The Marconi Review

117 2nd QUARTER 1955 Vol. XVIII

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THE MARCONI REVIEW

No. 117. Vol. XVIII *2nd Quarter, 1955.*

Editor: L. E. Q. WALKER, A.R.C.S.

THE DESIGN OF A ZONED DIELECTRIC LENS FOR WIDE ANGLE SCANNING

BY D. H. SHINN, M.A., Ph.D.

In the following article formulæ are presented for the design of a radio lens with a spherical outer surface; a numerical example is given.

The effect of " shadows " due to steps on the lens surface is discussed.

Introduction

THE most convenient way of scanning when using a radio lens is to move the feed sideways from the focus of the lens. This causes the beam to deteriorate; it is important to design the lens so that this deterioration is as small as possible. It is well known[1] that, in order to achieve this, the lens should be approximately spherical with its focus at the centre of the sphere.

In practice one of the surfaces of the lens is made spherical, the mean shape of the other surface being made approximately spherical by " stepping." If the inner surface is made spherical, then the rays emanating from the focus pass undeviated through this surface. The outer surface must then be designed to refract the rays so that they are parallel to the axis. The design of such a lens, as of any lens where refraction takes place at one surface only, is a comparatively easy matter.

Such a lens has been made, and its electrical properties are very satisfactory. However, the fact that steps have to be made on the outer surface of the lens is unattractive, since the stepped profile may collect snow, ice, dust, etc., and would require radome protection. The alternative of making the outer surface spherical and stepping the inner surface was suggested by Mr. J. F. Ramsay. This provides a thin lens which does not require radome protection.

This article deals with the design of such a lens. The general principles of the method of design are given by Silver.[2] Steps on the inner surface affect the aperture field of a lens in a different way from steps on the outer surface. This matter is discussed in an Appendix.

The Design of the Lens

In Fig. 1, O is the focus of the lens. The front surface of the lens, QABC, is a portion of a sphere centre O. P is a point on the back surface of the lens. A ray passing through the lens follows the path OPBM. AL is the tangent to the front surface at A. R, the radius of the sphere, may conveniently be called the focal length of the lens.

At the front surface the angle of incidence in the lens is β and the angle of refraction α.

Hence

$$\sin \beta = \frac{1}{\mu} \sin \alpha. \tag{1}$$

The optical path length from O to L is p, where

$$p = l + \mu t + R\,(1 - \cos \alpha). \tag{2}$$

This must be a constant (plus or minus an integral number of wavelengths) for all values of α.

Also

$$l = \sqrt{R^2 + t^2 - 2Rt \cos \beta}. \tag{3}$$

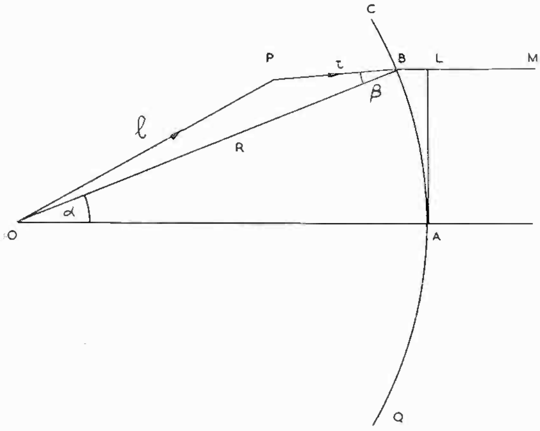


Fig. 1

Equations (1), (2) and (3) are sufficient to determine t when α is given, apart from an arbitrary constant. In order to determine this constant, it is necessary to start from some defined point on the back surface of the lens. We will suppose that this is the point at the edge of the lens and is given by $\alpha = \alpha_0$, $t = t_0$. α_0 is equal to $\sin^{-1}(1/2F)$, where F = focal length/aperture; t_0 is the minimum thickness of the lens, which is determined from mechanical considerations.

As α decreases, so t increases. Eventually a point is reached where a reduction of the optical path length by one wavelength would cause the thickness to be reduced to t_0. At this point a step is made in the back surface of the lens, so that the thickness is in fact reduced to t_0. As α decreases further, t increases again, and the process is repeated until the centre of the lens is reached. The values of α at the steps are given approximately by

$$\cos \alpha_n = \cos \alpha_0 + \frac{n\lambda}{R}\left(1 - \frac{t_0}{\mu^2 R}\,\frac{\cos \alpha_0}{\cos \beta_0}\right) \tag{4}$$

If the equation (4) is used to find α_n, the value of t corresponding to α_n will not be exactly equal to t_0, but it will differ only slightly. In fact, this equation is sufficiently accurate for the design of lenses. Its derivation, together with that of equations (5), (6), (7) and (9), is given in Appendix I.

If we wish to arrange that the thickness at the middle of the lens is equal to the maximum thickness elsewhere we must arrange that one of the $\cos \alpha_n$ is unity. This may be done by altering R slightly. If then $\cos \alpha_r$ is unity, the lens will contain r zones.

The equation determining t in terms of α is

$$t = \frac{k + R \cos \alpha - n\lambda}{\mu - \cos \beta} \tag{5}$$

where

$$k = -R \cos \alpha_0 + t_0 (\mu - \cos \beta_0) \tag{6}$$

This equation for t is approximate. A more accurate value of t is given by

$$t = \hat{t} + \frac{t_0^2 \sin^2 \beta_0 - \hat{t}^2 \sin^2 \beta}{2R (\mu - \cos \beta)} \tag{7}$$

where $\hat{t}$ is the value of t given by equation (5). It is necessary to use equation (7) only for thick lenses or lenses of wide angle. Otherwise equation (5) will suffice.

By using one of these equations together with equation (4) we can obtain sufficient information to draw the lens contour. The surface must everywhere be calculated to an accuracy $\frac{\lambda}{36 (\mu - 1)}$. The accuracy in the path length is then 10°. Subject to this condition it is possible to approximate to the centre zone by a portion of a sphere. It may be possible to approximate to the other zones by portions of cones; if not, portions of spheres will certainly suffice. In the first lens designed from these equations it was found that the maximum error in path length due to taking the second zone to be conical was about 5°. The maximum error due to taking the central zone to be spherical rather than its true shape was about 0·2°.

The back surface of the lens should be stepped in the vicinity of $\alpha = \alpha_n$ so that the line along the step is the external bisector of $\angle$ OPB in Fig. 1. This reduces as far as possible the effect of shadows at the steps.

The second order term in equation (7) has a maximum value either when t reaches its first maximum value, or possibly when $\beta = 0$. These two values should be calculated; if they are both small, second order terms may be neglected throughout.

Method of Computation

t_0, α_0, μ, R, and λ, are given

(*a*) Find α_n from equation (4) for $n = 1, 2. \ldots$.
Adjust R if necessary so that one of the $\cos \alpha_n$ is equal to unity. Let this be $\cos \alpha_r$. Then the lens will consist of r zones (i.e., a central zone and $(r - 1)$ outer zones).

(*b*) Find k from equation (6).

(*c*) For each α_n find β_n from equation (1) and hence t from equation (5). Find also t', which is obtained from equation (5) with $(n - 1)$ substituted for n.

(*d*) Find t for $\alpha = 0$, and a point about midway between $\alpha = \alpha_{r-1}$ and $\alpha = \alpha_{r-2}$.

(*e*) Find the second order term in equation (7) for $\alpha = \alpha_1$, $n = 0$; and for $\alpha = 0$. If these terms are negligible pay no further attention to second order terms. If they are not negligible corrections must be made to all the t's so far calculated.

(*f*) For each t and t' check from equations (2) and (3) that the optical path lengths are the same to the required order of accuracy, apart from multiples of a wavelength.

(*g*) For each t and t' find

$$\left.\begin{aligned} x_n &= R\cos\alpha_n - t\cos(\alpha_n - \beta_n) \\ y_n &= R\sin\alpha_n - t\sin(\alpha_n - \beta_n) \\ \zeta_n &= R\cos\alpha_n - t'\cos(\alpha_n - \beta_n) \\ \eta_n &= R\sin\alpha_n - t'\sin(\alpha_n - \beta_n) \end{aligned}\right\} \tag{8}$$

(*h*) The first three of these points are shown in Fig. 2. The point T is given by

$$(-x_0 q_1 + \zeta_1 (q_1 + 1), -y_0 q_1 + \eta_1 (q_1 + 1))$$

where $q_1 = \dfrac{\mathrm{RT}}{\mathrm{RQ}}$ The value of q_1 can be found from the co-ordinates of Q, R, and U, but it is easier to find it from approximate formula

$$\frac{q_1}{1 + q_1} = \frac{(t'_1 - t_1)\sin\beta_1}{R\sin(\alpha_0 - \alpha_1)} \tag{9}$$

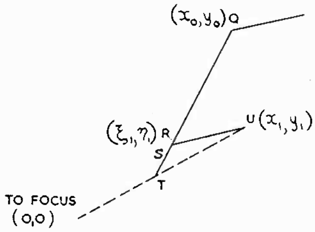


FIG. 2

q is the ratio of the "shadow" area to the correctly illuminated portion. It should not be allowed to exceed about 0·3.

Calculate also q_{r-1}. The values of q between q_1 and q_{r-1} can be found by interpolation. The point S, (ζ', η'), is given by

$$\left\{\zeta', \eta'\right\} = \left\{-x_0\frac{q_1}{2} + \zeta_1\left(\frac{q_1}{2} + 1\right), -y_0\frac{q_1}{2} + \eta_1\left(\frac{q_1}{2} + 1\right)\right\} \tag{10}$$

The step should be made along US.

We now have sufficient information to draw the lens contour. Three points which we have found on the centre zone determine a sphere. The next zone may also have to be a portion of a sphere. The other zones will be portions of cones. The surface must everywhere be positioned to an accuracy $\dfrac{\lambda}{36(\mu - 1)}$. The maximum error in the path length is then $\dfrac{1}{36} \times 360° = 10°$.

Example of Computation. Polyethylene Lens for $\lambda = 8{\cdot}6$ mm.

$t_0 = 0{\cdot}625$ in., $\sin\alpha_0 = \dfrac{1}{3}$, $\mu = 1{\cdot}515$, $R = 36$ in., $\lambda = 0{\cdot}3385$ in.

$$\cos\alpha_n = \cos\alpha_0 + \frac{\lambda n}{R}\left(1 - \frac{t_0\cos\alpha_0}{R\mu^2\cos\beta_0}\right) \tag{4}$$

$$\cos\alpha_0 = 0{\cdot}942809, \quad \sin\beta_0 = \frac{1}{4{\cdot}545} = 0{\cdot}2200$$

$$\cos\beta_0 = 0{\cdot}9755$$

$$\frac{t_0 \cos \alpha_0}{R\mu^2 \cos \beta_0} = 0{\cdot}0073106$$

$$\frac{\lambda}{R}\left(1 - \frac{t_0 \cos \alpha_0}{R\mu^2 \cos \beta_0}\right) = 0{\cdot}00933404$$

Hence $\alpha_5 = \cos^{-1} 0{\cdot}98948$

$\alpha_6 = \cos^{-1} 0{\cdot}99881$

$\alpha_7 = \cos^{-1} 1{\cdot}00815$

Here α_6 is near enough to zero (it is 2° 48′). The central zone will extend from $\alpha=0°$ to $\alpha=\alpha_5$. (If we wish to make α_6 exactly zero we must take $R=35{\cdot}25$ in.)

$$k = (\mu - \cos \beta_0)\, t_0 - R \cos \alpha_0$$

$$\therefore \quad k = -33{\cdot}6039$$

TABLE I

n	0	1	2	3	4	5	(5)
s α_n	942809	952143	961477	970811	980145	989479	1
ı α_n	33333	30565	27489	23985	19828	14468	0
ı β_n	2200	2018	1815	1583	1309	0955	0
s β_n	9755	9794	9834	9874	9914	9954	1
$+ R \cos \alpha_n - n\lambda$	3372	3348	3323	3298	3273	3249	7036
$+ R \cos \alpha_n - (n-1)\lambda$ ...		6733	6708	6683	6658	6634	
$- \cos \beta_n$	5395	5356	5316	5276	5236	5196	5150
... ...	6250	6251	6251	6251	6251	6253	13662
... ...	35·3906	35·3880	35·3855	35·3829	35·3804	35·3776	34·6338
$+ \mu t_n - R \cos \alpha_n + n\lambda$ ...	2·3964	2·3964	2·3964	2·3962	2·3962	2·3962	2·3961
... ...		12571	12619	12667	12716	12768	
... ...		34·7697	34·7598	34·7498	34·7398	34·7293	
$+ \mu t_n' - R \cos \alpha_n + (n-1)\lambda$		2·3969	2·3969	2·3967	2·3966	2·3965	
s $(\alpha - \beta)$	9930	9942	9954	9965	9977	9988	1
ı $(\alpha - \beta)$	1177	1073	0958	0831	0683	0495	0
$- x_n$	2·680	2·344	2·009	1·674	1·338	1·003	1·366
... ...	11·926	10·936	9·836	8·583	7·095	5·178	0
$- \zeta_n$		2·973	2·643	2·313	1·983	1·654	
... ...		10·869	9·775	8·529	7·051	5·145	
$(\alpha_{n-1} - \alpha_n)$		·0292		·0363		·0544	
'n		·069	·055	·042	·029	·016	
$- \zeta'$		2·993	2·659	2·326	1·992	1·659	
... ...		10·796	9·711	8·474	7·007	5·114	

he last column in the computation, for a point between α_4 and α_5, has been omitted because of lack of space. this column sin β_n was taken to be 0·1132. The results of the column are $R - x = 1{\cdot}507$, and $y = 6{\cdot}117$.

