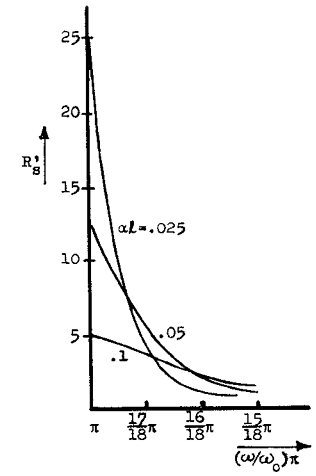


Fig. 3—Relative power dissipation measured by $R_s'$ vs frequency $\omega$, for various values of the loss parameter $\alpha l$.

hence, the Fig. 3 behavior in no way contradicts the behavior of $Q$ with loss and frequency.

A properly designed lossy slot will not have the relative power dissipation so large at the slot resonant frequency $\omega_0$ that sufficient power will dissipate within the pass band to interfere with operation there. Nor should it be so small that sufficient residual power remains to start oscillation. One design procedure is the following:

1) Decide from a calculation of power flow across the coupling holes how much relative power $P_d/|V_c|^2$ is to be dissipated per cavity. Convert this to the equivalent circuit relative dissipation by

$$\begin{aligned} P_d'/|V_c'|^2 &= (P_d/k_\pi^3\tau)(k_\pi^2/|V_c|^2) \\ &= (P_d/|V_c|^2)(1/k_\pi\tau). \end{aligned} \tag{14}$$

($V_c$ is the amplitude of electric field in volts/meter.)

2) Choose a loss parameter

$$\alpha l = (\omega\mu l/2k)(L_0/\mu)(G/d)$$

from Fig. 3 for the desired power dissipation bandwidth about the half-wavelength frequency $\omega_0$ of the slot. This expression involves two parameters: $(L_0/\mu)$, the slot transmission line inductance/unit length along the long axis divided by $\mu$, and $(G/d)$, the ratio of the lossy surface conductance presented to the slot divided by the gap length in Fig. 1.

3) From the known parameters $k_\pi$; $H_{cx}$ at the slot; $\omega\mu$; $l$, the slot length; and $\tau$, the cavity volume, choose $(L_0/\mu) \cong (d/h)$ from (10b) and (12) for sufficient relative power dissipation at frequency $\omega_0$.

4) Return to the expression for $\alpha l$ in 2) and, with $L_0/\mu$ now known, determine $G/d$.

We shall see next that the relative power dissipation at $\omega_0$ tends to be unduly large unless $L_0/\mu \cong d/h$ of the slot is designed rather small.

Some numerical results now follow. Suppose we have the parameters

$$\text{cavity}\begin{cases} k_\pi = 75 \sim 3.6 \text{ kmc} \\ H_{cx} = 1.1^2 \\ l = 4.15 \times 10^{-2} \text{ meter} \\ \tau = 12.2 \times 10^{-5} \text{ meter}^3 \end{cases}$$

$$\text{beam}\begin{cases} \text{radius } 1/4 \text{ inch} \\ \text{current } 50 \text{ amperes} \\ \text{voltage } 100 \text{ kv.} \end{cases}$$

We estimate from the gain per cavity of the small-signal growing wave, which exists for synchronism of the slow space charge mode with the "cold" circuit near the $\pi$-cutoff, a value of $P_{\text{flow}}/|V_c|^2$ of $6.8\times10^{-7}$. Let us dissipate this amount of relative power through the slot, so that $P_d/|V_c|^2$ has this value. We choose $\alpha l = 0.025$ in Fig. 3 so that the slot dissipation will be effective over 10° or so, corresponding to $\Delta f = 0.2$ kMc. From (14) we get $P_d'/|V_c'|^2 = 7.5\times10^{-5}$. Then, from (13) we find $(L_0/\mu) \cong d/h$ to be about 0.052. This value is impractically small but we can insert a lossy slot into every fifth cavity of the chain and dissipate five times the relative power in that cavity. Then $d/h$ becomes about 0.26. From (13b) for $\alpha$ we get a value of $G/d$ of about $1\times10^{-2}$. For a $\frac{1}{32}$-inch-wide slot, $G = 10^{-5}$ mho per unit surface area.

Despite the critical nature of the relative power dissipation and the loss bandwidth upon $G$, the idea of lossy slot coupling for combating undesirable cutoff oscillations looks promising.

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[2] $\overline{H}_c$ is easily estimated from the formula for $\overline{H}_c$ of the $TM_{010}$ mode of a closed cylindrical cavity, satisfying (6). It is $i_\phi\sqrt{3.7}J_1(k_1r)$, where $k_1 = 2.4/$(cavity radius).

