A High-Power Wide-Band Waffle-Iron Filter*

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Summary—**This paper describes the design and measured performance of an L-band model of a high-power wide-band low-pass waffle-iron filter. Three different waffle-iron filters with staggered stop bands are connected in series to give a combined stop band that extends from 2.2 Gc to 13.7 Gc. where the attenuation is 60 db or greater. The waffle-iron filter attenuates all propagating waveguide modes which can propagate at frequencies in the above stop band. In the pass band the waffle-iron filters are matched to full size L-band waveguide using quarter-wavelength stepped transformers. The pulsed power-handling capacity without breakdown is measured to be over 1.4 Mw peak power with air at atmospheric pressure filling the filter.**

Introduction

THE WAFFLE-IRON filter described in this paper is designed for use in high-power systems where it is desirable to suppress the harmonic frequencies generated by the transmitter. The filter consists of three different waffle-iron filters in series which have a combined stop band including the second through tenth harmonic frequencies. A photograph of the filter opened up and disassembled for inspection is shown in Fig. 1. The three waffle-iron filters are connected together through quarter-wavelength transformers, which match their impedances in the pass band (1.25 Gc to 1.35 Gc). Not shown are the three-section quarter-wavelength transformers that match the input and output ends to the full-size waveguide. The waffle-iron filter was originally conceived by Cohn.[1,2] The high-power capacity of the waffle-iron filter has previously been demonstrated.[3]

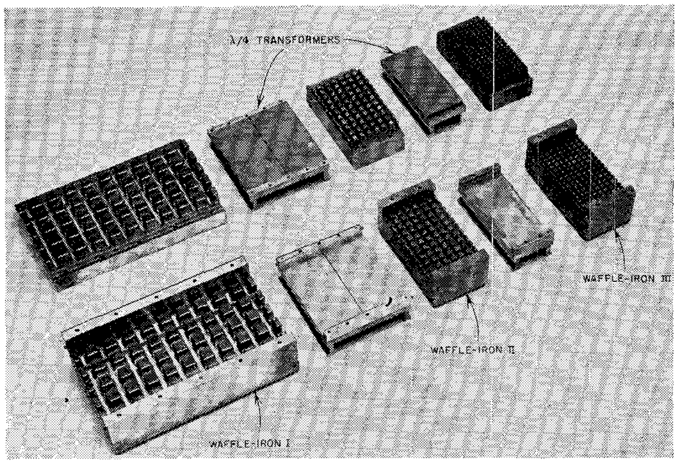

Fig. 1—Disassembled waffle-iron filters and connecting quarter-wave transformer sections.

Theoretical Design of Waffle-Iron Filters

General

The waffle-iron filter is a corrugated, varying-impedance, waveguide filter, based on the one shown in Fig. 2, but longitudinal slots added. The addition of the latter makes the filter response dependent upon frequency instead of guide wavelength for TE_{m0} modes. The attenuation of the TE_{m0} modes can be explained by decomposing these modes into two TEM waves traveling diagonally. Because of the two-dimensional symmetry of the waffle-iron filter, the TEM waves are attenuated alike, independent of the direction of travel, as long as the center-to-center spacing of the waffle-iron sections is small compared to one-half wavelength. Thus, for closely spaced teeth, the waffle-iron filter attenuation depends only upon the frequency and is independent of the mode of propagation. The waffle-iron filter described here is an approximation to this ideal, because the center-to-center spacing of the teeth is an appreciable fraction of a wavelength; however, the experimental measurements show that all modes are attenuated by the waffle-iron filter. The orthogonally polarized (TE_{0n}) modes are reflected before they reach the filter because the height of the impedance matching waveguide connected to the filter is much less than one-half wavelength. Modes with both components of polarization are partially reflected and partially converted to TE_{m0} modes at the input to the waffle-iron filter and are subsequently attenuated by it. Therefore, the waffle-iron filter described attenuates all propagating waveguide modes whose frequency lies in the stop band of the filter.

The procedure used to design the waffle-iron filters is as follows. First, one determines the dimensions of the corrugated waveguide filter of Fig. 2 that give the required frequency pass and stop band assuming that a TEM mode is propagating longitudinally. Then the longitudinal slots, whose dimensions are the same as those of the transverse slots, are added as shown in Fig. 3. The only dimension of the first design which must be

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[1] S. B. Cohn, C. Flammer, E. M. T. Jones, and B. M. Schiffman, "Design Criteria for Microwave Filters and Coupling Structures," Stanford Research Inst., Menlo Park, Calif., Tech. Rept. No. 2, Contract DA 36-039 SC-74862; June, 1958

[2] S. B. Cohn, "Design relations for the wide-band waveguide filter," Proc. IRE, vol. 38, pp. 799–803; July, 1950.

