An analysis of F as a function of G for the case of a passive network shows that F is a monotone decreasing function of G. Therefore it follows that the condition of maximum gain would correspond to that of minimum noise figure of the network. Consequently, if the mixer can be considered as a network whose noise contribution is of thermal nature, one would be interested in minimum loss for minimum noise figure.

Signal-Source Impedance Setup for Minimum Noise Figure

On the basis of the foregoing analysis an outline is given of the experimental setup for minimum noise figure source impedance.

1) General precautions should be taken as outlined by Wheeler and Dettinger [3].
2) The IF output is terminated by Pound's IF circuit [7]. With the switch in the short-circuit position, the VSWR is measured on the RF side and matched.
3) With the switch in the open-circuited position, tune the circuit to provide maximum VSWR $=r$ on the RF side which was previously matched, and measure r.
4) The plane corresponding to a maximum or minimum in the standing wave whose VSWR $=r$ is recorded and ρ is calculated.
5) A discontinuity is introduced in the line to set up a real impedance of magnitude $\rho=\sqrt{r}$ at the recorded plane.

Circumstances did not permit supplementing these considerations with experimental data.

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[3] Wheeler, H. A., and Dettinger, D. *Measuring the Efficiency of a Superheterodyne Converter by the Input Impedance Circle Diagram.* Wheeler Monographs, Wheeler Laboratories, Inc., Great Neck, N. Y., pp. 33–38; March, 1949.

[4] Torrey, H. C., and Whitmer, C. A. *Crystal Rectifiers.* New York: McGraw-Hill Book Company, Inc. (1948), pp. 115–116.

[5] *Ibid.* Eqs. (111) and (112), p. 138.

[6] Roberts, S. "Conjugate-Image Impedances," Proceedings of the IRE, Vol. 34 (April, 1946), pp. 198P–204P.

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[8] Haus, H. A., and Adler, R. B. "Optimum Noise Performance of Linear Amplifiers," to be published.

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A Broad-Band High-Power Vacuum Window for X Band*

H. J. SHAW† and L. M. WINSLOW‡

Summary—**Recent developments in high-power tubes for the 3-cm wavelength region have created a need for waveguide output windows which are capable of transmitting peak power in excess of 1 megw and average power in the neighborhood of 1 kw, and which have frequency bandwidths of about 15 per cent. This paper describes a structure which is designed to meet these electrical requirements, and which also has desirable physical and fabricational properties. A dielectric plug, which forms the vacuum seal, is used as one element of a three-element filter. The design procedure and experimental results are discussed.**

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Introduction

Vacuum windows present one of the major problems at present in the design of practical high-power microwave tubes. In the 3-cm wavelength region, recent developments[1] in high-power tubes have created a need for output windows which are capable of transmitting peak power in excess of 1 megw and average power in the neighborhood of 1 kw, and which have frequency bandwidths of about 15 per cent. Such windows are used in the output waveguides of high-power tubes to allow transmission of RF power from the

[1] M. Chodorow, E. L. Ginzton, J. Jasberg, J. V. Lebacqz, and H. J. Shaw, "Development of high-power pulsed klystrons for practical applications," to be published.

evacuated output cavities of the tube to a pressurized external circuit.

A dielectric element is employed which can be made transparent to the RF wave by suitable impedance matching. This can be accomplished by shaping the dielectric, as, for example, in tapered cone windows[1–3] and stepped windows[4,5] or by utilizing matching sections separate from the dielectric.[1,6,7] The present design, referred to as a filter window, uses separate matching elements, with the over-all structure designed as a three-element band-pass filter for broad-band operation.

Electrical Design

A half-wavelength dielectric plug of characteristic admittance Y_1 in a waveguide of characteristic admittance Y_0 has the following input admittance.

$$\frac{Y_{\text{in}}}{Y_0} = \frac{Y_1}{Y_0}\left(\frac{Y_0 + jY_1 \tan \beta l}{Y_1 + jY_0 \tan \beta l}\right) \tag{1}$$

where

$\beta = 2\pi/\lambda_{g1}$ = propagation constant in dielectric,

λ_{g1} = wavelength in dielectric plug in waveguide.

l = length of dielectric plug along the axis of propagation.

