A 4/6 Gc/s Circularly-Polarized Diplexer for the Goonhilly Satellite-Communication Aerial*

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The diplexer described transmits some 4 to 5 kilowatts of micro-wave power and simultaneously receives a signal of the order of a micro-microwatt from a communication satellite, when used in conjunction with the earth-station aerial at Goonhilly.

The earth-station transmitter and received frequencies are 6.39 and 4.17 Gc/s. respectively, the sense of polarization of the transmit signal into the dish aerial being left-handed circularly polarized and that of the received signal from the dish aerial being right-handed. Thus a broadband reciprocal polarizer is required in addition to the diplexer. The details of the diplexer and the broadband polarizer, which constitute one integral unit (Fig. 1) are discussed below.
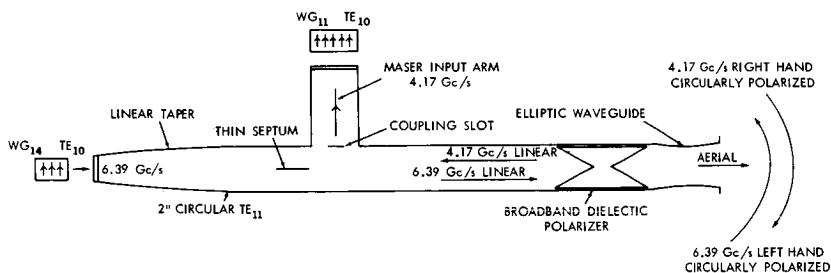

Fig. 1 — A diplexer assembly for circularly polarized waves in the 4 and 6 Gc/s bands.

THE DIPLEXER

The transmitter power is launched in the TE_{11} mode in 2-in. circular guide through a linear taper from a rectangular waveguide

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(WG_{14}). With the TE_{11} mode, separate regions of maximum and minimum power density are produced at 90° intervals around the periphery of the circular guide. If a region of minimum power density due to the transmittal signal is chosen,[1] the received signal may be launched so that its plane of polarization is transverse to that of the transmitted signal in this region. This can be achieved by suitable orientation of the broadband polarizer axis in relation to the axis of the transmit field electric vector. Under these circumstances the minimum coupling region due to transmit field is the maximum coupling region due to received field, and the transmit electric vector is orthogonal to the received field electric vector.

If a narrow slot is cut in this region of the circular guide, it will be non-radiating so far as the transmit field is concerned but will be excited by the received field, since the slot is transverse to the received field electric vector. The coupling slot is common to the round guide and the transverse plane of the rectangular waveguide (WG_{11}). The slot will not couple the whole of the received energy to the branched rectangular waveguide, but if a thin polished metallic septum is placed in the circular guide so that the received field electric vector is co-planar with the septum, then the entire received energy will be reflected and coupled to the rectangular waveguide. The field configurations and a cutaway view of the diplexer are shown in Fig. 2.

Considering the diplexer as a third-order waveguide junction (Fig. 2) it is noted that there is a plane of symmetry across the terminals of arm 3. If the septum is placed at appropriate distance from the
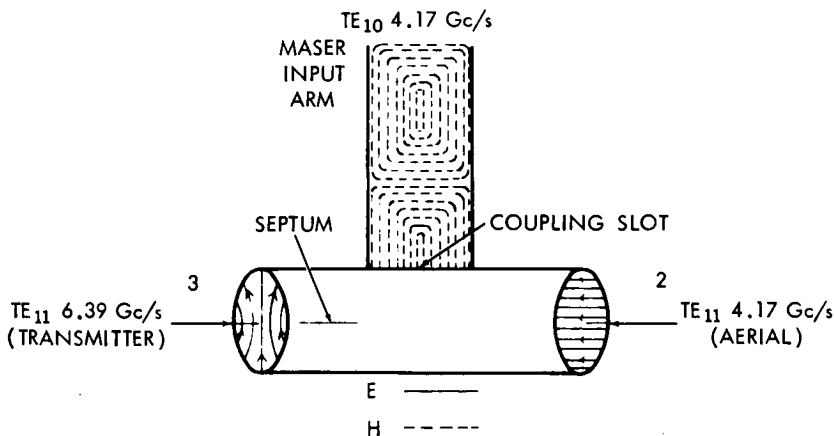

Fig. 2a — Field configuration of the orthogonal TE_{11} modes.