The following are now tabulated for $n=0, 1, 2, 3, 4, 5$; also for $\alpha=0$ and for a point between $\alpha=\alpha_4$ and $\alpha=\alpha_5$:

(a) $\cos \alpha_n$ from equation (4)

(b) $\sin \alpha_n$

(c) $\sin \beta_n$ from equation (1)

(d) $\cos \beta_n$

(e) $k+R\cos\alpha_n - n\lambda$ (this is a linear function of n)

(f) $k+R\cos\alpha_n - (n-1)\lambda$, except for $n=0$

(g) $\mu - \cos\beta_n$

(h) $\hat{t}_n = \dfrac{k+R\cos\alpha_n - n\lambda}{\mu - \cos\beta_n}$

(i) The second order term $\dfrac{t_0^2 \sin^2\beta_0 - \hat{t}_n^2 \sin^2\beta_n}{2R(\mu - \cos\beta_n)}$, unless it is negligible.

(j) $t_n = \hat{t}_n +$ this term

(k) $l_n = \sqrt{R^2 + t_n^2 - 2Rt_n\cos\beta_n}$

(l) $l_n + \mu t_n - R\cos\alpha_n + n\lambda$

(m) $\hat{t}'_n = \dfrac{k+R\cos\alpha_n - (n-1)\lambda}{\mu - \cos\beta_n}$, except for $n=0$

(n) The second order term $\dfrac{t_0'^2 \sin^2\beta_n - t_n'^2 \sin^2\beta_n}{2R(\mu - \cos\beta_n)}$, unless it is negligible.

(o) $t_n' = \hat{t}_n' +$ this term

(p) $l_n' = \sqrt{R^2 + t_n'^2 - 2Rt_n'\cos\beta_n}$

(q) $l_n' + \mu t_n' - R\cos\alpha_n + (n-1)\lambda$

(r) $\cos(\alpha_n - \beta_n)$, and $\sin(\alpha_n - \beta_n)$

(s) x_n, y_n, ζ_n and η_n from equations (8)

(t) $\sin(\alpha_n - \alpha_{n+1})$

(u) q_n from equation (9)

(v) ζ' and η' from equation (10)

These quantities are tabulated in Table I. The maximum value of the second order term (equation (7)) is 0·0012 in.; it has therefore been omitted.

From the coordinates (x_4, y_4), (ζ_5, η_5), and those of the point between them we can find how far the middle point lies from the straight line joining the other two. In this case it is 0·010 in. The maximum allowable error is $\dfrac{\lambda}{36(\mu-1)} = 0{\cdot}018$ in. It is therefore permissible to make the second zone a portion of a cone.

The first zone is a sphere whose radius can easily be calculated from (x_5, y_5) and $(x_6, 0)$ the coordinates of the point where $\alpha=0$, i.e. the point on the axis. The radius of the sphere is 37·1 in. The error in the position of the back surface due to the assumption that it is a sphere rather than its correct shape can be shown to be about $\dfrac{(x_5 - x_6)^3}{4y_5^2}$. This is 0·0004 in., which is very small.

The profile of the lens is shown in Figure 3, and a photograph in Figure 4. The scanning performance of this lens is described in Reference 3.

Constructional and Electrical Tolerances

It may be shown that each of the errors in Table II causes a maximum phase error of $+36°$, i.e., $\lambda/10$.

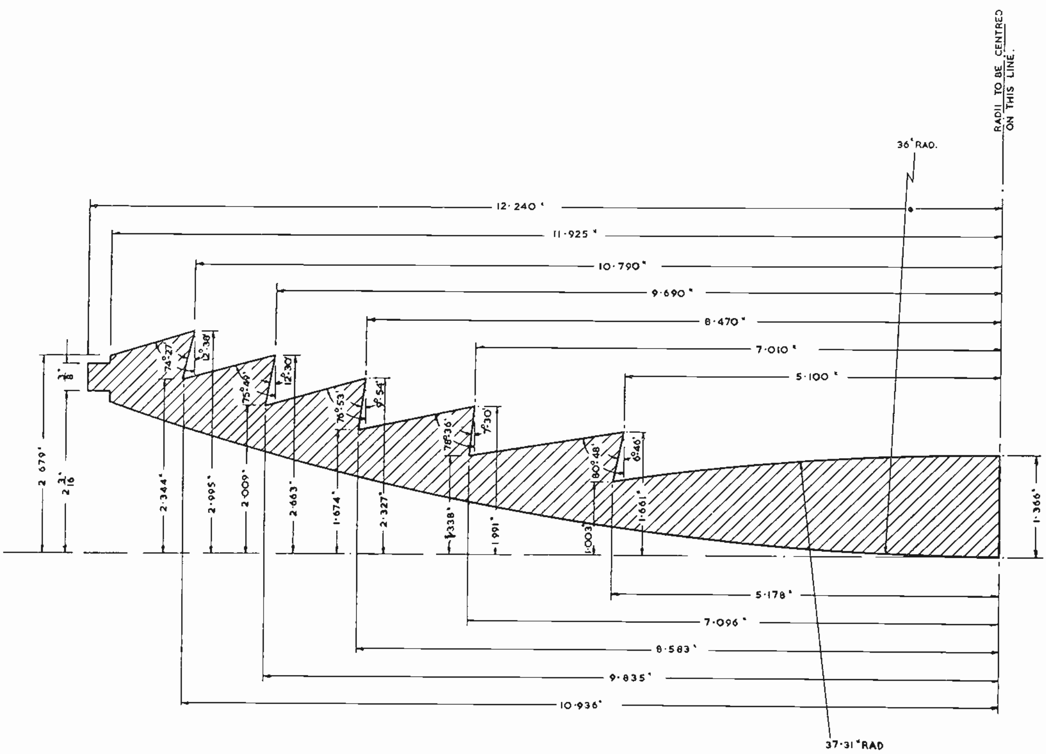

RADII TO BE CENTRED ON THIS LINE.
36" RAD.
12·240"
11·925"
10·790"
9·690"
8·470"
7·010"
5·100"
2·679"
1·366"
5·178"
7·096"
8·583"
9·835"
10·936"
37·31" RAD

FIG. 3

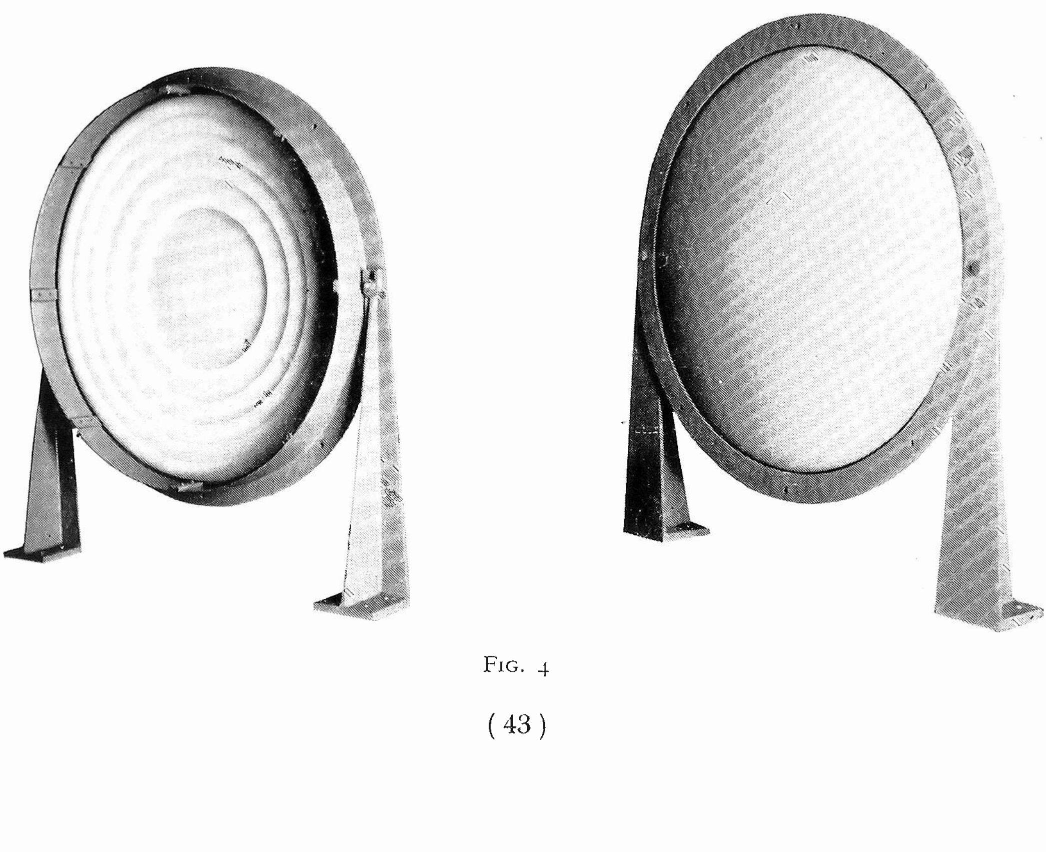


FIG. 4

TABLE II

Quantity	Error when $F = 1$	Error when $F = 1{\cdot}5$	Error in the above Example
Focal length	$-\ 0{\cdot}5\lambda$	$-\ 1{\cdot}65\lambda$	$-\ 0{\cdot}559$ in.
Thickness	$\dfrac{\lambda}{10\ (\mu - 1)}$	$\dfrac{\lambda}{10\ (\mu - 1)}$	0·066 in.
Diameter	$0{\cdot}34\lambda$	$0{\cdot}56\lambda$	0·190 in.
Axial dimension at edge of lens	$-\ 0{\cdot}5\lambda$	$-\ 1{\cdot}65\lambda$	$-\ 0{\cdot}559$ in.
Dielectric constant ...	$\dfrac{\mu - 1}{10}$	$\dfrac{\mu - 1}{10}$	0·052
Wavelength	$-\dfrac{0{\cdot}8\lambda^2}{R}$	$-\dfrac{1{\cdot}8\lambda^2}{R}$	0·0057 in. (1·7%)

APPENDIX 1

Derivation of Equations (4), (5), (6), (7) and (9)

It will be assumed that $\dfrac{t}{R}$, α and β, are small. All formulae are expanded in series as far as terms of the second order.

From equation (3)

$$l = R - t\cos\beta + \frac{t^2}{2R}\sin^2\beta \tag{A1}$$

Hence, from equation (2)

$$p = 2R - R\cos\alpha + t\ (\mu - \cos\beta) + \frac{t^2}{2R}\sin^2\beta.$$

Now p must be a constant, plus or minus an integral number of wavelengths. Let us put $p = q + 2R - n\lambda$, where q is a constant and n is an integer which is zero at the edge of the lens. Then

$$t\ (\mu - \cos\beta) = q - n\lambda + R\cos\alpha - \frac{t^2}{2R}\sin^2\beta \tag{A2}$$

At the edge of the lens,

$$t_0\ (\mu - \cos\beta_0) = q + R\cos\alpha_0 - \frac{t_0^{\,2}}{2R}\sin^2\beta_0 \tag{A3}$$

From (A2) and (A3),

$$t\ (\mu - \cos\beta) = t_0\ (\mu - \cos\beta_0) - R\cos\alpha_0 + R\cos\alpha - n\lambda + \frac{t_0^{\,2}}{2R}\sin^2\beta_0 - \frac{t^2}{2R}\sin^2\beta \tag{A4}$$

Hence equations (5), (6) and (7) may be deduced.