## Authors' Comment*

The idea suggested by Bevensee for coupling energy out of a periodic system by a means which is effective only over a narrow pass band is one of many possibilities which have been considered in this Laboratory. Another alternative, described by Rynn,[3] for instance, involves the use of another propagating structure which is itself lossy and which is coupled to the main structure. In this case, conditions are arranged for the phase velocities of the two structures to be equal over only the narrow oscillation pass band.

A note of caution should be introduced. It will be realized from our analysis that a long slot is capable of presenting a large impedance over a wide frequency band. Consequently, if additional slots are cut into every fifth cavity of the system, as Bevensee suggests, there is the strong possibility that new stop bands will be introduced in the region of $\pi/5$, $2\pi/5$, $3\pi/5$, and $4\pi/5$ phase shift between cavities, and cutoff oscillations may occur at the corresponding frequencies. The introduction of extra resonant elements in an already complicated propagating system can sometimes hinder rather than help.

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## Broad-Band Hybrid Junctions*

A coaxial version of the wide-band stripline magic T described by E. M. T. Jones in the March, 1960 issue of these Transactions was developed jointly at the Mullard Research Laboratories and the Laboratories of the General Electric Company, England, some years ago. It has proved a powerful component in the design of broad-band receiver circuits and has the advantage of small size and geometrical symmetry in addition to wide frequency coverage.

In particular, the circuit has been used in broad-band balanced mixers, balanced modulators, single side-band modulators, limiters and isolating power splitters. In each case, the property of a 180° hybrid, by which isolation is independent of the value of two balanced terminating impedances, gives the device advantages over the more usual broad-band 90° hybrid circuits. Mullard balanced mixers type L361 ($S$-band) and L360 ($X$-band) are examples of the commercial application of the circuit.

Devices have been successfully operated in the frequency range 1.0–11.5 kMc, and for many applications it has proved convenient to divide this range into five overlapping bands.

The simplest embodiment of the hybrid is used, in which one arm contains a shorted coupled line filter section and the other three arms are simple lines for which $\theta = \pi/2$ at midband. In this case, one set of conditions for satisfactory operation is

$$Z_1 = Z_2 = 0.71Z$$

and

$$Z_{oo} = Z_{oe} = 1.33Z,$$

whence

$$\theta = \beta = \frac{\pi}{2}$$

at midband, where

$\theta$ = the electrical length of the three similar arms,
$\beta + \pi$ = the electrical length of the filter section,
$Z$ = the characteristic impedance of the three similar arms,
$Z_{oo}$ = the characteristic impedance of the unbalanced mode,
$Z_{oe}$ = the characteristic impedance of the balanced mode,
$Z_1 = Z_2$ = the hybrid terminating impedances.

Circuits with open-coupled line sections and other systems of compensation have not justified the additional mechanical complexity. Moreover, the basic circuit has the advantage of superior isolation symmetry between the various terminals. If an attempt is made to recover this symmetry by compensating all three remaining arms, instead of one as described, extremely broad-band isolation characteristics can be obtained, but the input match of the device suffers.

Typical theoretical and experimental performance figures for the basic circuit over

* Received by the PGMTT, August 8, 1960.

the octave range $60° < \theta < 120°$ are shown in Table I.

TABLE I

| | Theoretical | Experimental |
|---|---|---|
| Isolation | >22 db | >18 db |
| Input Match | <1.5:1 | <1.4:1 |

The performance figures observed from the four possible input terminals are similar over this frequency range.

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[2] Mullard Ltd., S. J. Robinson, and N. E. Goddard, British Patent Application no. 770317.
[3] A. B. McNaughton, "A new broad-band coaxial hybrid ring," *Proc of the Internatl. Congress on Ultra High Frequency Circuits and Antennas*, Paris, France; October, 1957.

## Lightweight $Y$-Junction Strip-Line Circulator*

In a recent issue, the practical realization of a $Y$-junction strip-line circulator was described[1] which used disks of yttrium iron garnet located at the junction of the $Y$, magnetically biased above resonance at approximately 2200 gauss. By using a material with a lower saturation magnetization (magnesium, manganese, aluminum ferrite, $4\pi M_s = 600$) we have reduced the bias field required to approximately 190 gauss for frequencies in the 2-kMc range and to approximately 800° gauss for frequencies in the 1-kMc range, thus reducing considerably the weight of the circulator. If the circulator is to be operated as a switch, the reduced field requirements permit faster switching times or, for a given switching time, a considerable reduction in power supply requirements.

Fig. 1 shows the results of a circulator operating at a fixed magnetic bias of 190 gauss. Although no attempt was made to determine the optimum ferrite diameter for this frequency range, it is felt that the performance of the circulator would be improved if a more optimum diameter were used.