E_t TRANSVERSE COMPONENT OF THE E VECTOR
    DUE TO TRANSMITTED SIGNAL FIELD
E_r TRANSVERSE COMPONENT OF THE E VECTOR
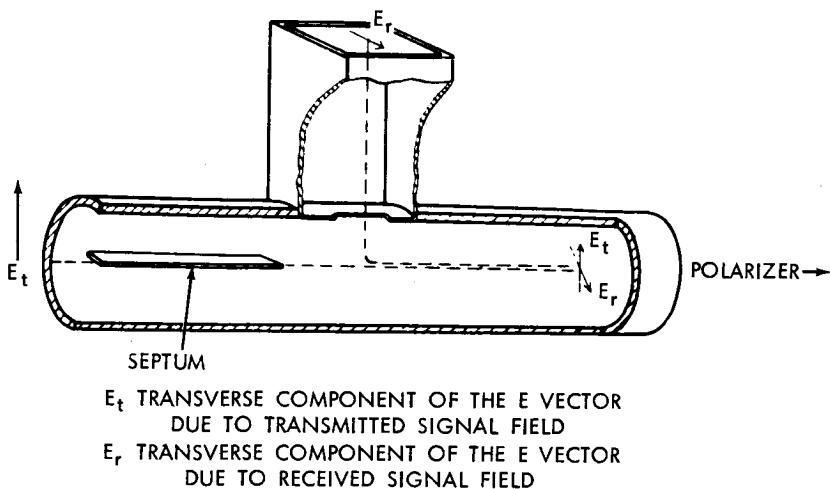   DUE TO RECEIVED SIGNAL FIELD

Fig. 2b — The diplexer.

terminal plane of this arm, then the maser input arm (i.e. the wave-guide 11 arm) and the aerial arm will behave as a perfect transmission line provided that the impedance in the branched guide is suitably adjusted in relation to the slot impedance Z', as shown in the transformer representation of the diplexer (Fig. 3).

The coupling between the aerial arm and maser input arm is achieved through a narrow rounded slot centered in the transverse plane of the rectangular waveguide 11. The interface thickness between the round and the rectangular waveguide is extremely small. The effect of this slot on the fundamental mode of a waveguide may be computed from an equivalent circuit in which the diaphragm is represented by a two terminal impedance shunted across a transmission line which is as-
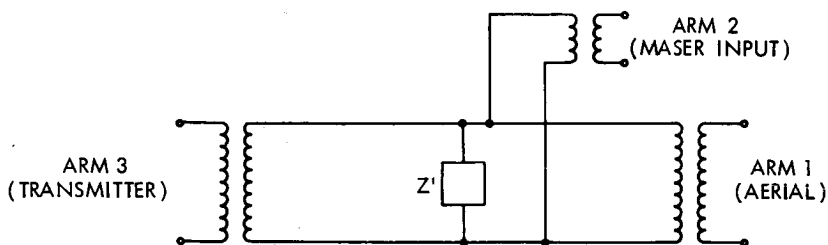

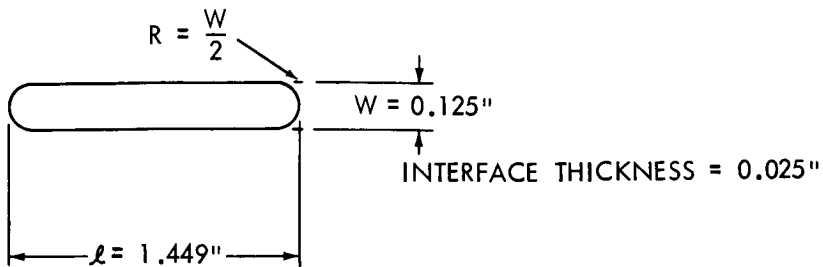Fig. 3a — Transformer representation of the diplexer.