In order to deduce equation (4) we put $t = t_0$, $\alpha = \alpha_n$ and $\beta = \beta_n$, in equation (A4). This leads to

$$n\lambda = R(\cos\alpha_n - \cos\alpha_0) + t_0(\cos\beta_n - \cos\beta_0) + \frac{t_0^2}{2R}(\sin^2\beta_0 - \sin^2\beta_n) \qquad \text{(A5)}$$

Neglecting $\frac{t_0}{R}$ we obtain

$$\cos\alpha_n = \cos\alpha_0 + \frac{n\lambda}{R} \qquad \text{(A6)}$$

Also

$$\sin\beta_n = \frac{1}{\mu}\sin\alpha$$

$$\sin\beta_0 = \frac{1}{\mu}\sin\alpha_0$$

$$\cos\beta_n = (1 - \sin^2\beta_n)^{\frac{1}{2}}$$
$$= 1 - \tfrac{1}{2}\sin^2\beta_n - \tfrac{1}{8}\sin^4\beta_n$$

and

$$\cos\beta_0 = 1 - \tfrac{1}{2}\sin^2\beta_0 - \tfrac{1}{8}\sin^4\beta_0$$

therefore

$$\cos\beta_n - \cos\beta_0 = \tfrac{1}{2}(\sin^2\beta_0 - \sin^2\beta_n)\left\{1 + \tfrac{1}{4}(\sin^2\beta_0 + \sin^2\beta_n)\right\}$$
$$= \frac{1}{2\mu^2}(\sin^2\alpha_0 - \sin^2\alpha_n)\left\{1 + \frac{1}{4\mu^2}(\sin^2\alpha_0 + \sin^2\alpha_n)\right\}$$
$$= \frac{1}{2\mu^2}(\cos^2\alpha_n - \cos^2\alpha_0)\left\{1 + \frac{1}{2\mu^2} - \frac{1}{4\mu^2}(\cos^2\alpha_n + \cos^2\alpha_0)\right\}$$

Substituting for $\cos\alpha_n$ from equation (A6), we obtain

$$\cos\beta_n - \cos\beta_0 = \frac{n\lambda\cos\alpha_0}{R\mu^2}\left(1 + \frac{n\lambda}{2R\cos\alpha_0}\right)\left(1 + \tfrac{1}{2}\sin^2\beta_0 - \frac{n\lambda\cos\alpha_0}{2R\mu^2} - \frac{n^2\lambda^2}{4R\mu^2}\right)$$
$$= \frac{n\lambda\cos\alpha_0}{R\mu^2\cos\beta_0}\left(1 + \frac{n\lambda}{2R}\left(1 - \frac{1}{\mu^2}\right) + \text{higher order terms.}\right) \qquad \text{(A7)}$$

Equation (4) follows from (A5) and (A7). In equation (4) the term

$$\frac{n\lambda}{2R}\left(1 - \frac{1}{\mu^2}\right)$$

in (A7) has been neglected. Thus equation (4) produces values of $\cos\alpha_n$ which are slightly greater than they should be. This leads to values of t_n which are also slightly greater than they should be. But, since the maximum error so incurred is generally very small (in Table I it is 0·0003 in.) it does not matter.

In order to deduce equation (9) we note that the point T is given by

$$(-x_0 q_1 + \zeta_1(q_1 + 1),\ -y_0 q_1 + \eta_1(q_1 + 1))$$

Since T lies on the line joining the origin to the point (x_1, y_1)

$$\frac{-x_0 q_1 + \zeta_1 (q_1 + 1)}{-y_0 q_1 + \eta_1 (q_1 + 1)} = \frac{x_1}{y_1}$$

It follows that

$$\frac{q_1}{1 + q_1} = \frac{x_1 \eta_1 - y_1 \zeta_1}{x_1 y_0 - y_1 x_0}$$

From equations (8)

$$x_1 \eta_1 - y_1 \zeta_1 = R\,(t_1' - t_1) \sin \beta_1$$

$$\begin{aligned} x_1 y_0 - x_0 y_1 = R^2 \sin (\alpha_0 - \alpha_1) \\ - 2Rt \sin \left(\alpha_0 - \alpha_1 - \frac{\beta_0 - \beta_1}{2}\right) \cos \left(\frac{\beta_0 + \beta_1}{2}\right) \\ + t_1^2 \sin (\alpha_0 - \alpha_1 - \beta_0 + \beta_1). \end{aligned}$$

If $\frac{t}{R}$ is small, the second and third terms in this expression may be neglected; it follows that

$$\frac{q_1}{1 + q_1} \doteq \frac{(t'_1 - t_1) \sin \beta_1}{R \sin (\alpha_0 - \alpha_1)}$$

APPENDIX 2

'Shadows due to Steps'

Figure 5 shows a portion of a lens stepped on the front surface, Figure 6 a portion of a lens stepped on the back surface. It is clear that the shaded areas are "shadows," i.e., no ray within them proceeds correctly from the focus to infinity. But it is also

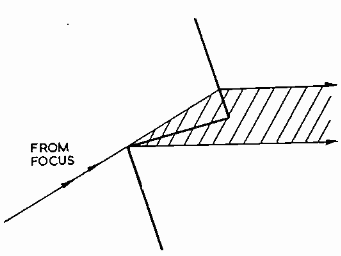


FIG. 5

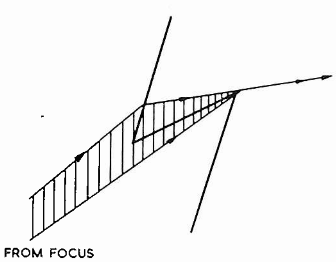


FIG. 6

clear that, whereas steps on the front surface cause gaps in the illumination of the lens aperture, steps in the back surface cause additional reflection from the back surface, but no gaps in the illumination. Thus the radiation pattern from the lens stepped on the back probably has smaller side-lobes than that from the lens stepped on the front, although the overall gains of the two systems are about the same. The choice between the lenses therefore depends partly on whether it is more important to avoid high side-lobes or back scatter.

The treatment is, of course, based on simple ray theory and is only to be regarded as qualitative. Diffraction at the steps is probably as marked as the refraction shown, and would mask the quasi-shadow effects indicated in an unpredictable way. It is possible that field measurements in the region of the steps may reveal the nature of the step distortions quantitatively, see, e.g., Fry and Goward (1), p. 148, 149.

Acknowledgment

The author wishes to thank the Board of Admiralty for permission to publish this work, which was carried out under an Admiralty Contract.

References

(1) D. W. Fry and F. K. Goward, "Centimetric Aerials," p. 162. Oxford University Press.

(2) S. Silver, "Microwave Antenna Theory and Design," p. 395. McGraw Hill Book Co., 1949.

(3) T. C. Cheston and D. H. Shinn, "Scanning Aberrations of Radio Lenses," *Marconi Review*, Vol. XV, pp. 174–184, 1952.

BOOK REVIEW

On receiving this book it was instinctive to turn again the pages of A. E. Kennelly's *Hyperbolic Functions Applied to Engineering Problems* written, as was Mr. Starkey's, as lecture notes about forty-five years ago, for here was another attempt to interpret a mathematical relationship for the benefit of engineers and to provide another tool for the solution of their problems. Although Kennelly thought and wrote in terms of power supply and telephonic frequencies, so well were the foundations laid that large numbers of microwave engineers are deeply indebted to him for his teaching, tables and charts in solving their transmission problems. It is perhaps significant that in his later books the applications were stressed rather than the functions themselves. Against this background Mr. Starkey's book is disappointing, for there is comparatively little appreciation of the engineers outlook, and it is to be regretted that the number of examples of applications to problems are so few. The engineer may be pardoned for querying whether he will gain by investing time and effort in mastering techniques requiring more than average mathematical ability or whether results could be achieved more economically by other methods. That advances in pulse techniques in the past two decades have in the main been through the use of visual (oscillographic) and graphical methods, in a large measure brought about by the non-linearity of electronic devices, cannot be overlooked. If the transform method provides a powerful design tool no really strong case has here been made for its adoption; even if limitations of space prevented discussion of applications in the text, one could reasonably expect to find included in the Bibliography in addition to the list of textbooks appearing there, selected references to the literature in which practical examples receive prominence.

That the subject itself has a fascination it is impossible to deny and one could wish for a more effective link between the engineer's criteria of bandwidth, risetime and overshoot—terms which, together with feedback and servo systems, do not appear in the text—and the mathematical description of circuit performance. One cannot help but feel that if certain gaps were bridged, more effective use could be made of the material that then would become available.

One of these is undoubtedly the lack of suitable material for factorising a polynomial, a procedure which becomes increasingly difficult with cubic and higher powers even when coefficients are numerical and virtually impossible except to a gifted few when otherwise. The engineer may be in part to blame for cumbersome manipulation but some guidance given here in this vital stage of procedure would have been invaluable.

In spite of its shortcomings this book provides much food for thought. The author has set himself a more difficult task and if the claim implied by the title is hardly fulfilled, it will be readily acknowledged that he has made a real contribution to the better understanding not only of the main subject but also of the allied one of complex frequencies, which receives but cursory mention in most texts.

Both the printers, Messrs. W. J. MacKay & Co., of Chatham, Kent, and the publishers are to be congratulated on the manner in which the book has been prepared.

Laplace Transforms for Electrical Engineers, by B. J. Starkey. Published for Wireless Engineer by Illiffe & Sons, Ltd., London. Price 30s.

A MEDIUM POWER TRAVELLING WAVE TUBE FOR 2,000 MEGACYCLES

By R. B. Coulson, B.Sc., B.E. and F. N. H. Robinson, M.A.

Three types of travelling wave tube have been developed by the English Electric Valve Co., Ltd., for use at 2,000 Mc/s, namely a low noise input tube, a tube suitable for intermediate amplifying stages and a power output tube. This article discusses the power output tube, which is considered to offer substantial advantages for use in the microwave links being developed by Marconi's Wireless Telegraph Co., Ltd., and gives a summary of its performance.

Introduction

THE travelling wave tube (T.W.T.) is one of the more recent additions to the microwave valve family. Since Kompfner's first paper[1] there has been a steady flow of theoretical papers on amplification by modulated electron beams, notable Pierce's report in 1947[2] and later his book (1952)[3]. However, although the physical fundamentals of the valve are now understood, the development from Kompfner's early experiments to a completed and saleable tube, has been a surprisingly slow and difficult process. One reason for this has been the laudable ambition of designers to produce a valve satisfying established concepts of size, shape, and installation. Its long and fragile appearance, together with its associated solenoid, affronts the aesthetics of radio engineers. There have been opinions that no future exists for the T.W.T. until it " looks like a 6L6," and can be as simply inserted into an equipment. This may be so, and a small " packaged " tube may soon be made. Meanwhile, as this paper will show, the valve can be made

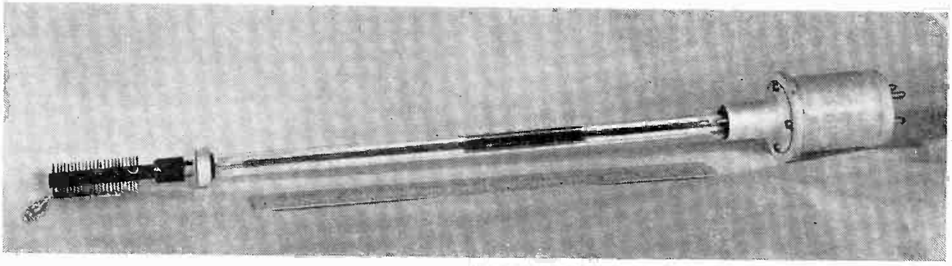


Fig. 1

very sturdy, and is capable of very good performance. The space required for a T.W.T., its solenoid and power supplies is far less than for triodes giving the same gain. There is the further attraction in the absence of critical circuitry. It presents immense possibilities in the field of radio relay links.