[3] H. Guthart and E. M. T. Jones, "A high-power *S*-band filter," IRE Trans. on Microwave Theory and Techniques, vol. MTT-10, pp. 148–149; March, 1962.

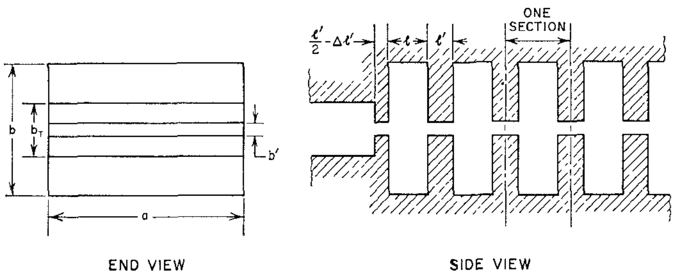

Fig. 2—A low-pass corrugated waveguide filter.

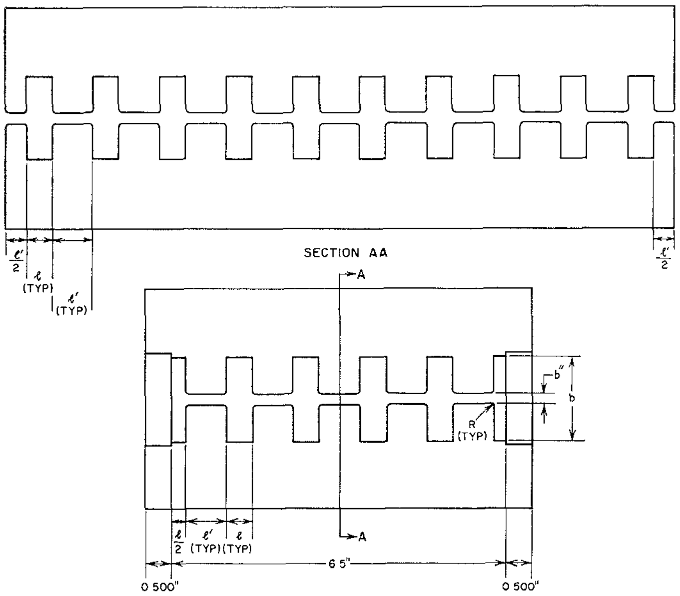

Fig. 3—Typical high-power waffle-iron filter.

changed is b'; b' is reduced to b'' so that the capacitance between the teeth of the waffle-iron filter equals the capacitance of the corrugated filter. It is assumed that the inductance of the filter is not changed by the addition of the longitudinal slots, because the slot width is much smaller than one-half wavelength and the magnetic field extends into the slot only slightly. Maintaining the capacitance and inductance of the waffle-iron filter equal to that of the corrugated filter ensures that the frequency response of the waffle-iron filter is the same as that of the corrugated filter, except for an improved stop band.

Design of Waffle-Iron Filter I

The three waffle-iron filters are designed to have the staggered stop bands shown in Fig. 4, where the attenuation constant of each filter is plotted against frequency. The cutoff frequency and the infinite attenuation frequency of Waffle-Iron Filter I are chosen to be $f_{cI}=2.0$ Gc and $f_{\infty I}=5.2$ Gc, respectively. The corrugated waveguide filter prototype is designed by the method due to Cohn,[2] using free-space wavelength rather than guide wavelength as a design parameter. The pass-band center frequency is chosen to be 1.3 Gc and the height of the terminating waveguide b_T is chosen to be 0.588 inch. The resulting dimensions for Waffle-Iron Filter I, determined from the design graphs of Cohn, are listed in Table I. The design tooth spacing b' is reduced by 25 per cent to a value of b'' of 0.210 inch to take into account the effect of reduced capacitance due to the longitudinal slotting. Based upon previous calculations and measurements, the length of ten sections of Waffle-Iron I should give about 80-db attenuation throughout the stop band.[1,3]

The dimensions of this first waffle-iron filter can be varied somewhat; the design given in Table I results from trade-off between power handling capacity and bandwidth. To increase the tooth spacing b'', one must either narrow the stop band or decrease sharply the tooth width l', which decreases the tooth area supporting the electric field. Fitting an integral number of filter sections within the waveguide width also limits the choice of filter dimensions. The stop band of Waffle-Iron Filter I should be as wide as permissible so that the number of filters required to produce a given stop band is minimized.