Fig. 3b — Dimensions of the coupling slot.

sumed to carry a fundamental mode of the waveguide. For all practical purposes[2] the reactance function of such a slot is given by the expression:

$$X = \frac{4\pi \ M Z_0}{ab \ \lambda_g} \tag{1}$$

where M is the magnetic polarizability of the slot, Z_0 is the characteristic impedance of the waveguide, a and b are the width and the height of the guide, λ_g is guide wavelength.

The approximate value of the magnetic polarizability is

$$M = \frac{\pi}{16} \ 6 \ w^2, \tag{2}$$

where 6 is the length of the slot and w is the width of the slot.

According to Slater[3] the approximate resonant length of a thin slot centred on the transverse plane of the rectangular waveguide is given by the expression

$$6 = \frac{\lambda_0}{2} \sqrt{1 + \left(\frac{2aw}{b \ \lambda_g}\right)^2}, \tag{3}$$

where λ_0 is the free space wavelength. For a rounded slot having w/l less than 0.11, Equation 3 can be further simplified to

$$6 = \frac{\lambda_0}{2} + 0.273w, \tag{4}$$

This empirical relationship agrees well with the experimental measurements and the slot is found to be resonant within the desired frequency range.

EXPERIMENTAL RESULTS

From Equation 4, the following data are obtained for the slot shown in Fig. 3b.

For a centre-frequency of 4170 Mc/s:

$$\text{Length of the slot } \ell \quad = 1.449 \pm 0.003 \text{ in.;}$$
$$\text{Width of the slot } w \quad = 0.125 \pm 0.003 \text{ in.;}$$
$$\text{Wall thickness between}$$
$$\text{the rectangular and}$$
$$\text{round waveguide} \quad = 0.025 \pm 0.001 \text{ in.}$$

Fig. 4a shows the insertion loss and the VSWR between the aerial and maser input arm and Fig. 4b shows the discrimination between the transmit and maser input arm. The discrimination achieved over the transmit frequency band exceeds 50 db.

THE BROADBAND POLARIZER

The principles of the broadband polarizing device may be best understood by considering the characteristics of a circularly polarized
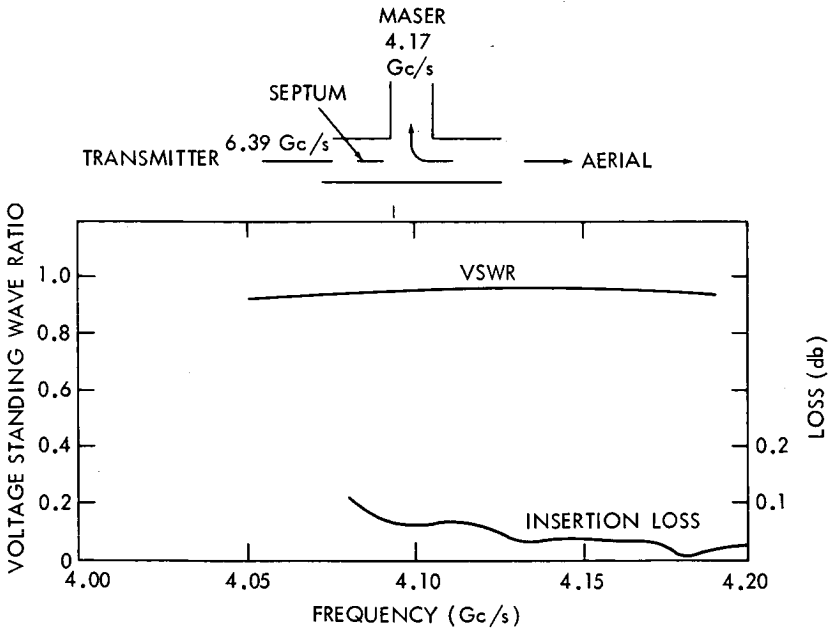