At the frequency for which $l = \lambda_{g1}/2$, Y_{in} is equal to Y_0, and an impedance match results. In the neighborhood of this frequency, the input impedance of the dielectric plug is similar to that of a parallel resonant circuit, and can be described in terms of the resonant frequency and loaded Q. To evaluate the loaded Q, the $\tan \beta l$ in (1) is first expanded about the point $\beta l = \pi$. The resulting equation may be put into the form

$$\frac{Y_{\text{in}}}{Y_0} \approx 1 + j4Q_L \frac{\Delta f}{f_0} \cdot \tag{2}$$

This may be recognized as the input admittance of a parallel resonant circuit connected across a waveguide of characteristic admittance Y_0, where f_0 is the resonant frequency and Q_L is the Q of the circuit when loaded on both sides by the characteristic admittance Y_0. In terms of parameters for the dielectric plug, Q_L is found to be

$$Q_L \approx \frac{\pi}{4}\left(\frac{\lambda_{g0}}{\lambda_{g1}} - \frac{\lambda_{g1}}{\lambda_{g0}}\right)\left[1 - \frac{1}{K}\left(\frac{\lambda}{2a}\right)^2\right]^{-1} \tag{3}$$

[2] J. E. Shepherd, "Harnessing the Electron," *Sperry Eng. Rev.*, vol. 10, pp. 7–8; March/April, 1957.

[3] L. H. LaForge, "Application of ceramic sections in high-power pulsed klystrons," *Amer. Cer. Soc. Bull.*, vol. 36, pp. 119–120; March, 1956.

[4] L. Ragan, "Microwave Transmission Circuits," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., pp. 218–227; 1948.

[5] H. K. Jenney, F. E. Vaccaro, "A step-type, broad-band X-band ceramic waveguide window," IRE Trans. on Electron Devices, vol. ED-3, pp. 30–32; January, 1956.

[6] H. G. Hereward and M. G. N. Hine, "A method of broadbanding waveguide windows," Proc. IRE, vol. 42, pp. 1450–1451; September, 1954.

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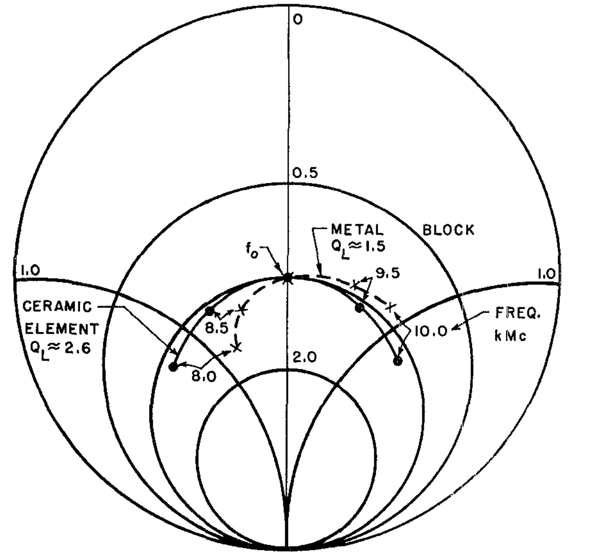

Fig. 1—Smith chart representation of theoretical input admittance of ceramic element and metal block elements.

where

λ_{g0} = guide wavelength in air-filled guide,

λ_{g1} = guide wavelength in dielectric-filled guide, and

K = relative dielectric constant.

For rectangular waveguide, we have

$$l_0 = \frac{\lambda_0}{2}\left[K - \left(\frac{\lambda_0}{2a}\right)^2\right]^{-1/2} \tag{4}$$

and

$$\frac{\lambda_{g0}}{\lambda_{g1}} = \left[K - \left(\frac{\lambda}{2a}\right)^2\right]^{1/2}\left[1 - \left(\frac{\lambda}{2a}\right)^2\right]^{-1/2} \tag{5}$$

where

λ = free space wavelength,

l_0, λ_0 = resonant values of l, λ, and

a = waveguide width (major axis).