All external corners in the regions of high electric field strength are rounded as shown in Fig. 3; the amount of rounding was determined from the graphs given by Cohn.[4] The rounding is sufficient to keep the maximum electric field strength at the rounded corners to within 1.4 times the electric field strength at the middle of the tooth. The degree of rounding for each waffle-iron is listed in Table I.

Design of Waffle-Irons II and III

The design of the next two waffle-irons is accomplished by using the equivalent circuit data for E-plane T-junctions given in Marcuvitz.[5] The ratio b'/b becomes much greater than 0.1 where the graphs of Cohn[2] do not apply. The tooth spacing b'' was maintained equal to that of the first waffle iron to maintain the breakdown strength of the second two approximately equal to that of the first waffle iron. The corrugated waveguide filter prototypes can be designed using the equivalent circuit of Fig. 5; the symmetry of the waffle iron allows an electric wall to be centered between the teeth. The equivalent circuit values for n, X, d, and d' are given by Marcuvitz.[6] The image impedance Z_I of the filter can be calculated from the bisected circuit of Fig. 5(c) as follows:

$$Z_I = \sqrt{Z_{sc} Z_{0c}} \tag{1}$$

[4] S. B. Cohn, "Rounded Corners in Microwave High-Power Filters and Other Components," Stanford Research Inst., Menlo Park, Calif., Tech. Note No. 1, Contract AF 30(602)-1998, June, 1960; also, IRE Trans. on Microwave Theory and Techniques, vol. MTT-9, pp. 389–398; September, 1961.

[5] N. Marcuvitz, "Waveguide Handbook," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 10, pp. 336–350; 1951.

[6] *Ibid.* When using Marcuvitz's curves for the E-plane T-junction, the parameter b/λ_g must be replaced by $2b/\lambda_g$.

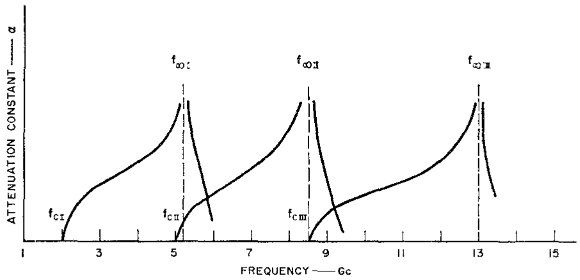

Fig. 4—Attenuation constants of waffle-iron filters.

TABLE I
DIMENSIONS OF WAFFLE-IRON FILTERS

Waffle	Dimensions (Inches)					Number of Sections		Length (Inches)	Radius of Rounded Corners (Inches)
	b'	b''	b	l	l'	In Width	In Length		
I	0.280	0.210	1.61	0 510	0.790	5	10	13.0	0.063
II	0.280	0.210	0.986	0.231	0.360	11	7	4.137	0.063
III	0.280	0.210	0.700	0.150	0.256	16	9	3.654	0.045
IV	0.280		0.560	0.100	0.195	22	15		

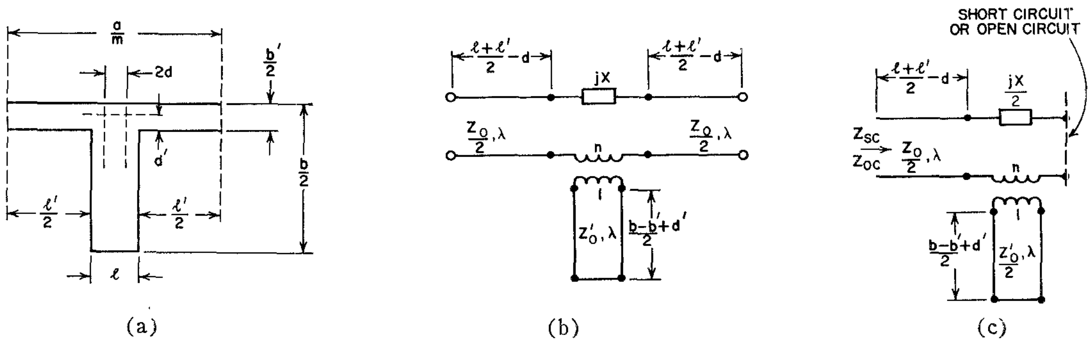

Fig. 5—Full-filter section—cross section of waffle-iron filter and equivalent circuit [at (c) the equivalent circuit has been bisected].

