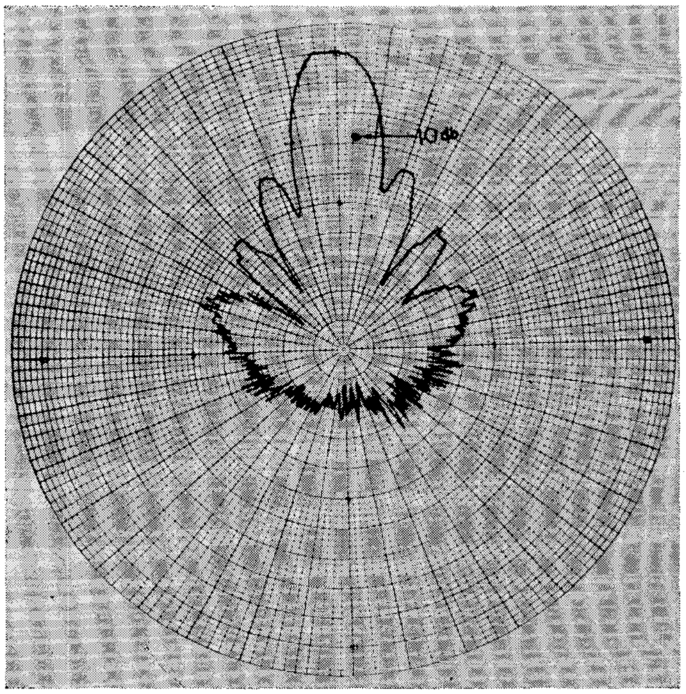


Fig. 7—H_1 plane.

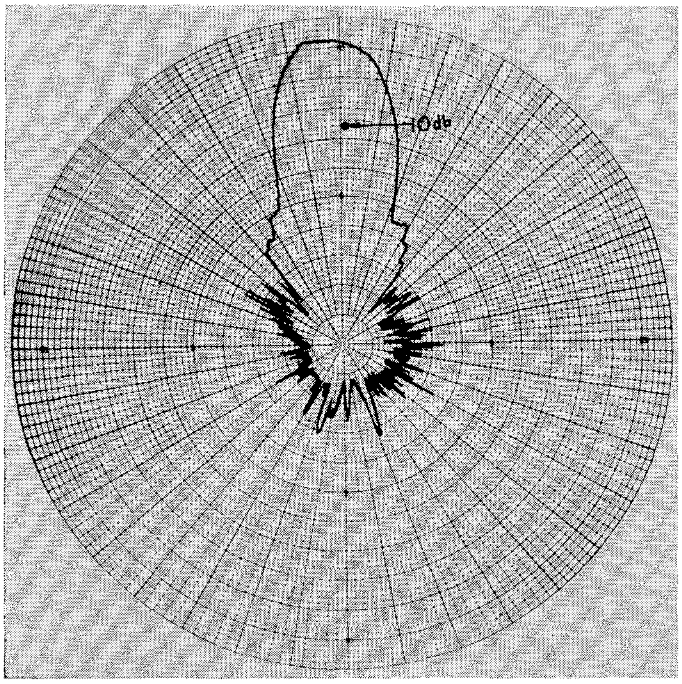


Fig. 6—E_2 plane.