A low value of Q_L is desired for broad-band operation. As can be seen from (4) and (5), Q_L is low for low dielectric constant and for waveguide operating far from cutoff. Fig. 1 illustrates the theoretical resonance properties of the specific commercial ceramic (Wesgo AL300) used in the present windows. It has a dielectric constant of about 9.3. The resonant frequency is 9.0 kmc, and the bandwidth over which the insertion loss is less than 0.1 db (VSWR less than 1.35) is 490 mc. The comparison of theoretical and experimental values of reflection coefficient is shown in Fig. 2.

To obtain greater bandwidth than provided by the resonant dielectric plug alone, the ceramic section is used as one element of a multielement band-pass filter. Filters of the type employed here have approximately the same bandwidth as a single element, when compared at the 3-db insertion-loss points. However, if the insertion loss is to be restricted to lower values, as in the 0.1-db example above, then the multielement filter may have a bandwidth much larger than that of a single ele-

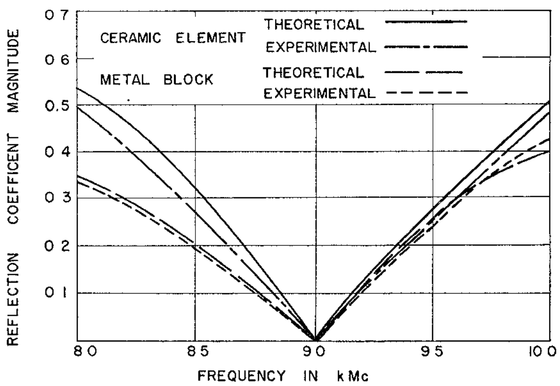

Fig. 2—Reflection coefficient vs frequency for ceramic element and metal block elements.

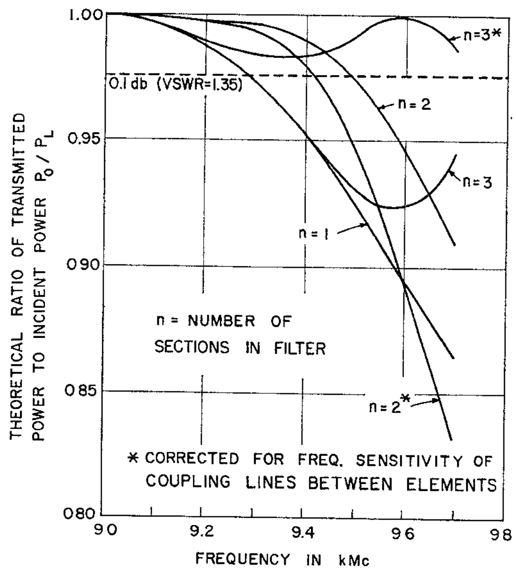

Fig. 3—Filter transmission characteristics for $Q_L=2.8$.

ment. The present filter is designed as a quarter-wavelength-coupled resonant element filter. The electrical characteristics of quarter-wavelength-coupled filters have been described by Ragan.[8] If all the elements have the same Q_L and resonant frequency, the ratio of incident power P_0 to transmitted power P_L, for n elements, is shown to be

$$\left(\frac{P_0}{P_L}\right)_n = 1 + x^2 U_n^2(kx) \tag{6}$$

where $U_n(kx)$ is the Tchebycheff polynomial of the second kind, k is a frequency-sensitivity correction, and x is the frequency variable. Specifically:

$$\begin{aligned} U_1(kx) &= 1 \\ U_2(kx) &= 2kx \\ U_3(kx) &= 4k^2x^2 - 1 \\ U_{n+1}(kx) &= 2kxU_n(kx) - U_{n-1}(kx) \end{aligned} \tag{7}$$

$$k = 1 + \frac{\pi}{4Q_L}\left[1 - \left(\frac{\omega_c}{\omega}\right)^2\right]^{-1} \tag{8}$$

$$x \approx 2Q_L \frac{\Delta f}{f} \tag{9}$$

w_c = waveguide cutoff frequency.