or

$$Z_I = \frac{Z_0}{2}\sqrt{\frac{2 + \cot\theta\left(\dfrac{X}{Z_0/2} + \dfrac{n^2 Z_0'}{Z_0/2}\tan\theta'\right)}{2 - \tan\theta\left(\dfrac{X}{Z_0/2} + \dfrac{n^2 Z_0'}{Z_0/2}\tan\theta'\right)}} \tag{2}$$

where

$$\theta = \frac{2\pi}{\lambda}\left(\frac{l + l'}{2} - d\right),$$

$$\theta' = \frac{2\pi}{\lambda}\left(\frac{b - b'}{2} + d'\right),$$

and λ is the free-space wavelength. The attenuation constant α and the phase constant β per filter section can be calculated as follows:

$$\tanh\left(\frac{\alpha}{2} + \frac{j\beta}{2}\right) = \sqrt{Z_{sc}/Z_{0c}} \tag{3}$$

or

$$\tanh\left(\frac{\alpha}{2} + \frac{j\beta}{2}\right) = \sqrt{\frac{\dfrac{X}{Z_0/2} + \dfrac{n^2 Z_0'}{Z_0/2}\tan\theta' + 2\tan\theta}{\dfrac{X}{Z_0/2} + \dfrac{n^2 Z_0'}{Z_0/2}\tan\theta' - 2\cot\theta}}. \tag{4}$$

Next the cutoff and infinite attenuation frequencies are determined from (2) and (4). The general behavior of the image impedance is shown in Fig. 6. The image impedance goes to infinity at the cutoff frequency f_c, thus f_c can be determined by setting the denominator of (2) equal to zero. The upper edge of the stop band occurs when the image impedance goes to zero at $f = f_c'$, therefore, the upper edge of the stop band is determined by setting the numerator of (2) equal to zero. The frequency at which the attenuation constant α becomes infinite gives f_∞ which is determined from (4) when the square root equals one, or when $\tan\theta'$ approaches infinity, or equivalently when the side arm is about one-quarter wavelength long, as follows:

$$\frac{\lambda_\infty}{4} = d' + \frac{b - b'}{2}. \qquad (5)$$

The upper edge of the stop band f_c' occurs when the length of the full filter section is about one-half wavelength long; thus the infinite attenuation frequency must be chosen to be less than the frequency at which the filter section is one-half wavelength long.

The above equations are used to perform a trial-and-error calculation to determine the filter dimensions to give the chosen critical frequencies. The typical design procedure follows: the value of $b' = 0.280$ inch is chosen to match that of Waffle-Iron I; a reasonable value of l is chosen; the value of b is determined from (5) using the chosen value of infinite-attenuation wavelength; using the chosen value of cutoff frequency given in Fig. 4, the denominator of (2) is set equal to zero to determine the value of l'. These design calculations are repeated several times, changing various chosen parameters until reasonable dimensions are obtained. The ratio of $l'/(l+l')$ was designed to be the same value in all three waffle irons to maintain a reasonable tooth area and to maintain the power-handling capacity. The dimensions so determined of Waffle-Iron Filters II and III are shown in Table I. In the final design the length of one section $l+l'$ must equal a/m so that an integral number of filter sections will fit within a waveguide width. Calculations of attenuation constant showed that to exceed a 60-db insertion loss at and above 5.75 Gc, seven sections of Waffle-Iron Filter II are needed. To exceed a 60-db insertion loss at and above 9.25 Gc, nine sections of Waffle-Iron Filter III are needed. In Filters II and III, the dimension b'' was chosen 25 per cent lower than b' or 0.210 inch.