This report describes the development and construction of valve type N1001, suitable for use at 2,000 Mc/s. Fundamentally it is identical with that analysed by Pierce, utilising a helix as delay line. See Fig. 1. Low level gain is in excess of 40 db. and 20 watts are available at somewhat reduced gain. The valve is perfectly stable, and can be used in either wave guide or coaxial systems. It can be installed in any position, although a vertical mount is more convenient. One valve can be replaced with another without realignment in the magnetic field and with only slight adjustment of the matching. The voltage standing wave ratio at either the input or output is less than 1·3 over $\pm$ 200 Mc/s, and less than 1·05 over $\pm$ 20 Mc/s. The operating voltage is about $2\frac{1}{2}$ Kv.

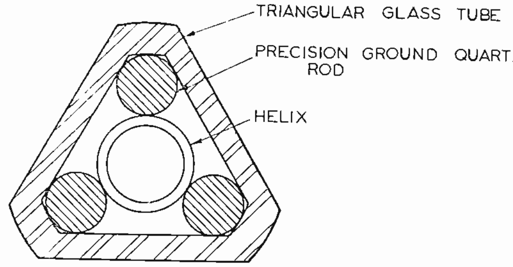
When the work was begun, only scant tentative specifications were set down. These were that the tube should be capable of giving 5 watts out, with a gain of at least 20 db. The potential users were anxious that the operating voltage should be kept below 1,000 volts, but, while it was acknowledged that this would be a desirable feature, the first valves were designed for 2,000 volts to simplify construction. Rather than reduce this figure, it will be seen that the voltage has actually been increased in the interests of valve performance.

Initial Design

There was a certain amount of "intelligent guessing" at the beginning, particularly in the prediction of efficiency and gain. The design took the following sequence:—

(*a*) Helix dimensions.
(*b*) Helix support.
(*c*) Matching methods.
(*d*) Electron gun.
(*e*) Magnetic focusing.
(*f*) Envelope construction.
(*g*) Collector design.

The attenuator, a vital part of the valve, was not seriously tackled at first. It has proved to be the most difficult and critical feature of all.



Cross section of T.W.T. showing method of supporting helix

FIG. 2

Helix Design

From Pierce's work it was deduced that for optimum gain, the radius a, of the helix should be such that, in Pierce's notation,

$$\gamma a = 1{\cdot}2 \text{ to } 1{\cdot}5$$

γ is approximately equal to ω/u_0

where ω = signal frequency.
,, u_0 = electron velocity corresponding to a beam potential V_0.

With V_0 equal to 2,000 volts,

$$\gamma = 4{\cdot}72$$

and $a = 0{\cdot}317$ cm. at 2,000 Mc/s.

This leads to a helix of 0·7 mm. wire wound on a mandrel 6 mm. diameter, with a pitch of 1·75 mm. The tube was found to have an operating voltage of 1,600, due to the presence of the glass supporting tube.

After several experiments, the following were found to be the most favourable dimensions:—

Wire diameter	= 0·6 mm.
Mandrel diameter	= 4·5 mm.
Winding	= 18 turns per inch.
Operating voltage	= 2,200 (low level).
Length of helix	= $12\frac{1}{2}$ in.

Helix Support

Considerable thought and effort was devoted to the problem of supporting the helix. The following were considered to be the minimum requirements:—

(i) The helix should be held continuously and firmly along its whole length.

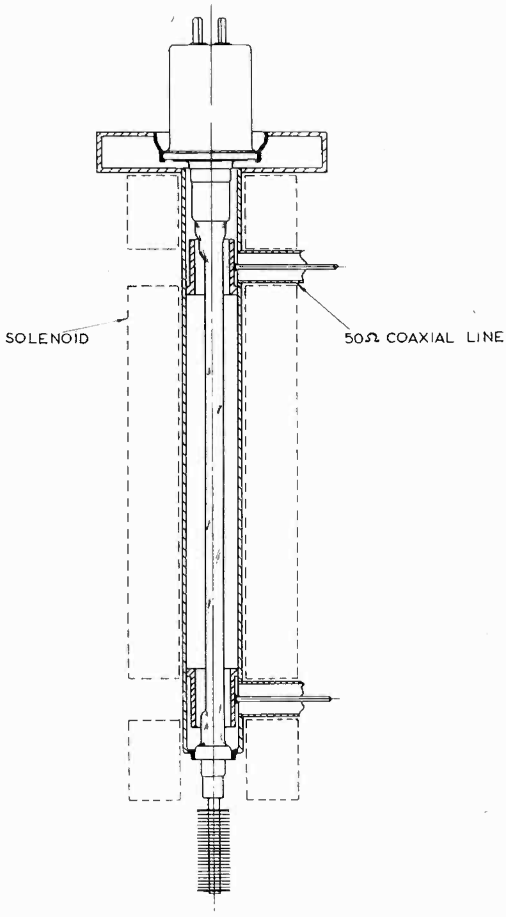
(ii) No damage should result if the helix is heated up to 850° centigrade.

(iii) It should be perfectly straight.

(iv) It should be simple, easy to assemble, and adapted to conventional valve manufacturing methods.

(v) There should be a minimum of dielectric material near the helix, within the r.f. field.

Several schemes were tested. Three ceramic rods were clamped around the helix by means of springs. This had the disadvantage that the straightness of the helix depended on that of the rods. It was clumsy, and difficult to insert in the glass envelope with a definite relation to the axis of the electron gun.

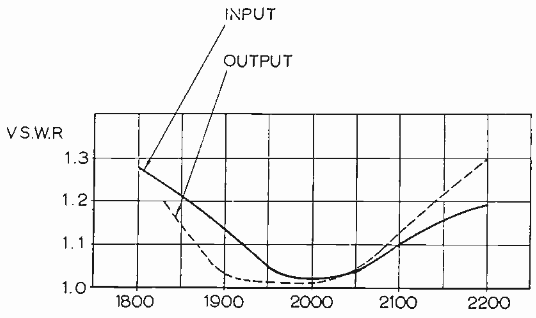


TYPICAL COAXIAL MOUNTING MATCHED AT 2000 Mc/s

FIG. 3

Triangular glass tubing was made by collapsing a circular tube on to a triangular steel mandrel, the helix being held in contact with each of the sides of the triangle. Some successful tubes were made with this construction. Although it was possible to heat the helix to a surprisingly high temperature during pumping, tubes finally failed in use, when, due to incorrect focusing, intercepted beam current caused local heating cracking the glass.

The final method was a logical development from the last. The triangular glass was made slightly larger, and the helix was supported between three quartz rods held in the corners. See Fig. 2. This has been adopted in the final design. It satisfies all the above conditions and, further, lends itself to the making of the attenuator. The triangular glass forms part of the vacuum envelope and the assembly is extremely robust. If, through faulty focusing, the intercepted current becomes excessive, no damage occurs to the envelope. However, to avoid the liberation of gas from the heated helix, it is advisable to limit the helix current to less than 2 mA.

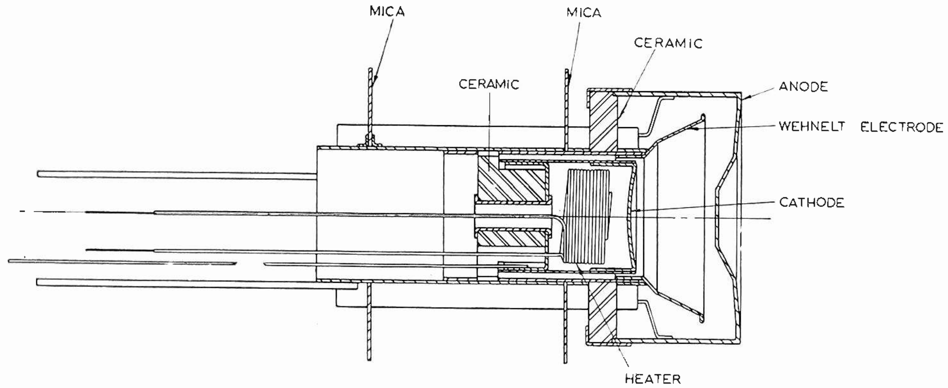


Typical measurements taken on a waveguide unit.

FIG. 4

Matching Methods

Although a great variety of methods were investigated, the conventional method of matching the helix to a wave guide was finally adopted. The helix wire is bent straight at each end to form a short antenna connected effectively to the face of the wave guide either directly, or via an r.f. choke. A circuit suited to coaxial matching is shown in Fig. 3.



ELECTRON GUN ASSEMBLY

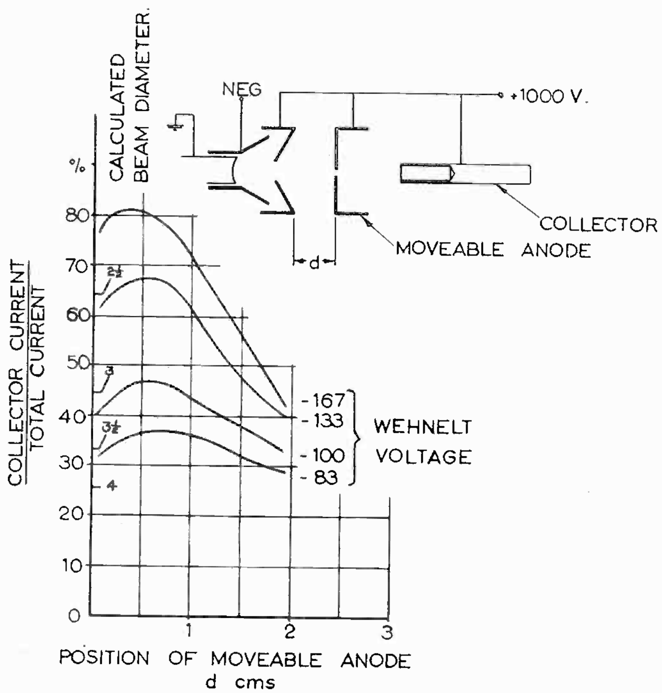
FIG. 5

A typical plot of S.W.R. against frequency is given in Fig. 4. The S.W.R. is less than 1·3 between 1,800 and 2,200 Mc/s.

It has not yet been possible to make valves of such a consistency that, at any given frequency, it is possible to replace a valve in a pre-matched system without any adjustment, if a S.W.R. of less than 1·3 is desired.

Gun Design

Before a tube had actually been constructed, the necessary beam current was roughly estimated to be 50 mA, assuming an efficiency of no more than 5%. An electron gun was designed to produce a beam converging from a coated cathode 10 mm. diameter to a parallel beam 3 mm. diameter. At 50 mA, the cathode loading is about 70 mA/sq. cm., low enough for reasonable expectation of life.



Beam Convergence measurements made using a moveable Anode.

FIG. 6

The gun electrode shapes and the method of construction are shown in Fig. 5. Three leads in parallel are connected to the anode. The effect is to reduce their inductance, which becomes important when the valve is used as a frequency-changer. Some experiments have been done to ascertain whether the beam converges according to theory. A gun with a movable second anode followed by a fixed collector was mounted in a sealed-off envelope. The second anode had a hole 2 mm. diameter, and by measuring the current intercepted and transmitted through this hole, an estimate was made of the diameter of the beam. Some results are presented in Fig. 6. It was not possible to make realistic measurements at full voltages and currents due to overheating the movable electrode. The tests were therefore done at scaled down voltages. A great deal of consistency was not obtained, but there were definite indications that the " cross-over " point was occurring closer to the cathode than was expected.

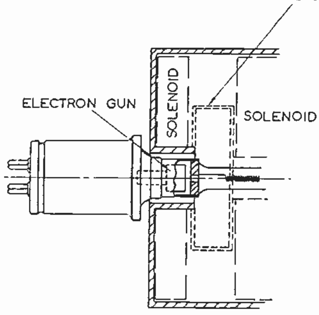
Magnetic focusing

Brilloin's principle of magnetic focusing[4] was adopted. The method has been further discussed by Wang[5] and Samuel[6]. In these papers, it is deduced that maximum economy of magnetic field results if the cathode is screened from it and if the electron beam enters the magnetic field at a point where the beam is still converging. Recently, Mueller and Bruck[7] [7a] have given a theoretical explanation of this. Referring to Fig. 7, the magnetic screen about the cathode is formed, first by mounting the gun in a Kovar* pressing, and secondly by forming the second

* Trade name for a nickel-iron alloy suitable for sealing to Kodial glass.

anode from a thick piece of Kovar. In addition, further screening is carried out externally to the valve, by enclosing the gun pressing in an iron jacket. The magnetic circuit is completed by enclosing the solenoid in an iron tube, fitted with iron discs at either end.