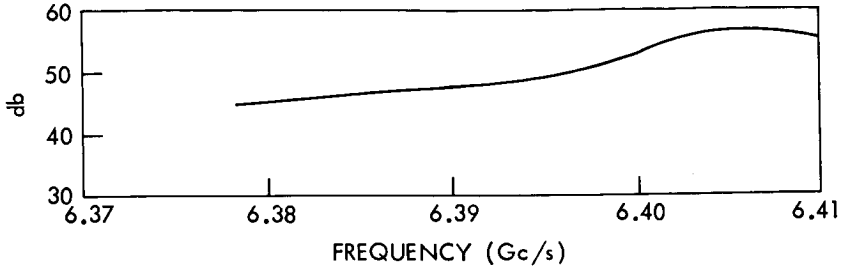Fig. 4a — Insertion loss between aerial and maser input arm.

Fig. 4b — Discrimination between transmit and maser input arm.

wave. Consider two linearly polarized waves, propagating in a positive Z direction in space quadrature as shown in Fig. 5a, and described by

$$E_1 = E_0 \sin (\omega t - \beta Z), E_2 = \gamma E_0 \sin (\omega t - \beta Z + \theta), \qquad (4)$$

where γ is constant; and the phase constant, $\beta = 2\pi/\lambda_g$.

If we consider $\theta = \pi/2$ at a plane $Z = 0$, then

$$E_1 = E_0 \sin \omega t \text{ and } E_2 = \gamma E_0 \cos \omega t; \qquad (5)$$

eliminating the time dependence gives the locus of these waves:

$$\frac{E_1^2}{E_0^2} + \frac{E_2^2}{\gamma^2 E_0^2} = 1 \qquad (6)$$

This is the equation of an ellipse with axes $2 E_0$ and $2 \gamma E_0$.

The resultant of these two components traces out this ellipse as it rotates in time. Such a rotating wave is termed an elliptical polarized wave, the polarization ellipse at a plane $Z = 0$ being shown in Fig 5b. A special case arises if $\gamma = 1$, when the locus reverts to a circle giving a circularly polarized (CP) wave. Circular polarization is therefore an ideal case of elliptic polarization, and is generally approximated to in practice by elliptical polarization with an axial ratio approaching unity. Such a wave is also referred to as "Circularly Polarized" without further qualification. The most usual manner of denoting the quality of such a wave is by the following ratio:

$$\frac{\text{Minimum of the transverse component of the electric field}}{\text{Maximum of the transverse component of the electric field}} = \frac{E_0}{\gamma E_0} = \frac{1}{\gamma}. \qquad (7)$$

Sense of Polarization

It should be noted that the sense of polarization is ambiguous unless one clearly states the reference plane. The CCIR adopted, at its Xth

POLARIZATION ELLIPSE
AT A PLANE Z=0
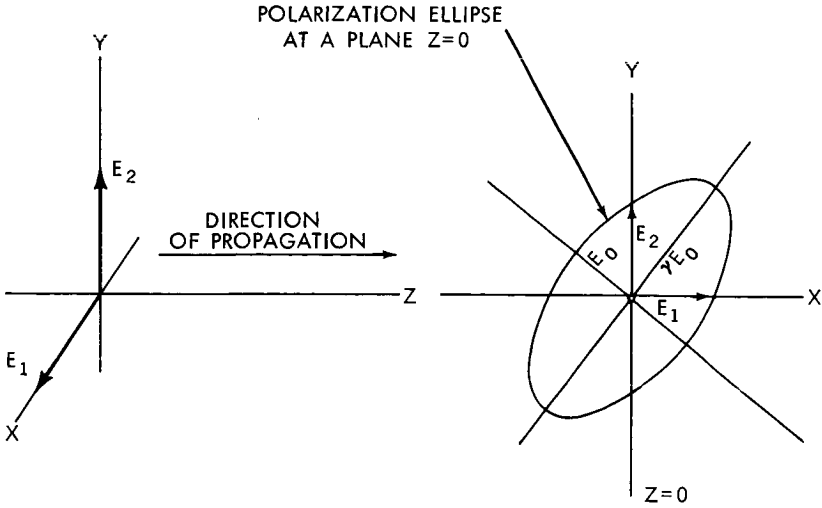
(a) Linearly polarized components of an elliptically polarized wave.
(b) Polarization ellipse.
Fig. 5 — Elliptically polarized waves.