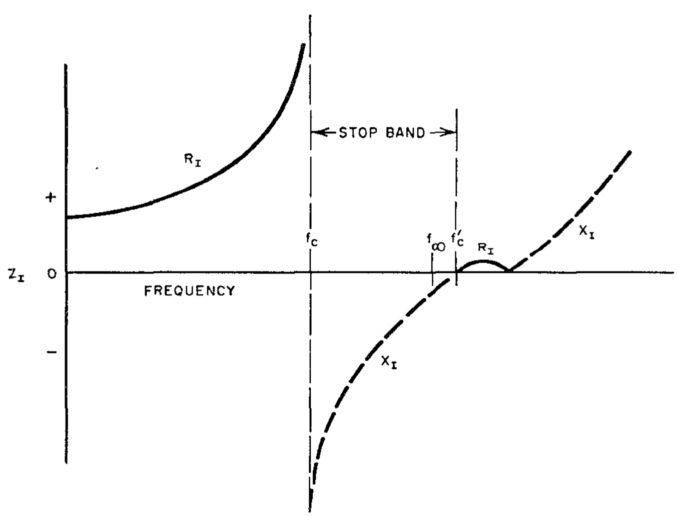

Fig. 6—Typical image impedance characteristics for a corrugated structure such as Fig. 2 having infinite width.

The theoretical design of a fourth waffle-iron filter—Filter IV—is given in Table I. With this waffle-iron filter added into the assembly, the stop band could be extended to 18 Gc, which includes the thirteenth harmonic frequency. The design cutoff frequency and infinite-attenuation frequency of Waffle-Iron Filter IV are 13 Gc and 18 Gc, respectively. Fifteen sections are required to achieve 60-db attenuation at 13.5 Gc and above.

Experimental Measurements

Low Power Measurements

It is convenient to use a slotted waveguide of reduced height to measure the pass-band image impedance of each waffle-iron filter. Each filter is connected in turn between the reduced-height slotted line and a waveguide of the same height (0.555 inch) containing the matched load. The experimental technique described by Dawirs[7] is used to measure the image impedance of each waffle-iron filter. The measured results are shown in Fig. 7 in terms of the height of a waveguide that has the same characteristic impedance as the image impedance of each waffle-iron filter. Note that the variation in image impedance over the frequency range shown in Fig. 7 is greater for Filter I than for Filters II and III; this is because Waffle-Iron Filter I is being operated closer to its cutoff frequency than are Waffle-Iron Filters II and III. The variation in image impedance of Waffle-Iron Filter I can be reduced by adding matching sections at each end.[3]

Quarter-wave transformers are designed to match the waffle irons to each other and to full-size waveguide in the design pass band of 1.25 to 1.35 Gc. Using the image impedance data of Fig. 7 and the quarter-wave transformer tables of Young[8] the two-section quarter-wave transformer designed to match Waffle-Iron Filters I and II is shown in Fig. 8. A one-section quarter-wavelength transformer of height 0.341 inch similarly matches the impedances of Waffle-Iron Filter II and Filter III. The three-section quarter-wave transformers matching the Filters I and III respectively to full-size L-band waveguide are shown in Fig. 9 with the corners rounded.

The VSWR obtained with the combination of three waffle-iron filters and four transformers is 1.2 or less from 1.25 to 1.4 Gc, and is less than 1.23 from 1.24 to 1.5 Gc. The pass-band insertion loss of the complete waffle-iron filter assembly was measured by placing a short circuit at the output and measuring the VSWR at the input; the insertion loss is less than 0.1 db throughout the 1.25 to 1.4 Gc frequency band.

[7] H. N. Dawirs, "Graphical filter analysis," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 15–21; January, 1955.

[8] L. Young, "Tables for cascaded homogeneous quarter-wave transformers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 233–237, April, 1959; and Correction, vol. MTT-8, pp. 243–244, March, 1960.

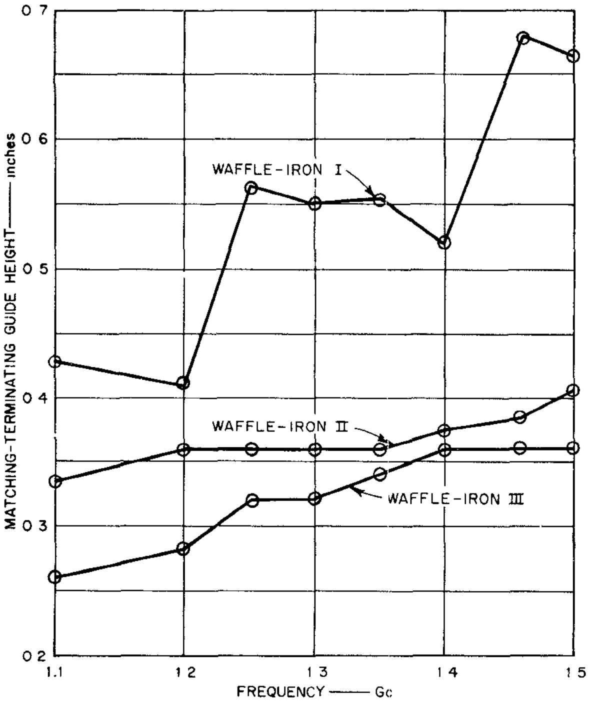

Fig. 7—Measured waffle-iron image impedance.