There is a slight falling off of the field across the input and output wave guides due to the interruption caused in the solenoid. A typical plot of the magnetic field along the tube is shown in Fig. 8. It rises to about 400 gauss in the centre, tapering off at each end.



ARRANGEMENT FOR MAGNETIC SCREENING OF THE GUN

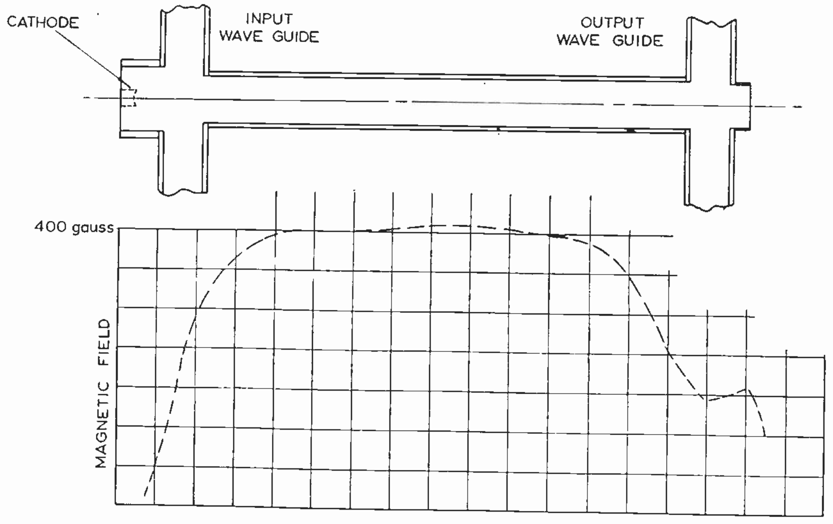
(Hatched areas are of magnetic material)

FIG. 7

Envelope Construction

The envelope, by means of glass-metal seals, supplies bearing surfaces for mounting the valve, and also for making r.f. contact with the helix. The glass-metal seals are made by conventional high frequency heating techniques. This method is favoured as it allows the various parts to be held in jigs with great precision. Each envelope is checked before using, to ensure that there is perfect alignment. This is done by an optical, sighting method.

The distance between the disc-seals can be controlled within ± 0·010 inches.



THE DISTRIBUTION OF MAGNETIC FIELD IN A TYPICAL WAVE GUIDE MOUNT

NOTE The measurement has been made without a valve in position, so that the affect of the magnetic screen inside the valve is not indicated.

FIG. 8

The ends of the helix are connected to these seals, so that sagging due to mounting the tube vertically is impossible.

Collector Design

The collector is made of copper to conduct the heat out so that it may be dissipated in radiator fins. The beam current is collected in a deep hole drilled in the copper to prevent the escape of secondary electrons to the helix, thereby

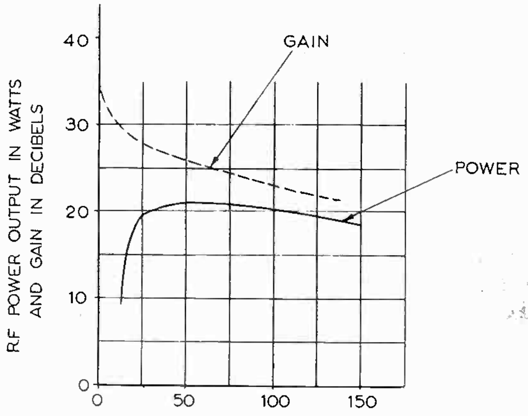
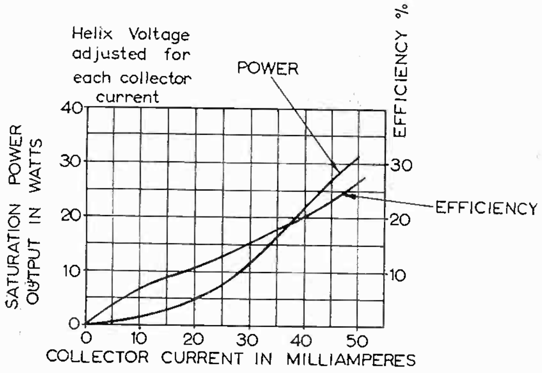


FIG. 9



Variation with collector current of the maximum obtainable power and electronic efficiency

FIG. 10

confusing the monitoring and safety devices. It is possible to run the collector at some hundreds of volts less than the helix before the helix current begins to rise without affecting the r.f. performance.

Under normal operation, more than 100 watts are dissipated in the cooling fins, which were designed according to the principles set out in a report by Young[8].

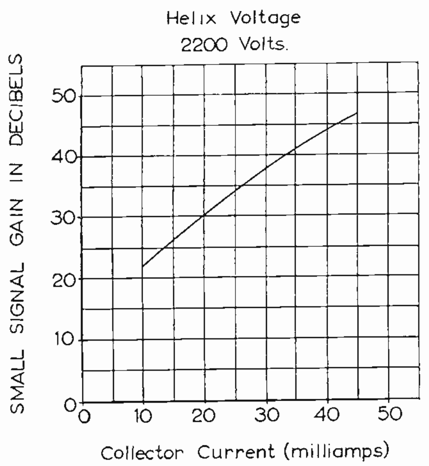
Average Performance

The following are normal operating conditions:—

Heater voltage	6·3 V.
Heater current	1·6 A.
Typical anode voltage	1,300 V.
Anode current	nil
Wehnelt voltage	—100 V.
Helix voltage (low level) ...	2,200 V.
Helix voltage (high level) ...	2,600 V.
Helix current	1 mA. (max)
Collector current	40 mA.
Low level gain	40 db.
High level gain	27 db.
Saturation output power ...	20 watts.
Magnetic field	400 gauss.

Fig. 9 shows the performance of the valve as a power amplifier, giving the variation of output with input power at 2,000 Mc/s. The helix voltage was maintained at 2,600. As the power output is increased from zero, the helix voltage, for maximum gain, must also be increased. At 20 watts output the optimum voltage is 2,600, at 30 watts it is 2,700. The output power is obtained at the expense of electron energy, and, therefore, as more power is taken out, the electrons slow down. Increasing the beam (helix) voltage speeds up the electrons to be again in synchronism with the waves in the helix. The limit to this process occurs when the beam at the output end of the helix is moving with the correct velocity while at the input end, it is too fast to contribute to the gain of the tube.

The dotted curve in Fig. 9 shows the gain computed from the ratio of the input and output powers. Near saturation, the gain begins to fall steeply, so that in an application calling for maximum gain, it is advisable to avoid driving the valve to the limit.



SMALL SIGNAL AMPLIFICATION

FIG. 11

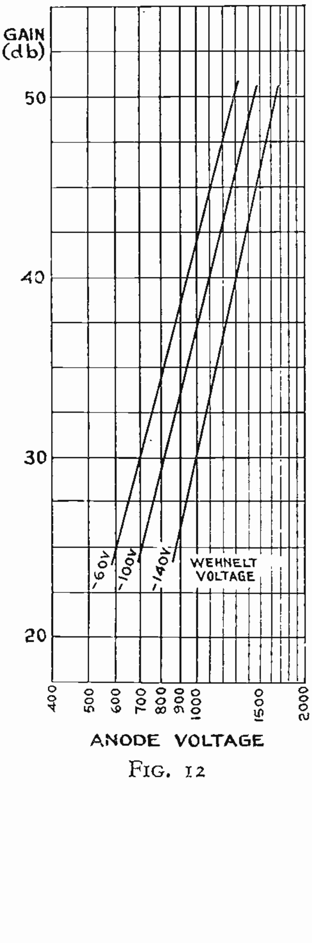
Fig. 10 indicates the maximum power obtainable at various values of beam current. The electronic efficiency rises with beam current as predicted by Nordsieck's theory[9].

Very high gain is possible at low level, i.e. less than 5 watts output. In Fig. 11, the gain is plotted against beam current.

As expected, the gain varies in proportion to the third root of the beam current. The curve shows the possibility of automatic gain control by variation of the beam current. This is further shown in Fig. 12, where, for an average tube, gain is plotted against the voltages applied to the first anode and Wehnelt electrode. The control of the beam current by the voltage on the Wehnelt electrode is limited to a small range only because of the deleterious effect on beam focusing.

Attenuator Design

The purpose of the attenuator is to prevent feedback along the helix. For complete stability, the insertion loss of the helix plus attenuator must be at least equal to the gain of the tube. In addition the attenuator must present a good match to the helix. In a tube with, say, 40 db. gain, the standing wave ratio on the helix due to reflections from the

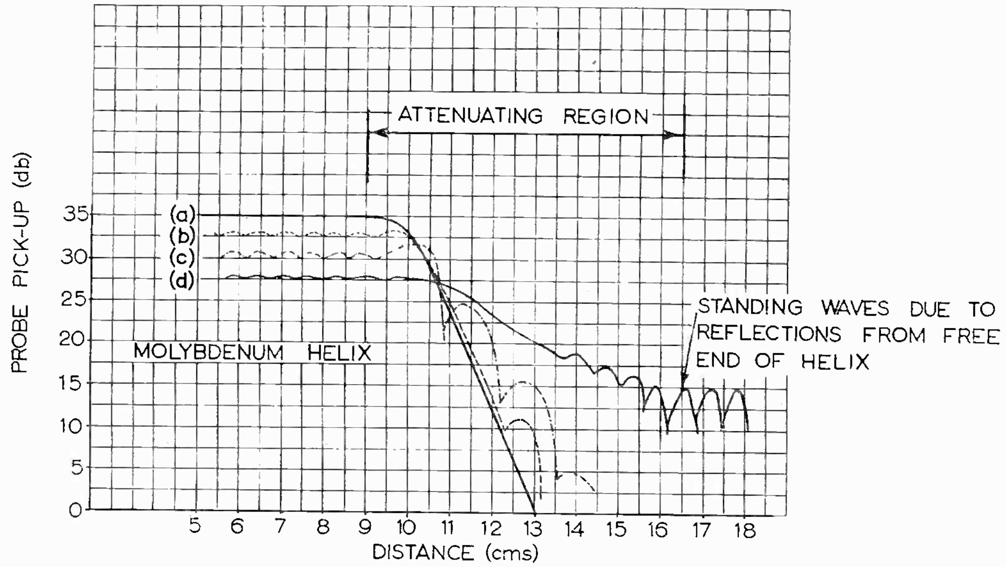


ANODE VOLTAGE

FIG. 12

attenuator, should not be greater than 1·03. If there is a distributed loss in the helix, this figure can be slightly increased.

A mixture of Aquadag* is sprayed on to each of the helix support rods, forming



Typical measurements of voltage wave on Helix in the vicinity of the attenuator.

FIG. 13

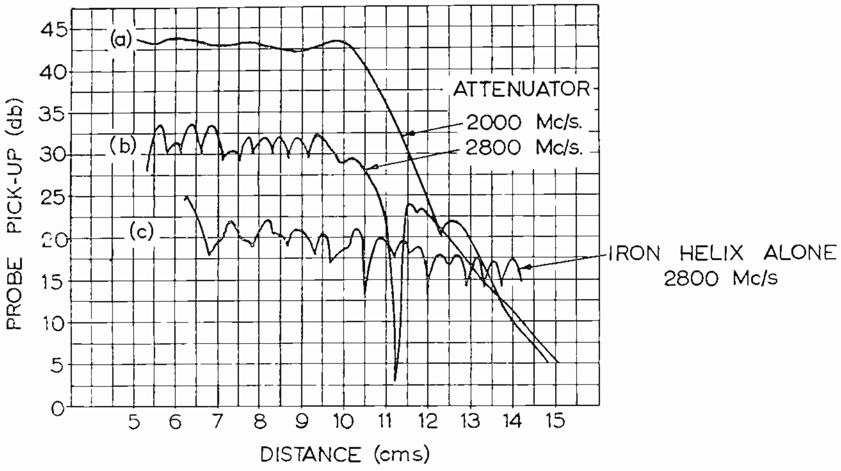
an attenuator $7\frac{1}{2}$ cm. long. The deposit is thickest in the centre tapering off at each end. Each set of three rods thus sprayed is tested before making into a valve. The S.W.R. on the helix is measured, as well as the rate of attenuation in the sprayed region. Some typical measurements are shown in Fig. 13. Curve (*a*) represents the desired result, i.e. there are no standing waves on the helix and the attenuation is smooth and continuous, at about 10 db./cm. Curve (*b*) is obtained fairly frequently, rather than (*a*) and on this evidence, the attenuator is passed as suitable. Curves (*c*) and (*d*) are the results for coatings respectively too thick and too thin. All these measurements were done at 2,000 Mc/s.