Plenary Assembly (Geneva, 1963),[4] a definition according to which a right-handed circularly polarized wave is one in which an observer, looking in the direction of propagation, sees the electric vector rotating clockwise in a fixed reference plane.

Design of the Dielectric Plate

The two orthogonal components given in Equation 5 may be generated by establishing a linearly polarized wave E (Fig. 6) at an angle
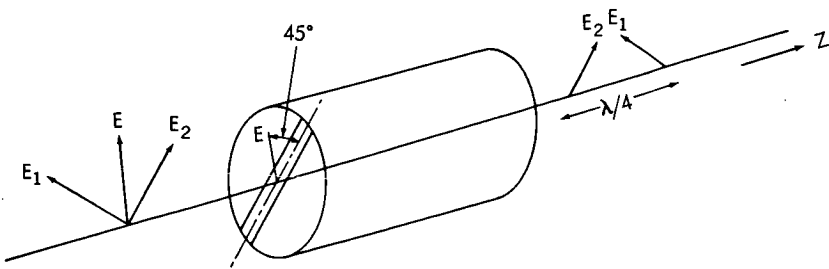
Fig. 6 — Generation of a CP wave.

of 45° to a differential phase shift section, such as a waveguide partially filled with dielectric.

Consider the incident wave E splitting into two orthogonal components E_1 and E_2. Assuming the dielectric plate thickness to be considerably smaller than the length of the plate (6), the wave E_2 in the plane of the plate will be retarded in phase compared to E_1, and the differential phase shift between E_1 and E_2 will be governed by the following relationship:

$$\phi = 2 \pi 6 \left(\frac{1}{\lambda_{g2}} - \frac{1}{\lambda_{g1}} \right) \tag{8}$$

where λ_{g1} and λ_{g2} are the guide wavelengths for the two orthogonal linearly polarized waves E_1 and E_2. Clearly the effective dielectric constant ϵ_2 corresponding to wave E_2 will be greater than the effective dielectric constant ϵ_1 corresponding to wave E_1 and consequently

$$\phi = 2 \pi 6 \frac{\sqrt{\epsilon_2 - (\lambda_0/\lambda_c)^2} - \sqrt{\epsilon_1 - (\lambda_0/\lambda_c)^2}}{\lambda_0}, \tag{9}$$

where λ_c is the cutoff wavelength of the dominant mode, and λ_0 is the free space wavelength.

For broadband operation the differential phase shift ϕ must remain approximately equal to 90° throughout the entire frequency spectrum of interest. The effective dielectric constants ϵ_1 and ϵ_2 are not directly computable and hence the length 6 can only be calculated by finding the propagation constants for the two orthogonal waves E_1 and E_2. In order to do this one must solve a transverse eigen-value equation for each wave which is due to the boundary conditions at the dielectric-air interfaces. Such a calculation has been made for a polarizer in square guide, and it has been found experimentally that the results hold good in a circular guide having the same cut-off frequency as that of the square guide.

Consider two orthogonal H-waves propagating in the Z direction in a partially dielectric-filled square guide (Fig. 7), E and H being of the form:

$$E = E_0 e^{j(\omega t - \beta z)}, H = H_0 e^{j(\omega t - \beta z)}, \text{ and } E_Z = 0.$$