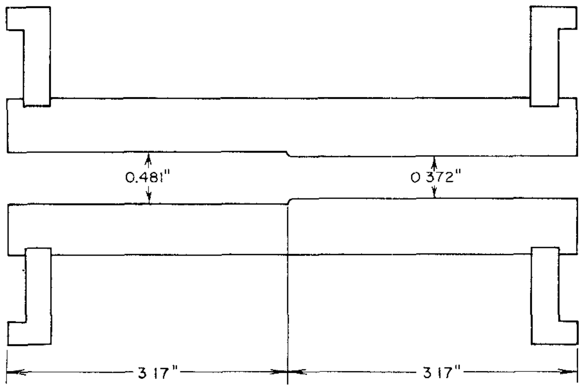

Fig. 8—Cross section of transformer between Waffle-Irons I and II.

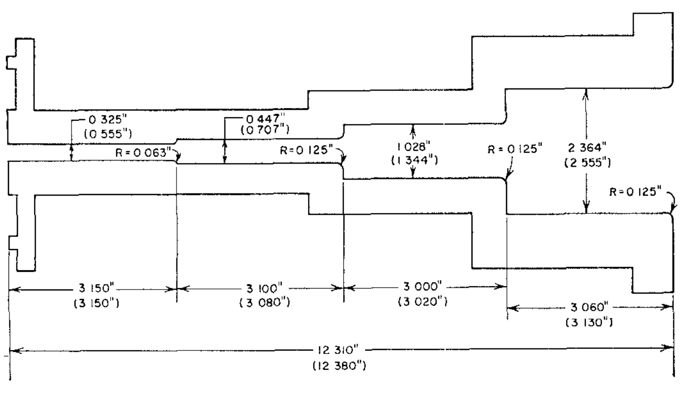

Fig. 9—Cross sections of input and output transformers—dimensions with and without parenthesis are for transformers which match Waffle Irons I and III, respectively, to L-band waveguide.

The measured stop-band insertion loss for all waveguide modes of each waffle-iron filter is shown in Fig. 10. The insertion loss of the TE_{10} mode is measured by using smooth tapered sections from a waveguide, which supports only the TE_{10} mode, to an L-band guide and then down to a 0.400 by 6.5 inch waveguide connected directly to the input and output of the waffle-iron filter. Higher-order modes are generated in the full-size input and output waveguides by placing irises in the waveguides or by twisting or shifting the waveguide junctions symmetrically on each side of the waffle-iron filters. No spurious response to any higher mode is measured and the insertion loss shown in Fig. 10 gives the minimum attenuation that any mode would experience when incident upon the waffle-iron filter. The stop-band insertion loss of the complete waffle filter assembly is shown in Fig. 11. It is greater than 60 db from 2.2 Gc to 13.7 Gc, except possibly in the frequency band of 7 Gc to 10 Gc where the limited power output from the signal gen-

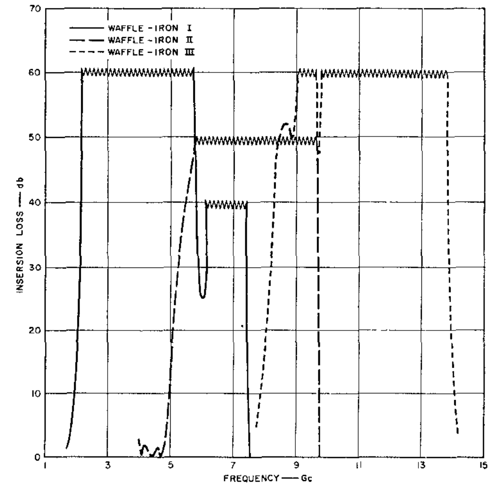

Fig. 10—Insertion loss of each waffle-iron filter.