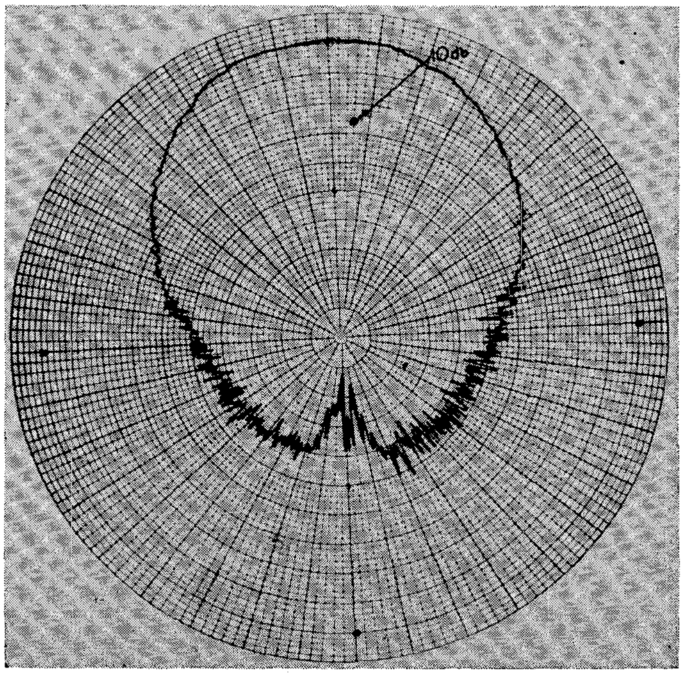
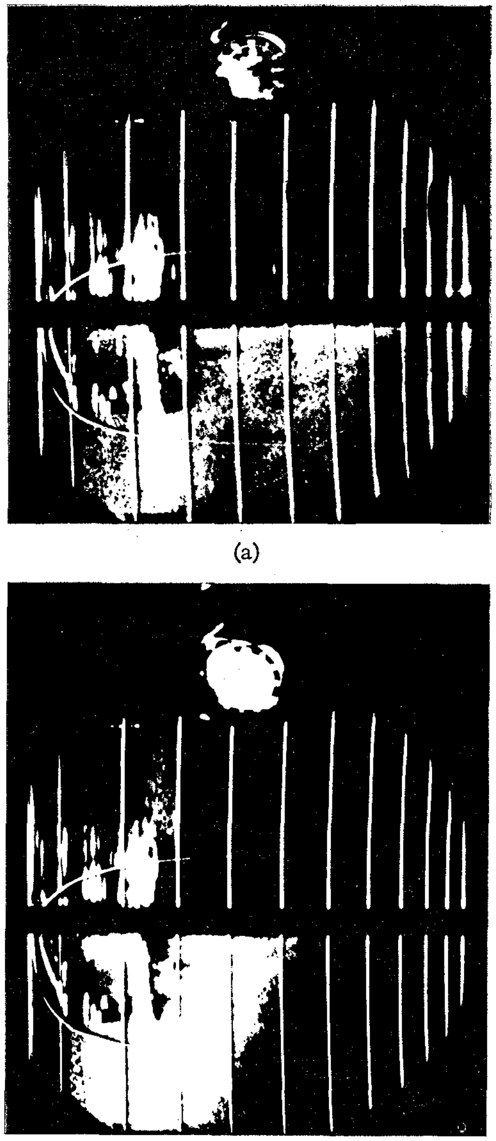


Fig. 8—H_2 plane.

One other necessary modification of an existing antenna which is to be converted from a linear system to one that uses circular polarization is a symmetrical mesh screen for the antenna skin. The need for this explains itself when we consider the fact that circular polarized beams contain E-vectors in two planes at right angles. Anything but a symmetrical mesh will cause additional phase shift due to the different path length for the two vectors.

The evaluation of these theoretical concepts came when the polarizer was used on the Laboratory for Electronics GCA system which has mechanically scanning antennas in azimuth and elevation. Fig. 9 (following page) shows actual rain cancellation on the GCA display system, which is time-sharing with the elevation on top and the azimuth below it. Each of the vertical lines represents one mile intervals. The curved lines through the first four range marks represents the cursor lines.

For this picture and for subsequent measurement we used a conventional linear feed horn in azimuth and the turnstile canceller on the elevation antenna. The picture shows a heavy milked-in area in azimuth out to about five miles while in elevation the slightly visible precipitation between two and three miles is quite a bit below the level of the fixed targets in the area. Experimentation is still going on, and as yet there is no accurate correlation between the meteorological measure of rainfall and cancellation. The results of corner reflector cancellation are indicative of the data that will be forthcoming.


(a)

(b)

Fig. 9—Photographs of the indicator-display system during a rain storm.