E_y is assumed to be continuous over the air-dielectric media I and II and dielectric-air media II and III. The phase shift for the com-
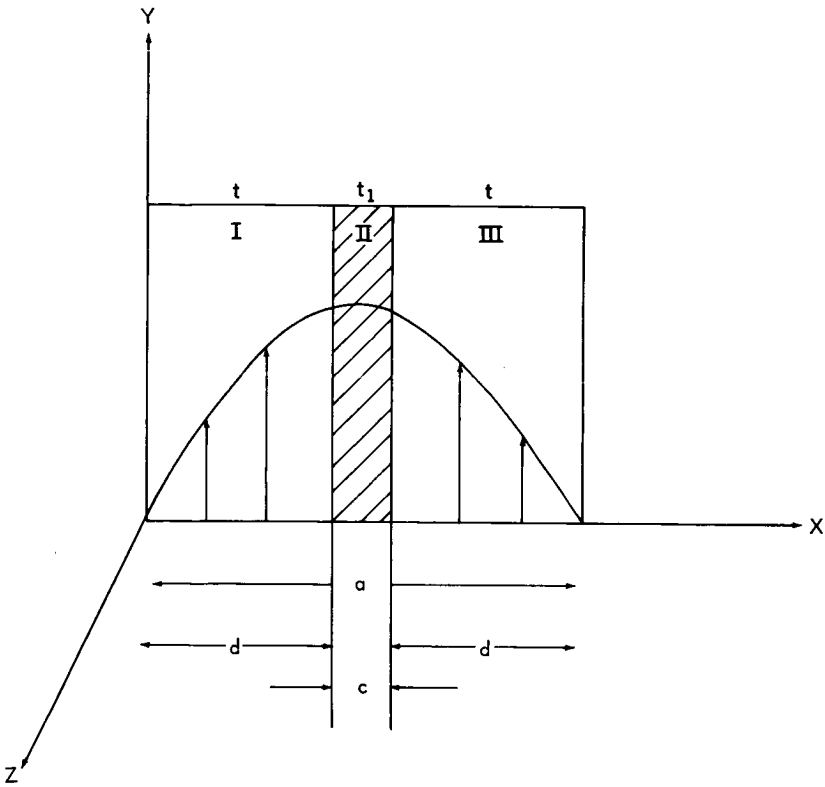
Fig. 7 — Partially dielectric-filled waveguide.

ponent of the circularly polarized wave which travels parallel to the plane of the dielectric wedge is:

$$\gamma_2 = \sqrt{ k^2 - (\rho/d)^2 }, \tag{10}$$

where
$$k = \frac{2\pi}{\lambda_0}$$

$$\frac{\tan \rho}{\rho} = \frac{s}{d} \cdot \frac{\cot q}{q}, \tag{11}$$

where ρ and q are unknown and $s = C/2$.

It has been shown[5] that ρ and q satisfy the following equation:

$$\left(\frac{p}{d} \right)^2 = k^2 - \beta^2 ; \left(\frac{q}{s} \right)^2 = K\, k^2 - \beta^2, \tag{12}$$

where $K = \epsilon_1/\epsilon_0$; therefore

$$q = s\sqrt{k^2\,(K-1)\,+\,(\rho/d)^2}. \tag{13}$$

A similar analysis can be made for the perpendicular component but in view of the fact that the thickness of the dielectric wedge is considerably smaller than the length it can be assumed that the phase shift for the perpendicular component is

$\gamma_1 = \dfrac{2\pi}{\lambda_g}$ per unit length where λ_g is air-filled guide wavelength.

The following parameters were used for computation of the differential phase shift ϕ (see Equation 8):

$$f = 4170 \text{ Mc/s};$$
$$a = b = 1.75 \text{ in.};$$
$$c = 0.125 \text{ in.};$$
$$s = \frac{C}{2} = 0.0625 \text{ in.};$$
$$d = 0.8125 \text{ in.}$$

For a dielectric consisting of $PTFE$ $K = 2.01$ and $k = \dfrac{2\pi}{\lambda_0} = 0.873$ radian.