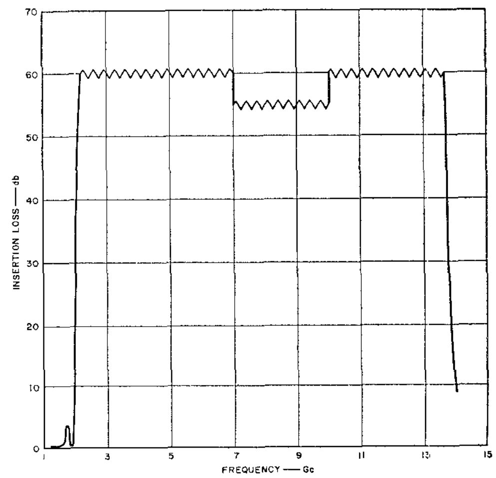

Fig. 11—Insertion loss of waffle-iron filter assembly.

erator does not permit the measurement of insertion loss greater than 55 db. The insertion loss of Fig. 11 is again the insertion loss to *any* propagating mode incident upon the waffle-iron filter assembly. Thus the *entire* frequency band is attenuated from the second through the tenth harmonic frequency of a transmitter operating in a 1.25 to 1.35 Gc fundamental-frequency band.

For Waffle-Iron Filters II and III, insertion-loss measurements were taken before and after the corners were rounded; it was found that the rounding shifted the stop band up in frequency by about 5 per cent.

Power Breakdown Measurements

The power-handling capacity of the waffle-iron filter was measured using the high-power facilities at Eitel McCullough, Inc. at San Carlos, Calif. The high-power tube used to perform the breakdown tests was the Eimac X832 experimental klystron amplifier. The X832 supplies pulses 2 μsec in length at a rate of 60 per second. The waffle-iron filter was connected in series between the klystron and a water load, which had a VSWR of 1.3. A cobalt-60 radioactive source was placed near the waffle-iron filter to insure that the air in the waffle-iron filter was ionized at points most susceptible to breakdown. In making the tests the power was increased until the waffle-iron filter arced; the power was then decreased until the arcing stopped. No gas was introduced into the waffle-iron filter to enhance the breakdown strength and all tests were made with air at atmospheric pressure inside the filter. The results of the measurements are summarized in Table II; it is estimated that the accuracy of the breakdown measurements is within about 15 per cent.

TABLE II
POWER-HANDLING CAPACITY OF WAFFLE-IRON FILTER

Frequency Gc	Measured Peak Power Capacity (Mw)	Peak Power Capacity Under Matched Conditions (Mw)
1.3	1.13	1.47
1.3	1.26	1.64

The measurements of the power capacity of the waffle-iron filter were made with a mismatched load. The capacity of the waffle-iron filter when it is a matched system can be calculated from the following relation:[9]

$$P_b/P_m = 1/S$$

where P_b is the net power transmitted at the onset of breakdown to the load which has a VSWR of S and where P_m is the power transmitted at the onset of breakdown to a matched load. Since the water load used in the measurement of power had a VSWR of 1.3, the power capacity of the waffle-iron filter in a matched system is equal to the measured capacity multiplied by 1.3. Thus the waffle-iron filter would be able to carry over 1.4 Mw peak power in a matched waveguide system.

CONCLUSIONS

Three low-pass waffle-iron filters have been successfully designed, constructed and assembled in cascade to give a 60-db insertion loss in a frequency band that includes the second through tenth harmonic frequencies. The pass-band VSWR is low, being less than 1.2 over the 1.25 Gc to 1.4 Gc band; the insertion loss is less than 0.1 db over the same band. The power-handling capacity is measured to be over 1.4 Mw peak power with air at atmospheric pressure inside the filter under matched conditions. When the air is pressurized to 30-psi gage, the power-handling capacity will increase by a factor of about 7.5 to 10.5 Mw peak power. The waffle-iron filter can withstand even higher powers if a high dielectric-strength gas is used. This waffle-iron filter can be used to virtually eliminate the harmonic-frequency outputs from a high-power transmitter. To reduce the reflected harmonic power, which re-enters the transmitter, an absorbing filter of moderate insertion loss may be connected between the transmitter and the waffle-iron filter.

ACKNOWLEDGMENT

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[9] G. L. Ragan, "Microwave Transmission Circuits," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 9, p. 34; 1948.