Even with attenuators with characteristics as in Fig. 13 (*a*), tubes were found to oscillate strongly at beam currents above 25 mA at a frequency of about 3,000 Mc/s. The standing waves on the helix were measured again at this higher frequency, and the results were very bad indeed. In fact it was found impossible to produce an attenuator with an associated S.W.R. less than 1·2 to 1·3. Some results are shown in Fig. 14. Even a lossy iron helix, without a lumped attenuator, gave a pattern as in curve (*a*) of Fig. 14. Several types of helices, with different diameters and pitches were investigated, and at the frequency for which $\gamma a = 1{\cdot}5$ or more, the pattern became confused.

There was reason to suspect the method of measurement. The voltage on the helix was measured by the pick-up on a probe arranged to move in a slot in a brass

* Trade name of colloidal graphite in water.

tube surrounding the helix. The attenuating region was arranged to be about in the centre of the slot, and power could be fed into either end of the helix. At times it was noticed that the slot was "alive." In addition the pattern was markedly influenced by the length of the probe. A loop probe seemed to give the least confused pattern, with the plane of the loop at right angles to the helix axis[10].



MISMATCH OF ATTENUATOR AT HIGHER FREQUENCY

FIG. 14

Some tubes were made to operate at a higher voltage by increasing the pitch of the helix, and these were, for the same beam current, much more stable, the gain being lower. A tube, with a helix of 26 t.p.i. instead of 18 t.p.i. oscillated very easily, even with two attenuators applied at distances of one-third and two-thirds along the helix.

Up to this point the helix had been made from molybdenum, which is almost lossless. When nichrome was used, the oscillations at 3,000 Mc/s., and indeed all other frequencies, were immediately cured. Later, an oscillation at 4,500 Mc/s. was discovered and traced to a wave guide mode of propagation inside the brass tube former of the solenoid. The cure was to reduce this internal diameter from $1\frac{3}{8}$ inches to $1\frac{1}{8}$ inches. With these modifications, the tubes now being produced, show no oscillation for beam currents up to 40 mA, i.e. at a gain of the order of 50 db.

The use of nichrome was found to have no effect on gain, although the saturation output power was reduced by about 1 db. About $\frac{1}{2}$ db of the power is recovered by copper-plating the last 2 inches of the helix.

Apart from the problem of instability, low gain and efficiency were observed in all the early tubes. As the technique of applying the attenuator improved, it became possible to reduce its length, and yet retain an adequately high insertion loss (about 75 db.). At the same time an improved efficiency was noticed. It was soon clear that the longer the section of "free" helix following the attenuator, the better. Against this there was the increased chance of oscillation in the output end of the helix.

Moreover, if the attenuator is too near the input, the gain is adversely affected. Using Pierce's formula, the gain is given by

$$G = A + BCN.$$

Theoretically, A is of the order of -10 db., and in N1001, the value lies between -12 and -20 db. In tubes where the free length of the helix before the attenuator was about 4 cm. the value of A was in the region of -40 db. The optimum dimensions have been found to be the following:—

Length of free input helix	...	10 cm.
Length of attenuator ...	...	$7\frac{1}{2}$ cm.
Length of free output helix	...	18 cm.

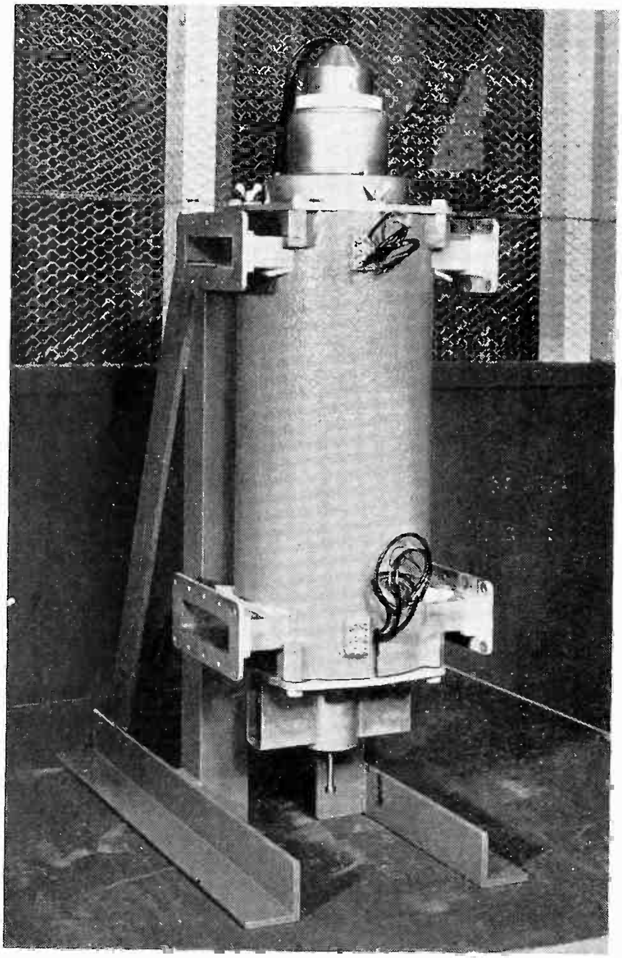


FIG. 15

Further discussion of the position of the attenuator is given in an Appendix.

The insertion loss of the attenuator varies considerably from valve to valve, from 75 to over 100 db., without any significant effect on tube performance. Much of this variation occurs during processing, especially outgassing the helix.

Installation

A wave-guide-solenoid mount is shown in Fig. 15. The input and output wave guides are respectively at the top and bottom of the picture. The ducting for cross-draught cooling can be seen at the very bottom of the mount. The valve is held securely in position by a spring, bearing against the alignment flange on the valve. This is contained in the housing at the top of the mount. No focusing alignment is needed when installing a new valve, this being done during factory testing.

Conclusion

N1001 is a travelling wave tube designed for use at 2,000 Mc/s. It is notable for its high gain, power output, and stability. Normally the beam current is limited to 40 or 50 milliamps to promote long life, more than 10,000 hours. At 40 mA the low level gain is about 45 db., while the saturation output power is about 20 watts.

Except for impedance matching, the valves are completely interchangeable in a correctly designed mount. No re-alignment is necessary. To reduce the S.W.R. at the terminals, the position of wave guide plungers may have to be adjusted.

At the cost of 6 db. gain, the valve may be conveniently used as a frequency changer, by modulating the helix voltage at the difference frequency.

Acknowledgment

The authors wish to acknowledge the assistance given by their colleagues who carried out most of the testing during the early stages of the work.

APPENDIX

The Position of the Attenuator in Power T.W.T.'s.

The electronic efficiency of travelling wave tubes has been shown by various authors to be proportional to the gain parameter, C, and, in fact, to be very nearly equal to $2C$ over a wide range of conditions. There is, however, another factor which can limit the power of a tube—the effective impedance presented to the beam by the entire helix beyond the attenuator.

Suppose that a beam of current I_0 is fully modulated in the initial part of the tube, then the component of the modulation at the signal frequency will be approximately $I = \frac{1}{2}I_0$. The beam thus modulated enters the final section of the helix of impedance Z which is N wavelengths long. It can be easily shown that the power induced in the helix is $P = \frac{1}{2}(\pi N)^2 Z_0 I^2$ (1)

If V_0 is the beam voltage, the efficiency, η, is given by

$$\eta = P/I_0V_0 \qquad = \tfrac{1}{2}(\pi N)^2 \frac{I_0 Z_0}{V_0} \qquad = \tfrac{1}{2}(\pi N)^2 C^3 \tag{2}$$

This efficiency will be less than the attainable efficiency

$$\eta = 2C \tag{3}$$

unless

$$\pi NC \geqslant \sqrt{2} \tag{4}$$

Thus the length of the output helix must be chosen to satisfy(4).

Since in the operation of a T.W.T. at high efficiencies the beam velocity is not usually in exact synchronism with the free wave on the helix, the power induced will be rather less than predicted by (1) and the condition (4) will become rather more stringent. In practice we have found that if NC in the last section falls below about 0·7, the efficiency is seriously affected. One result of these considerations may be noted. The gain of the last section of the tube considered by itself will be approximately given by

$$G = -10 + 45\,CN \text{ db.}$$
$$= 20 \text{ db. approximately.}$$

The attenuator will therefore have to be matched to this section with a reflection coefficient of less than 0·01 over the electronic bandwidth.

References

(1) R. Kompfner, *Wireless World*, Vol. 52, p. 369, 1946.
(2) J. R. Pierce, *Proc. I.R.E.*, Vol. 35, p. 111, 1947.
(3) J. R. Pierce, "Travelling Wave Tubes," *Van Nostrand*, 1950.
(4) L. Brillouin, *Physics Review*, Vol. 67, p. 260, 1945.
(5) C. C. Wang, *Proc. I.R.E.*, Vol. 38, p. 135, 1950.
(6) A. L. Samuel, *Proc. I.R.E.*, Vol. 37, p. 1252, 1949.
(7) M. Mueller, *Telef. Zeit.*, Vol. 26, p. 95, 1953.
(7A) L. Bruck, *Telef. Zeit.*, Vol. 26, p. 99, March, 1953.
(8) A. J. Young, *Marconi Review*, 94, July, September, 1949.
(9) A. T. Nordsieck, *Proc. I.R.E.*, Vol. 41, p. 630, 1953.
(10) F. Tischer, *Zeits. F. Ang. Phys. Springer, Berlin*, Vol. 4, p. 345 Book 9, 1952.
F. Tischer, *A.E.U.G.*, p. 127, 1952.

THE DEVELOPMENT OF NEW MATERIALS

By F. E. Robinson.

The following article may be considered as an extension of one under the above heading published in the "Marconi Review," July-September, 1949. Materials mentioned there will not be referred to again unless their properties have been improved in the meantime. Although what follows is primarily concerned with materials, the author is of the opinion that a description of new processes will not be out of place, because, as will be seen later, a new process may result in a well-known material being made suitable for a new purpose.

Metals and Alloys

ONE of the most widely discussed metals of recent times is Titanium, but in the non-technical press extravagant claims have been made as to its valuable properties without referring to its limitations.

Alloys of titanium usually contain about 93% of the metal to which other elements, notably iron, tungsten, silicon and carbon are added to obtain particular properties.

Some of the properties of the pure metal are given below:—

Melting point	1800°C.
Specific gravity	4·4
Tensile strength	39 tons/sq. in.
Elongation	23%
Reduction in area	50%
Hardness (Vickers diamond)	175
Electrical resistance	18 (Copper 10·2)

By suitable alloying, the tensile strength may be increased to 49–90 tons/sq. in., but the elongation will be reduced to 19%–6% hardness 175–335 (Vickers diamond).

These alloys may be one and a half times as heavy as the best aluminium alloys but may have more than double the strength.

Practically no oxidation takes place up to 120° C. and hence they do not tarnish. They would, no doubt, be useful for electrical contacts as their resistance is lower than many metals at present in use for this purpose. They are in fact, resistant to all forms of corrosion, and in sea water far superior to aluminium. Titanium-carbide (M.P. 3,140° C.) can be produced by heating titanium in an electric arc when it absorbs carbon. The resulting titanium carbide is harder than carborundum. Tungsten carbide, used for tool tipping, melts at 2,777° C. and so titanium carbide should form a very useful alternative.

The alloys are extremely susceptible to impurities and hence great care must be taken in their preparation, which, of course, adds to the cost. At the present moment, castings in a titanium alloy cannot easily be produced because the molten metal attacks and destroys the moulds but no doubt, in due course, a suitable inert material with which to form moulds will be found. Forging is difficult as alloys cannot be heated in air to a temperature above 980° C. as they then become very active chemically. An inert atmosphere, however, allows the use of higher forging temperatures. The tensile strength falls rapidly at elevated temperatures, so much so that at 400° C. an aluminium alloy is stronger than a titanium alloy. The frictional qualities of the alloys of titanium are very poor and they "pick" up when in contact with themselves or any other metal. They are, therefore, not suitable for bearings or rotating shafts. The disadvantages referred to above apply both to the pure metal and alloys of it.