The factor k is used to correct for the change in electrical length of the coupling lines between elements as the frequency changes. The power transmission ratios for filters with $Q_L=2.8$ and $f_0=9000$ mc in H-band waveguide are shown in Fig. 3. The uncorrected curves are computed with $k=1$, while for the corrected curves k is evaluated according to (8). An inspection of the curves shows an increase in bandwidth, for a specified insertion loss, as an advantageous effect of the frequency sensitivity of the coupling lines.

The three-section filter was chosen because of its low insertion loss and adequate pass band for our application. The ceramic is used as one element of the filter. The other elements may be composed of various types of resonant devices, such as waveguide cavities, irises, or capacitive obstacles.[9] The particular element chosen for our application is termed a resonant block, and consists of a metal rectangular parallelepiped placed in the waveguide to periodically change the waveguide impedance. It is in effect a form of capacitively coupled rectangular waveguide cavity. These blocks may take different physical forms, as shown in Fig. 4, while retaining similar electrical properties.

The blocks were chosen as the resonant elements because they lead to a simple assembly and can provide optical shielding of the ceramic, as discussed later. A single centered block used in conjunction with the symmetric blocks may shield the ceramic optically while operating as desired electrically.

In a similar manner, two asymmetric blocks connected to the opposite sides of the waveguide may be used, but local fields between elements have been observed to couple power into undesirable modes in the ceramic section. This effect is detected during cold testing as a narrow peak in the curve of reflected power as a function of frequency. In use, higher mode resonances in a window can cause sparking and power loss. An advantage of the present dielectric geometry is that the resonant frequencies are calculable as functions of the various dimensions.

The blocks have a resonant frequency and an effective loaded Q which are functions of the block and waveguide dimensions. The theoretical properties are shown on a Smith chart in Fig. 1, and a comparison between theory and experiment is shown in Fig. 2, for the particular case of $f_0=9.0$ kmc and $Q_L=1.5$. The electrical properties of the resonant blocks can be found by considering the admittance Y_1 for the waveguide section with the block,

[8] *Op. cit.*, pp. 613–716.

[9] L. M. Winslow, "A wide-band ceramic waveguide window," Engineer's thesis, Stanford University, Stanford, Calif.; August, 1956.

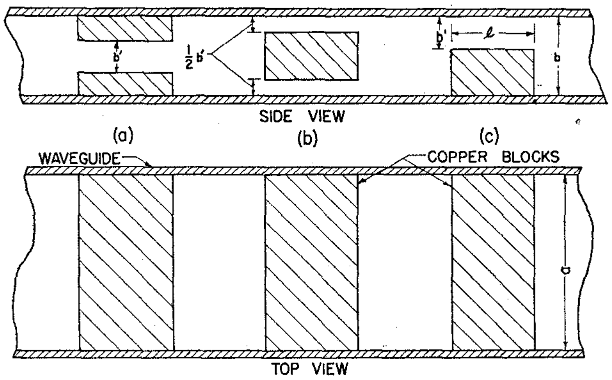

Fig. 4—Resonant block elements. (a) Symmetric block, (b) single centered block, (c) asymmetric block.

$$\frac{Y_1}{Y_0} = \frac{b}{b'} = c \tag{10}$$

where b is the height of the waveguide, and $b - b'$ is the height of an asymmetric block, or twice the height of a symmetric block, as shown in Fig. 4.

The resonant length is

$$l = \frac{\lambda_g}{2\pi} \tan^{-1}\left(\frac{2B_d c}{B_d^2 + 1 - c^2}\right) \tag{11}$$

where B_d = discontinuity susceptance at f_0.

