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A LUMPED CONSTANT COMPLEMENTARY FILTER FOR FREQUENCY RANGES 157 TO 212 MC AND 225 TO 400 MC

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ABSTRACT

A complementary filter has been developed which permits using one antenna for simultaneous operation of two electronic equipments in the respective frequency ranges of 157 to 212 Mc and 225 to 400 Mc. It consists of lumped constant components, where distributed effects were considered in the design values of the lumped parameters chosen. Separate low- and high-pass units were also constructed.

The filter has a VSWR less than 2:1 in its transmission regions. Its high-pass section has a maximum insertion loss of 1.6 db at 225 Mc which remains less than 1 db from 234 to 400 Mc. There is more than 70 db attenuation at 212 Mc and more than 50 db at 157 Mc.

The low-pass section has maximum insertion loss of less than 1.9 db at 212 Mc which remains less than 1 db from 208 to 155 Mc. It has an attenuation of greater than 70 db at 225 Mc and more than 40 db at 400 Mc.

PROBLEM STATUS

This is a final report; if not otherwise notified by the Bureau, the problem will be considered closed 30 days from the mailing date of this report.

AUTHORIZATION

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A LUMPED CONSTANT COMPLEMENTARY FILTER FOR FREQUENCY RANGES 157 TO 212 MC AND 225 TO 400 MC

INTRODUCTION

One method of diplexing two electronic equipments whose frequency ranges are separated by a buffer band is by means of a complementary filter in conjunction with a broadband antenna. The present investigation includes both the theoretical and practical considerations in designing a complementary filter using lumped constants for the frequency ranges 157 to 212 Mc and 225 to 400 Mc. Separate high- and low-pass units were constructed first and then joined together to make the composite filter.

Operational Considerations

The two equipments to be isolated are the IFF Radio Set AN/APX-2 which operates from 157 to 212 Mc and Radio Set AN/ARC-19 which operates from 225 to 400 Mc. Analysis of the output powers involved, sensitivities, and previous experience obtained in the design of a complementary filter to separate the same Radio Set AN/APX-2 from Radio Set AN/ARC-1, dictated extremely high attenuations at the critical frequencies. Specifically, to provide the needed isolation it was decided that each of the low- and high-pass units must rise from about 1 db at its cutoff frequency to greater than 70 db at the corresponding cutoff of its complement.

The steep attenuation requirements and small size considerations indicated the desirability of using lumped constants. At the frequencies involved, it was obvious that many distributed capacitances and inductances would appear and a major development problem proved to be compensation for these effects.

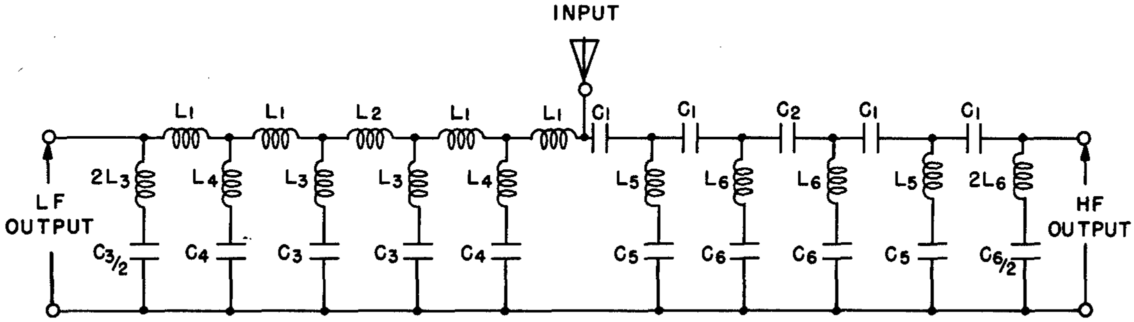
The details of design are quite standard. It may be well to recall, however, that a complementary filter (Figure 1) really consists of two filters, both a high- and a low-pass. These have their input terminals in parallel and their input shunt sections omitted.[1]

In the present investigation an external m of 0.42 instead of 0.6 was chosen to secure a proper impedance match throughout the frequency bands. Alternate $m = 0.3$ and $m = 0.42$ were used in the internal sections to secure the desired attenuations.

Theory

A complementary filter design is most easily achieved if both sections have the same theoretical cutoff frequency. In the present case, this was chosen as 218.5 Mc. Thus on a normalized frequency basis both 212 Mc and 225 Mc correspond to 0.97.

[1] Guillemin, E. A., "Communication Networks," I: 356-366, New York, Wiley, 1931



$C_1 = 16.9\ \mu\mu f$	$L_1 = 0.0315\ \mu h$
$C_2 = 14.5$	$L_2 = 0.0367$
$C_3 = 10.2$	$L_3 = 0.052$
$C_{3/2} = 5.1$	$L_4 = 0.073$
$C_4 = 7.3$	$L_5 = 0.0663$
$C_5 = 8.0$	$L_6 = 0.0430$
$C_6 = 12.3$	
$C_{6/2} = 6.2$	

Figure 1 - Schematic diagram of theoretical complementary filter

Accordingly, an external m had to be selected which would yield a satisfactory impedance match to 50 ohms at 0.97 of the cutoff frequency. Moreover, since the high-pass section has the greater frequency excursion, 225 to 400 Mc, both sides were designed for normalized frequency passbands of 0.56 to 1.0.