A three-bounce corner reflector is, in effect, a perfect specular reflector and its properties are the same as a perfectly spherical raindrop. It changes only the sense of polarization, but does not affect the circularity. A two-bounce corner reflector will not affect the circularity, but it returns the signal in the same sense of rotation as the transmitted energy and, therefore, will not cancel. This provides a convenient field test procedure for setting up the radar system with circular or linear polarizations. By knowing the level of the return from each of these targets when viewed on the nose of the beam with linear polarization, we can set up a reference level and find the difference for each of these targets when viewed with circular polarization.

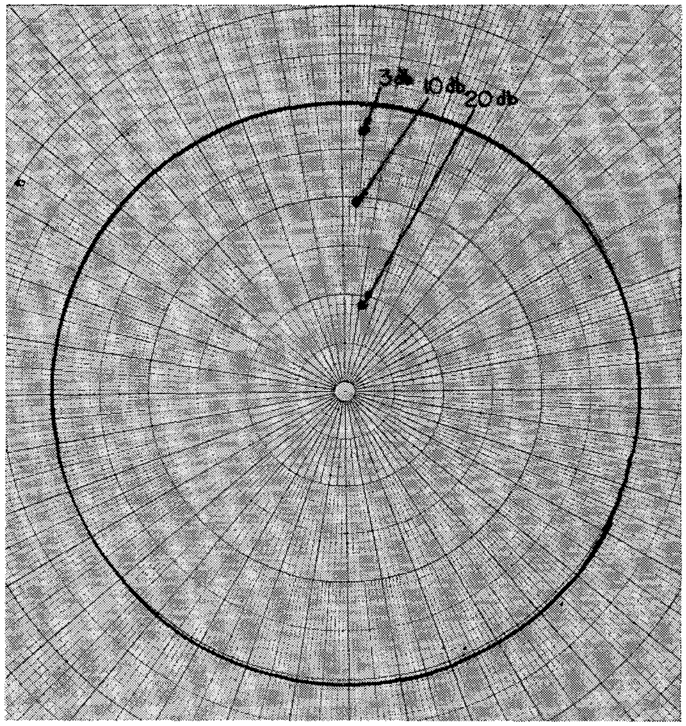


Fig. 10—Circular polarization with rectangular horn $f = 9{,}070$ mcs.

Net cancellation $= (L_2 - C_2) - (L_1 - C_1)$,

L_2 = linear polarized return from three-bounce reflector in db,

L_1 = linear return from two-bounce reflector,

C_2 = circular return from three-bounce reflector,

C_1 = circular return from a two-bounce reflector.

Target	Linear Pol.		Circular Pol.	Net Cancellation
#1	two-bounce	53 db	50 db	52 db
#2	three-bounce	60 db	5 db	

The attenuation measurements were made by inserting a calibrated attenuator between the preamplifier and the log. IF amplifier. The signals were viewed on an A-scope attached to the indicator.

The positions of the short circuits in the turnstile were rather critical, and finer adjustments allowed us to measure net cancellation up to 68 db. On the occasion of this measurement we viewed the targets on the indicator display system and found a difference of 50 db between the same target in azimuth, where there

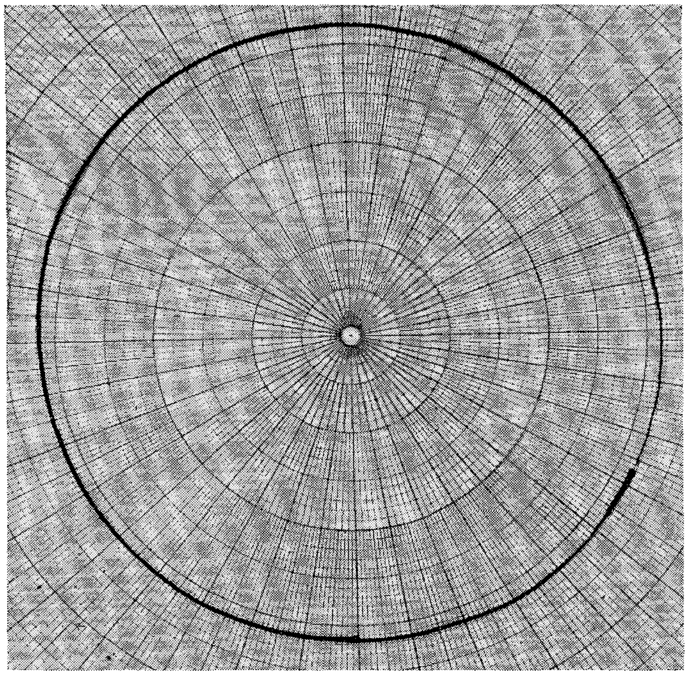


Fig. 11—Position of shorts set for circular polarization with rectangular horn removed and circular horn placed on turnstile $f=9{,}070$ mcs.