A fair approximation for Q_L may be made for small B_d as follows:

$$Q_L \approx \frac{\pi}{4}\left(c - \frac{1}{c}\right)\left[1 - \left(\frac{\lambda}{\lambda_c}\right)^2\right]^{-1}. \tag{12}$$

The filters discussed thus far have had identical Q_L's. Since the value of the Q limits the bandwidth, it is logical to decrease the Q. This can be done for the matching elements, but it cannot be done for the ceramic element. In the Tchebycheff design of quarter-wave-coupled filters, the end elements are of lower Q than the center elements, in which case the end elements act also as impedance transformers. In the present filter-window case, however, this scheme is not employed, as we desire to confine the matching elements to the vacuum side of the ceramic section, and thus one end element must be the ceramic element. Rather than complete an analytic solution to the problem of staggered Q, as applied to the present case, which would need to include frequency sensitivity of the line and element, the solution was found experimentally, first numerically on a Smith chart and then with a cold-test setup.

The final design for a filter window centered at 9.0 kmc was a structure using two elements with $Q_L = 1.5$ and the ceramic element of $Q_L = 2.6$. The physical picture is shown in Fig. 5, and the measured electrical properties are given in Fig. 6. The 0.1-db bandwidth is 1430 mc, or 16 per cent.

High-Power Properties

With regard to power handling capacity, both peak power and average power effects must be considered.

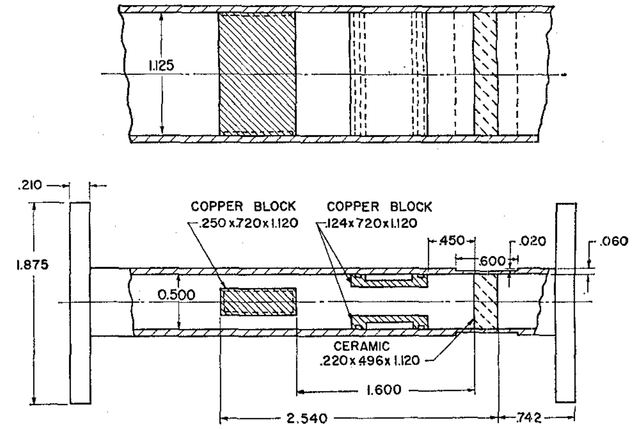

Fig. 5—Filter window in H-band waveguide centered at 9.0 kmc.

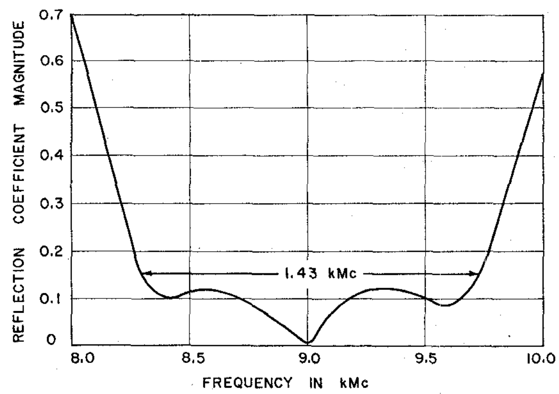

Fig. 6—Measured transmission properties of the filter window of Fig. 5.

Taking first the question of transmitting high peak power, one aspect concerns breakdown due to high RF electric field strength E. In the present design, the dielectric region and the waveguide on the output side of the assembly both have smooth detailed geometry, free of irregularities which can lead to localized regions of high E. Gaps between the interfaces of the ceramic edges and waveguide walls, where large E could be developed, are not difficult to avoid with the present geometry. Sharp edges caused by metallizing or by brazing material on the dielectric face on the output side of the window are avoided during fabrication, as mentioned later. The transmission properties of the dielectric plug are such that E within the dielectric never exceeds that in the output waveguide. Thus, in the dielectric and output waveguide sections, the full power capabilities of normal H-band waveguide should be realizable. The theoretical value of breakdown voltage at atmospheric pressure in uniform H-band waveguide at these frequencies corresponds to a peak power level of 1.77 megw.[10]

On the vacuum side of the dielectric section, breakdown due to high peak power would probably be an unimportant consideration were it not for possibilities of

[10] Ragan, *op. cit.*, p. 191.

multipactor[11,12] discharge. This is a form of secondary electron loading which can dissipate RF energy. It is an electron transit-time phenomenon and could in principle be established, at certain peak-power levels, in the spaces formed by the loading bars.