Titanium is, therefore, by no means an ideal metal for all purposes. As no economical method of extraction of titanium has been developed the metal is costly —the present-day price being of the order of £10 per lb. Great endeavour is being made to reduce this cost and in view of the fact that titanium is the ninth element in order of abundance in the Earth's crust such research would appear to be well worthwhile.

Cupal Bus Bar Metal

In the past it has been normal practice to employ only copper for electrical bus bars but on occasions aluminium has also been used. As aluminium bolts are not strong enough brass bolts are used to secure the aluminium bars. The potential difference between brass and aluminium causes electrolytic corrosion at the junction of the two metals and the resistance of the joint increases. Aluminium bars plated with up to 0·25 in. of copper on faces which are in contact or where cable connections are to be made have been developed in recent years. The trade name of this product is "Cupal." In this case the brass connecting bolts are in contact with copper and negligible corrosion takes place. The resistance of aluminium is 2·6 microhms per cm.^{3} and that of copper 1·7 microhms per cm.^{3} so that the sectional area of the aluminium bar to replace a copper bar for the same current carrying capacity must be increased. Some objections have been raised regarding the use of aluminium as the thermal conductivity of aluminium is lower than copper. In the case of the aluminium bus bar, however, the area of the cooling surface is 50% greater than that of the copper bar due to the increased sectional area.

In connection with cooling, it has been remarked that as aluminium does not tarnish the emissivity is low and hence the heat generated in the bus bar cannot radiate freely. The emissivity of unpolished aluminium is about 0·07 but the application of a coat of lead paint (the colour is immaterial) raises the emissivity of the surface to 0·94, a value higher than that of copper. The makers claim that the contact resistance of a joint using Cupal is less than that of a normal copper bus bar. In view of the fact that the copper bus bars are usually made of copper hardened by the addition of a small quantity of arsenic, which raises the resistance above that of soft copper plated onto aluminium, this assertion may well be true.

As the density of copper is 8·92 and of aluminium is 2·7 and aluminium is cheaper than copper, the cost of a Cupal bus bar is about half that of a copper one, assuming the current capacity of the bars to be the same.

Cast Iron

For many years engineers have looked upon cast iron as a metal which could be employed only in a very limited number of cases. Ordinary cast iron is very brittle and, indeed, under a tensile strength test it has no yield point or elongation. For this reason it is only used in structures where the members are stressed in compression.

A new process has been developed whereby cast iron is produced having properties which compare quite favourably with mild steel. This metal is referred to as "Spheroidal Graphite Cast Iron," because in the new process the graphite in the cast iron is changed from flake to spheroidal form. The improved properties are obtained by means of a patented process by which small proportions of magnesium are introduced to the iron under specified conditions.

Properties of this new cast iron are compared with normal cast iron below:—

	Grey Cast Iron	Spheroidal Graphite Cast Iron	
		As cast	Annealed
0·1% Proof Stress	—	31	24·8
Yield point tons/sq. in.	—	—	27
Max. stress tons/sq. in.	15·8	37–45	32
Elongation %	—	1–4	21
Reduction in area %	—	1	21
Mod. elasticity $\times 10^6$ in lbs/sq. in. ...	16·7	24	24
Diamond Hardness	229	196	190

It will be seen from the above figures that the new process has made available a cast iron which is capable of carrying compression, tensile and bending loads. As an example, internal combustion engine crankshafts have been cast and have proved to be satisfactory in service. This metal has also been used for bearings in heavy rolling mills, such bearings having a much longer life than similar bearings made of phosphor bronze. Spheroidal graphite cast iron may be welded by all the usual methods.

A new high strength weldable steel known as "Fortiweld" which has some very interesting properties, has now been developed and is in production. Mild steel with a carbon content of about 0·14% has a yield stress of 18·7 tons/sq. in. and is fairly easily welded. If the carbon content is increased or other elements added to give it increased strength, it is difficult to weld unless very special precautions are taken. In Fortiweld 0·0025% boron and 0·5% molybdenum are added to mild steel, the yield stress is increased to 34·8 tons/sq. in. and it is quite easily welded by normal methods.

It is interesting to note that the addition of 0·5% molybdenum increases the tensile strength of the steel but does not make it suitable for welding. It is the addition of boron which renders it capable of being welded, and it is all the more striking when we consider that the amount of boron added is about 1 ounce per ton of finished steel.

Fortiweld has good mechanical properties up to 400° C. and it may be employed as castings. It is being used at the present time in aircraft jet engines.

Powdered Metals and Alloys

Although the methods employed in Powder Metallurgy were explained in a previous article,* it is considered desirable that this subject should be briefly

* *Marconi Review.* July–Sept. 1949.

referred to again because the technique has been extended and improved since that time. Without going into great detail, parts are produced from powdered metals as follows.

The first part of the process is to form a cold moulding. The powders are compressed in a super-polished high tensile strength steel mould, the pressure employed depending upon the nature of the metals and the porosity required in the finished part. When the part is removed from the mould, it is said to be in the "green" state. It is not, however, fragile and can be handled without being damaged. The moulding is next placed in a furnace, in an inert atmosphere and heated to sinter the powder. The inert gas prevents oxidation of the part and hence maintains the highly polished surface of the moulding.

As for the process of sintering it may be useful to point out that it depends on the fact that no two metals have the same melting points and hence a mixture of two metal powders when sintered may be considered from a mechanical point as an alloy although it is not an alloy in the chemical sense of the word. If a moulding is made in the manner described above from a mixture of iron and copper powder and then sintered at the melting point of copper, the copper particles fuse and bond the iron particles together to form a more or less solid mass.

During the sintering process the moulding will support itself for, although the copper melts at a temperature of 1,083° C., the iron will remain solid up to a temperature of 1,535° C. A satisfactory powdered metal part cannot be made, of course, if the two metals employed have melting points of the same order.

An interesting application of this process is in the formation of tungsten carbide tips for cutting tools. In this case the mixture comprises tungsten carbide powder, melting point 2,800° C., and cobalt, melting point 1,480° C.

Although parts made from powdered metals are more or less porous (a desirable property when the part is to be used as a filter) they may be made non-porous by impregnation with, say, molten tin, melting point 232° C.

It is of interest to note that in the sintering process iron powder made from cheap scrap iron castings may be employed. Ductility and mechanical strength are imparted to the moulding by copper powder, thereby reducing the cost of a finished component.

Magnetic Materials

One of the most recently developed permanent magnets is of the columnar crystal formation, named "Columax." These magnets are isotropic, i.e. the magnetic force is not in a preferred direction as it is in the case of the Alcomax series which are anisotropic magnets.

Columax magnets are outstanding both from the BH(max.) and the coercive force Hc values (BH(max.) $7{\cdot}0 \times 10^6$ to $8{\cdot}0 \times 10^6$ and Hc 700 to 800 oersteds).

It is difficult to appreciate the great improvement in the qualities of permanent magnets by considering BH(Max.) and Hc values. The general trend of advancement is more readily followed by reference to Fig. 1, from which it will be noted that the development of Columax is an outstanding achievement.

A newcomer to the ranks of permanent magnet materials is a cobalt-platinum alloy, which has some unique mechanical and magnetic properties. It is claimed that a permanent magnet (having a cubic capacity of about 1 $cm.^3$) made up in this alloy has lifting power of the order of 24 times that of Alnico V. It also has a very high Hc (coercive) force. For small-sized magnets values of BH(max.) of 8×10^6 and of Hc of 4,500 oersteds have been obtained.

A curious characteristic of this cobalt-platinum alloy is that the enhanced magnetic qualities are lost as the cubic capacity is increased. For instance, if two magnets, one in Alnico V and the other in cobalt-platinum each of, say, 100 cubic cms. are compared then the Alnico magnet has superior magnetic properties.

It is appreciated that the cobalt-platinum alloy is a very expensive material, but, where a very small magnet with a high resistance to de-magnetisation is required, use may be found for it.

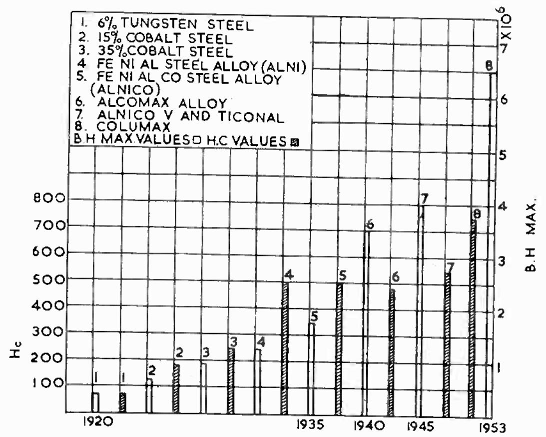


Fig. 1

An additional uncommon property of the cobalt-platinum alloy is its ductility. Machining presents no difficulties as it does with the majority of permanent magnet alloys. It is a curious fact that platinum (which for practical purposes is non-magnetic) when alloyed with cobalt should give rise to such extraordinary magnetic properties. Odd though it may appear, present-day thought seems to favour investigation on non-magnetic elements alloyed to magnetic elements to produce magnetic materials having superior properties to those obtained from purely magnetic elements. No doubt this dates from the time when a non-magnetic element, i.e., aluminium, was first employed in the production of magnetic materials. Even silver and copper have been used in some recent magnetic materials.

Powdered Iron Magnets

Although compressed iron dust has been employed in radio apparatus for a number of years, it is only recently that the crystal size of the iron powder has been investigated.

Results have shown that the Hc value varies with the size of crystal or particle employed. This is well illustrated by the curve shown in Fig. 2. Powders of very small crystal size are now referred to as iron micro-powders and magnets are produced from these under very high pressure.

For a crystal size about $0{\cdot}0154\mu$, $Hc = 1{,}000$ oersteds, which is a suitable value for permanent magnets. For crystal sizes between $1{\cdot}0\mu$ and 10μ Hc falls to less than 10 oersteds, a value suitable for making radio dust iron cores.

Permanent magnets may be formed by using micro-powders of different elements. An alloy of iron 70% and cobalt 30% has a BH(max.) value of $1{\cdot}7 \times 10^6$, a value comparable to that of the Alnico magnet, but the S.G. is only 4·5 as against 8·1 for Alnico.

Thus a permanent magnet made from micro-powders has the same potential energy as an Alnico magnet made from twice the weight of raw material. As cobalt is an expensive metal there is a considerable saving in first cost. The final cost of the finished product is also reduced as micro-powder magnets can be moulded to very fine limits and no machining is necessary.

It should be noted that the above method of producing magnets is not a sintering process as no heat is employed and the adhesion of the iron particles is solely due to the high pressures employed.

The development of magnetic materials covers such a vast field that it is impossible to consider all the developments in this article, but one recently developed magnet called " Ferroxdure " is worthy of note as it differs in some very remarkable ways from magnets already referred to. It is made by sintering together the compressed oxides of iron and barium.

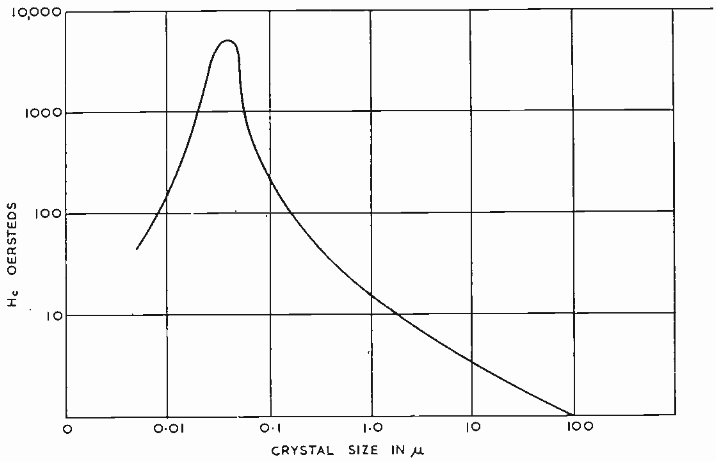


FIG. 2

Size of crystal-magnetic properties pure iron.