Solution of ρ is obtained from Equations 11 and 13:

$$y = \frac{\tan\rho}{\rho} = \frac{s}{d}\cdot\frac{\cot q}{q};$$
$$\rho = 73.2° = 1.27 \text{ radian.}$$

Therefore

$$\gamma_2 = \sqrt{\left(\frac{2\pi}{\lambda_0}\right)^2 - \left(\frac{\rho}{d}\right)^2} = 0.615 \text{ radian/cm},$$

$$\gamma_1 = \frac{2\pi}{\lambda_g} = \frac{2\pi}{12.2} = 0.515 \text{ radian/cm; and}$$

$$\phi = \gamma_2 - \gamma_1 = 0.1 \text{ rad/cm} = 14.6°/\text{inch.}$$

According to the above calculation the required length of the dielectric wedge is approximately 6.2 in. However, the preceding calculation does not take into account the effect of tapering, and this is difficult to allow for precisely. In order to determine the shape of the wedge (Fig. 8) the following procedure has been adopted.
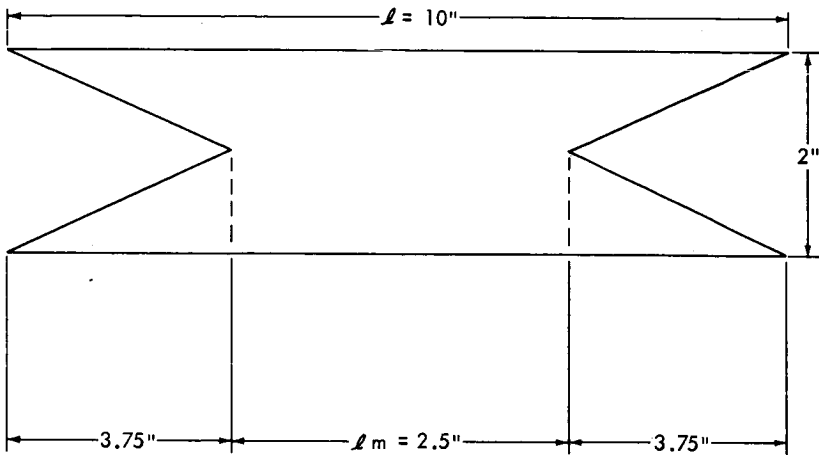
Fig. 8 — Dimensions of the polarizer.

Assuming a length of the wedge $= 6$ in., then the

minimum tapered length 0.75 λ_g at 4170 Mc/s $= 3.75$ in.,

diameter of the circular guide $= 2$ in.,

mid-section length of the wedge $6_m = (l - 7.5)$ in.

The overall effective area of the wedge is:

$$(6 \times 2) -7.5 = 12.4$$

$$6 = 9.95 \text{ inches.}$$

Based on the foregoing, a wedge was prepared with an overall length of 10 inches and 3.75 inches tapered length; the measured ellipticities were found to be better than 0.8 over the band 4 to 6.5 Gc/s.

The *PTFE* wedge is held in position inside the 2-in. circular guide by means of eight dielectric pins penetrating slightly into the narrow dimension of the wedge. These dielectric pins are in turn sealed by thin metal sleeves.

Dispersion in Dielectric Plates

In general the thicker plates have better dispersion characteristics but the discontinuity introduced by a $\frac{1}{4}$-in. thick plate is sufficient to cause generations of higher order modes at the transmitting frequency (6.39 Gc/s), and a $\frac{1}{8}$-in. thickness has therefore been used. This overcomes the difficulties due to overmoding but increases dis-

persion, the differential phase shift then being no longer constant over the required bandwidth. This has led to the investigation of means for providing compensation for dispersion.

Chu[6] has shown analytically that a slightly distorted circular guide can propagate two distinct transverse electric modes along the two axes of the ellipse. These two modes are usually known as the odd transverse electric (OH_1) and the even transverse electric (EH_1) waves. If a small section of elliptic guide (slightly distorted circular guide) is used in tandem with the polarizer and by giving proper orientation of the axes of the elliptic guide with reference to the dielectric plate it is possible to give slightly different phase velocities to the two orthogonal components of the circularly polarized wave.