was no canceller, and elevation where the canceller had been set to give a 68 db cancellation. The difference between a static measurement and a dynamic measurement can be accounted for by the fact that the circularity of the secondary beam breaks up at off angles due to the diffraction of the primary beam at the edges of the reflector surface.

Figs. 10–12 are recordings of the primary pattern polarization as determined from the turnstile short positions for optimum corner reflector cancellation.

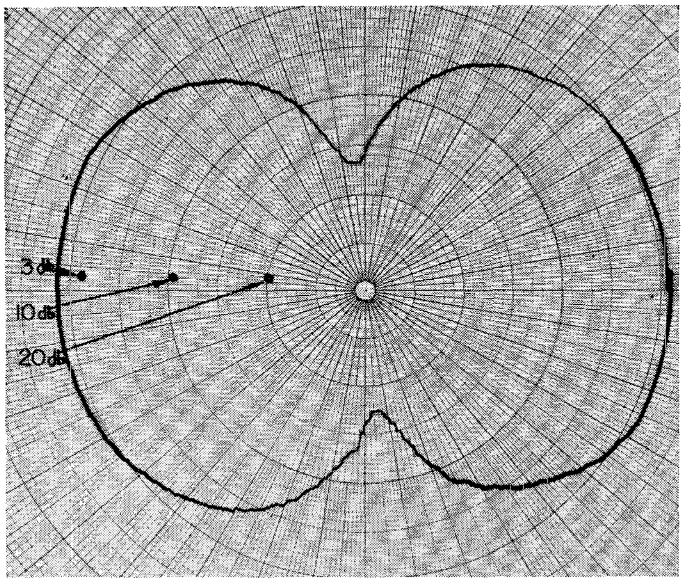


Fig. 12—Linear case, max. radar signal $f=9{,}070$ mcs.

Fig. 10 is the circular polarization with the pyramidal horn terminating the turnstile. In order to show the effects of this horn it was replaced with a circular horn keeping the same positions for the shorts in the turnstile arms. The pattern becomes elliptical to the extent of about 1.5 db. The final figure is a plot of the linear polarization with the pyramidal horn replaced on the turnstile. These values were recorded at 9,070 mcs.

The polarizer looks quite successful, but it bears more investigation. In the near future more quantitative data will be available for a better evaluation over existing polarizing systems.

Graphical Filter Analysis*

HARVEL N. DAWIRS†

Summary—**Some well known principles of filters and transmission lines are recalled and used to develop graphical methods of analyzing lossless transmission line filters consisting of a series of symmetrical and identical sections. The results of this development are used to construct a special filter analysis chart by means of which a filter may be completely analyzed from a Smith Chart plot of the input impedance characteristics.**

INTRODUCTION

FILTER calculations may become quite difficult in the microwave region where filter circuits are constructed of transmission line sections, since the equations involved are usually transcendental. However the important properties of lossless filters consisting of a series of symmetrical sections may be determined graphically on a Smith chart[1,2] by methods described in this paper. These methods may also be useful in analyzing mechanical filters in which the elements are essentially mechanical transmission lines.

It is to be noted that, while the methods presented are particularly adapted to transmission line circuits,

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† Department of Electrical Engineering, Ohio State University Research Foundation, Columbus, Ohio.

[1] P. H. Smith, "A transmission line calculator," *Electronics*, vol. 12, pp. 29–31; January, 1939.

[2] P. H. Smith, "An improved transmission line calculator," *Electronics*, vol. 17, pp. 130–132, 318–325; January, 1944.