The following figures are of interest: BH(max.) $1{\cdot}05 \times 10^6$, Hc 1,450 oersteds permeability 1·2, electrical resistance 10^8 ohms per cm^3. Curie temperature 450° C. S.G. 4·8 gm/c.c.

Ferroxdure may be considered as an insulator. It has low dielectric losses, may be used at high temperatures and is usefully employed in low frequency circuits at about 30 to 40 Kc/s.

Machining of Hard Metal Alloys

It is a well known fact that most of the alloys employed in the manufacture of permanent magnets are extremely hard and the only possible method of machining the magnet casting is by grinding. Any holes required had to be provided for when casting. A machine has been developed whereby the hardest of materials, even tungsten-carbide tool tips, may be machined.

Referring to Fig. 3, which shows a diagram of the machine, the condenser C is charged from the D.C. supply A through the resistance B and is discharged by sparking across the gap G. The frequency of these discharges is of the order of 1,000 per second. Bombardment of the work by sparks causes the metal K near the electrode D to disintegrate into small particles which are washed away by the oil in the tank E. It would appear that the disintegration is a mechanical process for there is no physical nor chemical change either in the work or the particles forced off.

The clearance between the electrode and the wall of the hole to be formed depends upon the gap and therefore upon the voltage across the gap, from which it follows that the electrode must be automatically lowered so that the gap remains constant. With a voltage of 200 the gap required is 0·006 inch and this will be the clearance in the finished hole, or in other words the diameter of the hole will be $\pm 0{\cdot}006$ inch. The time to drill a $\frac{1}{2}$ inch hole 1 inch deep takes about 35 minutes. The time will be reduced if a larger gap and a higher voltage are used but the clearance will be greater and hence the diameter of the hole will not be so accurate. The power required to operate the machine is 7 kW.

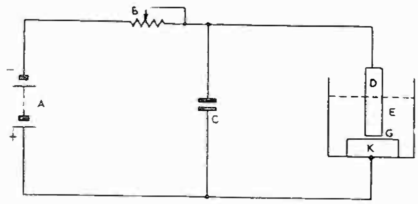


FIG. 3

The size and shape of the hole is governed by the size and shape of the electrode. If the electrode is screw threaded then the hole will be threaded but in this case the gap must be very small and the time to form the hole will be increased.

It will be obvious that the use of such a machine is somewhat limited, but it should at least be of value to manufacturers of permanent magnets.

Non-Metallic Materials

Nylon, available in the past only as cord, is not suitable as an insulator in high frequency circuits because of its high power factor (2·3) and S.I.C. (5·0). It is now available as a powder (trade name Akulon) which may be moulded, cast, or extruded at its melting point 220° C. Small gear wheels, bearings, etc., made in this way do not require any machining, but moulded rod and sheet can easily be machined if necessary.

Moulded parts have the following properties—S.G. 1·13. Tensile strength up to the elastic limit 9,000 lbs/sq. in. Ultimate tensile strength 37,000 lbs/sq. in. Elongation 460%. The coefficient of friction is very low, and two moulded gear wheels meshed together do not require any lubricant although water may be used for this purpose. The life of two such wheels is three times the life of wheels made in steel. The limits of temperature for working components made of Nylon are + 120° and −40° C.

As the electrical resistance is good—of the order of 1×10^{13} ohms per cm^3—bearings in the above material can be employed to insulate a metal spindle. Although the tensile strength is about half that of mild steel, lightly loaded steel gear wheels can be replaced by moulded wheels which are only one-seventh of the weight. The lightness of this new material will make it a valuable asset for the manufacturers of aircraft instruments.

Another well established material, Polyvinyl-Chloride (P.V.C.) which is used extensively as cable sheathing, is now being put to other uses, i.e. for separators between plates in secondary batteries and for very fine filters. A method of making porous P.V.C. has been evolved. P.V.C. is filled with sufficient fine grain maize starch so that the particles are in contact. The starch is then hydrolysed and removed from the plastic leaving a matrix of P.V.C. of uniform size. Hydrolysis causes the starch to swell slightly and the cells formed are therefore connected to adjacent cells by a small opening. The diameters of the cells and openings are perfectly uniform being, in a particular case, 0·015 mm. for the cells and 0·001 mm. for the openings, but these sizes may be varied if necessary. When aerated P.V.C.

is used as a filter, solid particles are stopped at the surface. Thus clogging does not occur, as it does in the case of paper filters, and cleaning of the filter is facilitated. The volume porosity is 85% and the thickness of a sheet is 0·75 mm., so that a battery with P.V.C. separators may be made more compact than with normal wood separators.

A similar process might improve the properties of other dielectrics used on high frequencies. I.C.I. are in fact carrying out development work on polythene. The polythene is mixed with a chemical which liberates a gas and forms numerous gas filled cells which are trapped when the material cools down. Advance information indicates that polythene so treated has a power factor of 0·005 and a dielectric constant of 1·4 which gives a loss factor of 0·0007 as against 0·0012 for the normal polythene.

Foam glass has been prepared in a similar manner and has the following properties. Power factor 0·005, dielectric constant 1·8 at 10 Mc/s, and S.G. 0·2. It is not porous and will float in water. It may be cut with a saw and is easily machined. As the finished product is only 6% glass it may be useful as a thermal insulant up to temperatures of 750° F. The heat conductivity is of the order 0·4 B.T.U.s per sq. ft. per inch thick per 1° F. The mechanical strength is very low, but for thermal insulation this may not be a necessary requirement.

PROPERTIES OF MATERIALS AT RADIO FREQUENCIES

	S.I.C.	Power Factor	Q.	Loss Factor	Frequency Mc/s.
Bakelite	4·3	0·03	33	0·13	1·0
Mica	7·0	0·0006	1,600	0·0042	1·0
Mycalex	6·1	0·003	330	0·018	1·0
Polystyrene ...	2·65	0·0005	2,000	0·0013	10·0
Polythene	2·3	0·0005	2,000	0·0011	10·0
Polyvinyl-Chloride (P.V.C.)	5·4	0·07	14	0·38	1·0
Porcelain	5·4	0·0063	160	0·034	10·0
Pyrex Glass ...	4·4	0·0006	1,650	0·0027	10·0
Quartz (fused) ...	4·2	0·00017	6,000	0·00072	10·0
WT/22 (Loaded Rubber)	3·6	0·0058	170	0·021	10·0

FIG. 5

Before leaving dielectric materials it is of interest to examine the properties of materials at radio frequencies. The values given in Fig. 5 in the column "Loss Factor" are obtained by multiplying the S.I.C. by the Power Factor and these values are generally accepted as an indication of suitability of dielectrics for use in radio frequency circuits. Until recently a loaded ebonite WT/22 was generally the most suitable material which could be machined easily, but at very high frequencies the loss factor of WT/22 is too high and it has been replaced by polythene which, as will be noted, has a very low loss factor which does not increase greatly at frequencies exceeding 10 Mc/s.

Mycalex absorbs moisture which results in a higher loss factor and its use is more or less confined to transmitters where it is dried out quickly because of heat being generated. Quartz has the lowest loss factor but it is only used in special cases because it cannot be machined.

Mica Pulp

A process has recently been evolved whereby scrap mica is treated to form what has been termed mica pulp and a short description of this process may prove of interest. The scrap mica is first heated up to a temperature of about 800° C. which causes it to be puffed, after which it is placed in a solution of sodium carbonate. This treatment removes all the air from between the layers. It is then drained and placed in a dilute solution of sulphuric acid which reacts with the alkali and gives off carbon dioxide which breaks the leaves apart causing them to swell to a thousand times the original thickness. The material is washed and is now referred to as mica pulp and mica sheet may be formed from it in a normal paper-making machine. The thickness of each minute leaf is about 1×10^{-3} mm. and the thinnest sheet which can be made from these leaves is about 20×10^{-3} mm. Sheets may be bonded together with silicone varnish which has a S.I.C. of 2·4 and a power factor of 0·0002. A plate so formed has electrical properties about equal to that of split mica.

PUBLICATION NOTICE

Amplitude-Frequency Characteristics of Ladder Networks

"Amplitude-Frequency Characteristics of Ladder Networks" (pp. 164 with 88 diagrams, price 25s.), a Marconi Monograph by E. Green, M.Sc., has now been published and copies are obtainable on application to:—

Technical Information Division,
Marconi House,
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This Monograph deals with the design of Ladder Networks to give desired exact amplitude characteristics. The general synthesis of these networks to give Butterworth or Chebyshev amplitude response in the pass band, dealt with in the first part of the book, is applied, in the second part, to the design of normal filters, broadband valve couplings or couplings between a transmission line and a reactive load. A full bibliography of the subject is given and a foreword has been written to the book by Milton Dishal of the Federal Telecommunication Laboratories, U.S.A.

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THE MARCONI REVIEW

No. 118. Vol. XVIII *3rd Quarter, 1955.*

Editor : L. E. Q. Walker, A.R.C.S.

WIDE BAND MICROWAVE RADIO LINKS

By S. Fedida, B.Sc. (Eng.), (Hons.), A.C.G.I., A.M.I.E.E.

A broad survey of the techniques used in the construction of wideband microwave links is given, with particular emphasis on the applications of travelling wave tubes, in these links.

Some of the design requirements are examined in the light of the conclusions of the C.C.I.R. Study Group IX, meeting at Geneva, at the end of 1954.

Historical

EXPERIMENTS made before the war[1] have shown that the use of radio links at VHF and UHF was quite practicable for the carrying of telephone and telegraph traffic. The development of these links, after the war, was, in the main, concentrated in the VHF bands, and the quality and reliability of these links was found to be comparable with that of coaxial cables, while the initial cost was considerably lower. Furthermore they provided an almost ideal medium for the conveyance of traffic, in relatively undeveloped countries, where the establishment of wire circuits is both an expensive and hazardous operation.

However, with the very considerable expansion of telephone traffic and the added requirement for the transmission of television signals, it was quite clear that only the UHF and SHF ranges could provide sufficient spectrum space to accommodate the very wide bandwidths that were becoming necessary. The VHF range was becoming overcrowded to such an extent that the design of equipment capable of carrying sufficient traffic of adequate quality was becoming extremely difficult and onerous, mainly because of bandwidth limitations.

In the case of radio links carrying 600 telephone channels, the signal bandwidth is approximately 2·5 Mc/s, while for a 625 line monochrome television signal, the highest modulation frequency is 5 Mc/s. The need for a high order of linearity in multichannel telephony systems, at any rate, requires the use of frequency modulation, Mycalex absorbs moisture which results in a higher loss factor and its use is more or less confined to transmitters where it is dried out quickly because of heat being generated. Quartz has the lowest loss factor but it is only used in special cases because it cannot be machined.

Mica Pulp

A process has recently been evolved whereby scrap mica is treated to form what has been termed mica pulp and a short description of this process may prove of interest. The scrap mica is first heated up to a temperature of about 800° C. which causes it to be puffed, after which it is placed in a solution of sodium carbonate. This treatment removes all the air from between the layers. It is then drained and placed in a dilute solution of sulphuric acid which reacts with the alkali and gives off carbon dioxide which breaks the leaves apart causing them to swell to a thousand times the original thickness. The material is washed and is now referred to as mica pulp and mica sheet may be formed from it in a normal paper-making machine. The thickness of each minute leaf is about 1×10^{-3} mm. and the thinnest sheet which can be made from these leaves is about 20×10^{-3} mm. Sheets may be bonded together with silicone varnish which has a S.I.C. of 2·4 and a power factor of 0·0002. A plate so formed has electrical properties about equal to that of split mica.

PUBLICATION NOTICE

Amplitude-Frequency Characteristics of Ladder Networks

" Amplitude-Frequency Characteristics of Ladder Networks " (pp. 164 with 88 diagrams, price 25s.), a Marconi Monograph by E. Green, M.Sc., has now been published and copies are obtainable on application to:—

Technical Information Division,
Marconi House,
Chelmsford.

This Monograph deals with the design of Ladder Networks to give desired exact amplitude characteristics. The general synthesis of these networks to give Butterworth or Chebyshev amplitude response in the pass band, dealt with in the first part of the book, is applied, in the second part, to the design of normal filters, broadband valve couplings or couplings between a transmission line and a reactive load. A full bibliography of the subject is given and a foreword has been written to the book by Milton Dishal of the Federal Telecommunication Laboratories, U.S.A.

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