The values of relative phase difference between the even and the odd mode in elliptic guide have been calculated for various values of δ. Ellipticities better than 0.9 over the band 4 to 7 Gc/s have been obtained (Fig. 9) using the elliptical guide compensating section in tandem with the dielectric plate polarizer.

The loss of the polarizer comprises two parts, i.e. loss due to dielectric absorption and loss due to imperfect circularity of polarization, the noise temperature due to the polarizer being about 1.5°K.
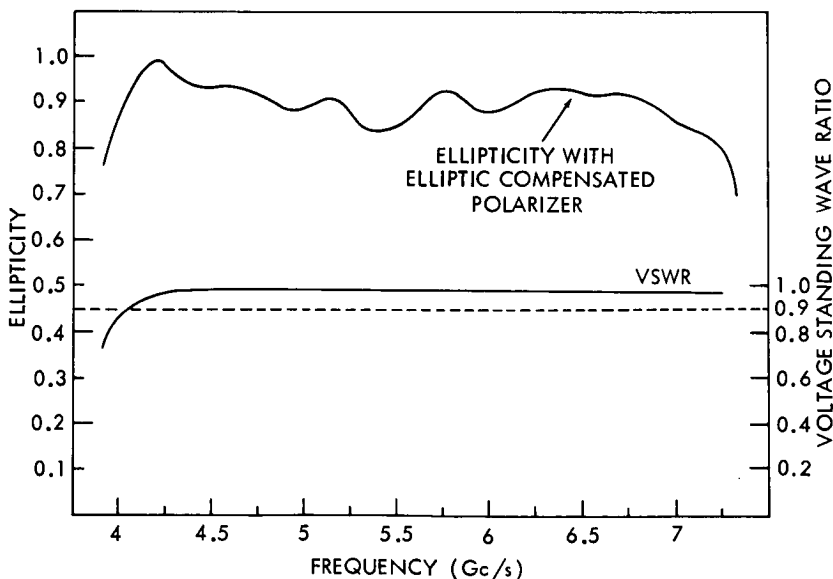

Fig. 9 — Polarizer characteristics.

Establishment of Field Vectors

Returning to the question of establishing two orthogonal fields for the transmitted and received signal (E_t and E_γ, Fig. 2b), consider the situation where the received signal from the aerial is to be right-handed circularly polarized and the transmitted signal into the dish aerial is to be left-handed. In both cases the component with suffix 2 (Fig. 10) is phase delayed. The polarizing section must then be oriented with reference to the transmit field electric vector E_t (Fig. 10a) while the received field electric vector $E_{\gamma 2}$ (Fig. 10b) is delayed by 180° with respect to $E_{\gamma 1}$, the resultant E_γ then being orthogonal to E_t.
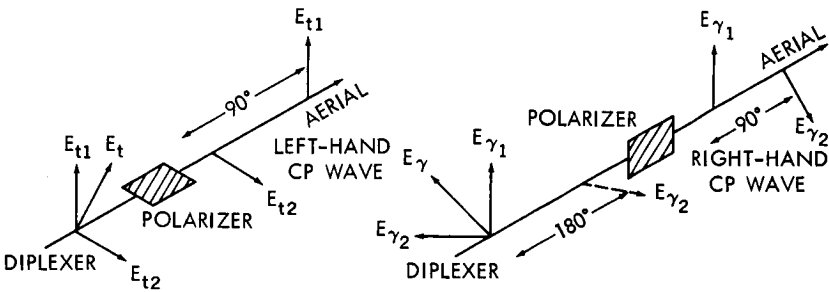

Fig. 10 — Establishment of two orthogonal fields at the diplexer.

CONCLUSION

The diplexer and the broadband polarizer system described have been successfully used in the Goonhilly Earth Station installation for tests with the Telstar satellite.

A slightly modified version has been used in a combined feed assembly to provide communication via both Telstar and Relay satellites; in this modified version of the diplexer the transmitter power (1.7 Gc/s) for Relay propagates through a 5-inch circular waveguide enclosing the 2-inch waveguide diplexer used for Telstar. This combined feed assembly is described in detail in a companion paper.*

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