Below 1400 Mc, the performance of the circulator was degraded at these low biasing fields, but by reversing the polarity of the magnetic field and biasing above resonance, good circulator action could again be obtained. Reversing the biasing field and biasing above resonance does not change the direction of circulation, as may be seen by referring to the equation below given by Auld[2] for the change in the $a$th eigenvalue ($\delta s_a$) of the scattering matrix of the symmetrical $Y$-junction due to the application of the magnetic biasing field. The magnetic biasing field splits the reciprocity degeneracy of the eigenvalues to give circulator action:

$$\delta s_a = -j\frac{b}{2\omega\mu_u^2}\sum_{p=-\infty}^{\infty} A_{-p}^{(-a)}A_p^{(a)} \cdot \left\{(\mu-\mu_u)\int_0^R f_{-p}^{(-a)}\cdot f_p^{(a)}rdr + j\kappa\int_0^R k\cdot f_{-p}^{(-a)}\times f_p^{(a)}rdr\right\} a\neq 0$$

where $\mu$ and $\kappa$ are the components of the peameability tensor and the other symbols are as defined by Auld.[2]

A typical variation of $\mu$ and $\kappa$ as a function of magnetic field is shown in Fig. 2. The magnetic biasing field is adjusted to make $\mu - \mu_u = 0$ either above or below resonance. Since $\kappa$ reverses sign above resonance, there is a reversal in the direction of circulation, but by reversing the biasing field, the direction of circulation remains the same. Fig. 3 shows the characteristics of a circulator biased above resonance but still only requiring a magnetic field of 820 gauss. Here again it is felt that the performance would be improved if ferrites of optimum diameter were used. Thus by using a material with a lower saturation magnetization than yttrium iron garnet, bias field requirements are reduced with a consequent reduction in weight of the circulator.

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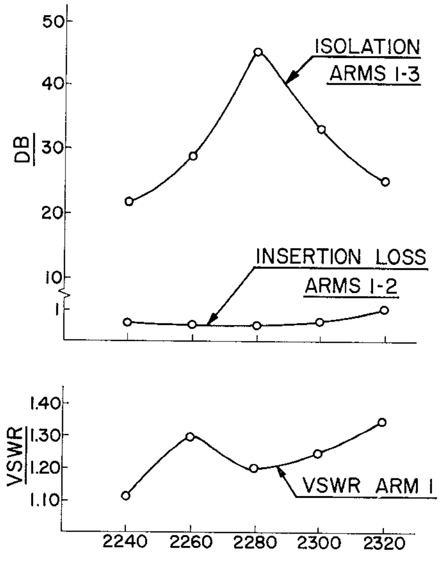


Fig. 1—Circulator characteristics with fixed dc magnetic bias; $H_{DC} = 190$ gauss.

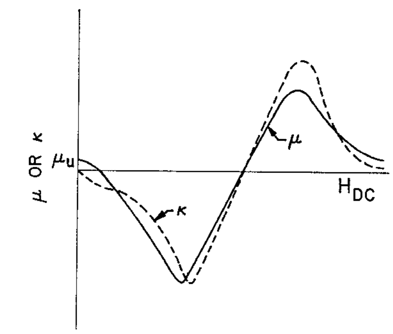


Fig. 2—Typical variations of real components of tensor permeability as a function of dc magnetic field.

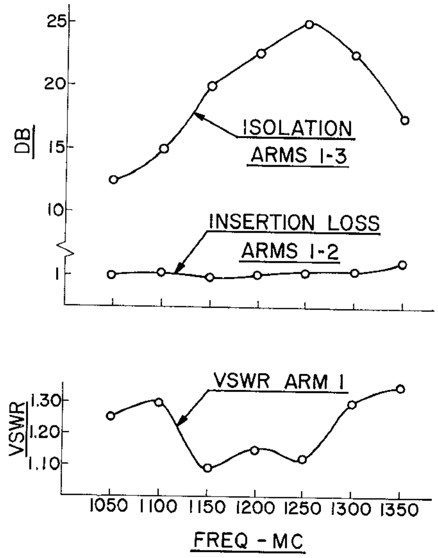


Fig. 3—Circulator characteristics with fixed dc magnetic bias; $H_{DC} = 820$ gauss.

* Received by the PGMTT, August 15, 1960.

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## A Novel Broad-Band Balun*

Broad-band baluns have recently become the subject of renewed interest, particularly those suitable to couple spiral or planar log periodic antennas to the commonly used coaxial lines.[1–3]

To make such a balun capable of operating over the frequency band of 1000–4000 Mc and to take advantage of the strip transmission line techniques, the broad-band

* Received by the PGMTT, September 6, 1960.

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[3] J. W. McLaughlin, D. A. Dunn, and R. W. Grow, "A wide-band balun," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 314–316; July, 1958.