There is considerable evidence that successful operation of windows at high peak powers requires shielding of the dielectric element from direct optical paths leading to interior of tube. This presumably avoids breakdown resulting from electrons reaching the dielectric. In the present design, the loading bars which provide electrical broadbanding also provide optical shielding.

With regard to average RF power capability, the following statements can be made. The rectangular geometry of the ceramic element has short paths from interior points of the ceramic to the top and bottom walls of the waveguide. This provides for cooling of the interior points, as heat developed within the ceramic due to dielectric RF loss can be effectively carried away through the conductivity of the ceramic. The axial distribution of E within the dielectric is such that it is never larger than in the external waveguide, and E^2 in the axial center of the dielectric is about 10 per cent of its value in the external waveguide. Thus, from the viewpoint of the gross ratio of heat conductance to total internal heat developed, the thick dielectric should be better than a thin one (except possibly in the case of forced convection cooling). This does not take account of the relation between spatial distribution of thermal stress and over-all symmetry of the dielectric which probably is also of importance.

The power handling capabilities of this window have been evaluated in two series of tests. One of these was a laboratory-type experiment in which a model of the window, constructed as described above, was inserted in the output waveguide system of a megawatt klystron, so that the output power of the klystron was transmitted directly through the test window and then to a matched load. To evaluate the window in the correct environment, the section of waveguide leading from the klystron to the test window was evacuated, so that the input section of the window containing the copper filter blocks operated in vacuum as it would if installed directly on a tube. The waveguide leading from the output side of the window to the matched load was pressurized at about three atmospheres. The pressure of three atmospheres was necessary to avoid breakdown in the waveguide circuitry associated with power monitoring apparatus. This was a fixed-frequency experiment with the klystron operating at 9000 mc. No breakdown of any kind was observed while transmitting peak power of 1 megw through the window. The klystron modulator capacity limited the average RF power through the window to 100 watts.

[11] K. Bol, "The multipactor effect in klystrons," 1954 IRE Convention Record, pt. 2, pp. 151–155.

[12] G. Abraham, "Interaction of electrons and fields in cavity resonators," Ph.D. dissertation, Stanford University, Stanford, Calif.; 1950.

A second evaluation, covering both peak and average power, was obtained from operational data on an industrial megawatt X-band klystron developed by General Electric Company, Palo Alto, Calif., on which the output window is an adaptation of the present design. Differences from the present window design consist of various changes in fabrication technique which adapt the window assembly to the particular processes employed for commercial manufacture. The output window on this tube has transmitted peak power on the range of 1 to 2 megw, and average power in the range of 1 to 2 kw, over the frequency range of 8500 to 9600 mc, which is the tuning range of the klystron. The tube was operated into a waveguide system pressurized in the range of one to three atmospheres.

Fabrication

In the models described here, the ceramic block is brazed directly into OFHC copper waveguide by procedures which have been successfully used in other ceramic applications.[3] The waveguide wall thickness is reduced to 0.020 inch in the region of the ceramic, and a molybdenum clamp is placed on the outside of the waveguide in this region to keep the copper from expanding away from the ceramic during brazing. The moly-manganese process is used to metallize the ceramic edges, and a hydrogen furnace braze to the waveguide is made using a Silcoro solder ring placed on the vacuum side of the ceramic. The copper matching blocks are brazed in beforehand using Nicoro solder. Stainless steel jigs are used to hold all internal parts in place during brazing.

No trouble has been experienced in obtaining vacuum-tight seals around the rectangular ceramic block. The simgle rectangular shape is easy to grind to close tolerance. The corners to be brazed are given a slight radius. Final grinding of the broad faces is done after metallizing of the edges; this cleans up any of the metallizing mixture which may have run over onto the faces. The completed window assembly has been subjected to repeated bakeouts at 450°C without trouble.

The thick ceramic block results in a rugged assembly. Forces due to pressurizing of the external waveguide, at several atmospheres if desired, present no problem. Since optical shielding of the ceramic is achieved by means of the matching bars, the assembly can be mounted directly at the output cavity of a klystron or traveling-wave tube, forming a compact output system.

Acknowledgment

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