These considerations led to choosing an external m of 0.42 and a nominal impedance for the filter of 60 ohms.[2] This corresponds to infinite attenuation frequencies of 198.6 and 240 Mc. It therefore seemed desirable to add $m = 0.3$ internal sections and secure infinite attenuation frequencies of 208 Mc and 229 Mc respectively.

Early Version

In the earliest version of the filter, ceramic capacitors were used in the series arms. Each shunt arm consisted of a length of Radio Frequency Cable RG-8/U in series with a coil. This, in effect, treated the length of cable as a capacitance.

One main difficulty with this filter lay in the inherent variation with frequency of the transmission-line capacitors. Accordingly, cables were cut for midband frequencies, cutoff frequencies, etc. An adequate low-pass unit was constructed for operation from 157 to 212 Mc on this design but no high-pass unit that covered the entire 225 to 400 Mc range was successful, although filters for the range 225 to 325 Mc and 250 to 400 Mc were obtained. A typical high-pass filter using transmission line type shunt arm capacitors appears in Figure 2.

[2] Shea, T. E., "Transmission Networks and Wave Filters," p. 299, New York, Van Nostrand, 1929

HIGH-PASS FILTER DEVELOPMENT

Unsuccessful Version with Covered Ceramicon Series Arm Capacitors

Construction Procedure - The shunt arm capacitors (Centralab type 854) were fitted with brass bases and sleeves and adjusted by means of a Q-meter to the design value, using a frequency of 120 kc and the substitution method. The shunt arm coils were wound to a good approximation of the correct value, the number and spacing of turns being determined primarily by previous experience since the values were of the order of 0.05 μ h. All coils were wound from Number 16 tinned wire on a form with inside diameter of 0.275 inch.

The shunt arms were soldered in place, one end of each terminating on a porcelain standoff insulator having a negligible capacitance to ground. A slotted line was used to tune the shunt arms to resonance. The position of a null with the line terminated in a shorted connector (Figure 3) was noted. The shunt arm was then substituted as the load, and the coil was compressed or expanded so as to obtain the very same null position. To accomplish this substitution it was necessary to use an auxiliary tuning probe (Figure 3) which was screwed into the hole of a special box cover having the hole directly over the appropriate shunt section.

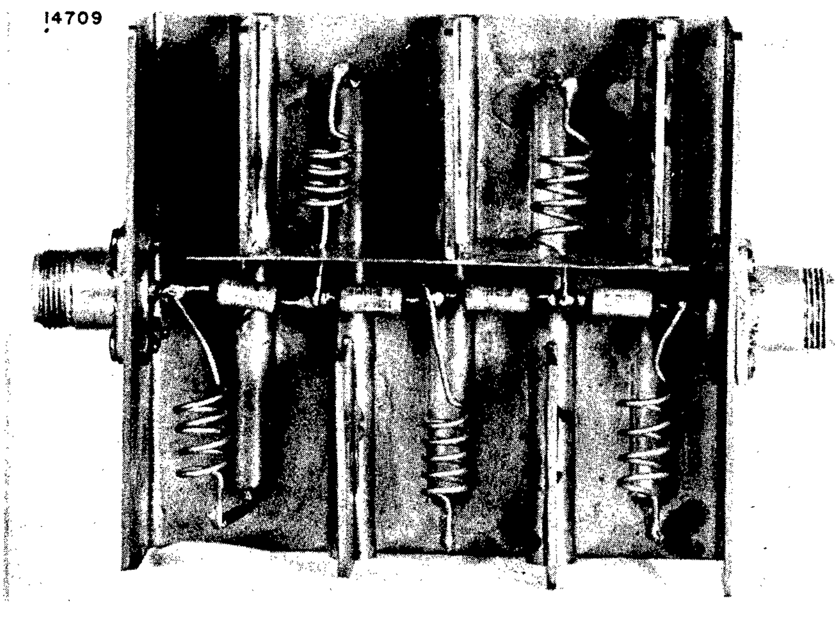


Figure 2 - High-pass filter using transmission line shunt sections

The series arm capacitors (Erie Ceramicon type) were chosen about 1 $\mu\mu$f below the theoretical values to allow for the effect of inherent series inductance. The series arm capacitors were soldered into place and a complete VSWR versus frequency curve was plotted for the filter. The results obtained were so far from satisfactory that a more accurate determination of the inherent inductance of these capacitors was deemed necessary. A complete complementary filter made according to the above mentioned techniques is shown in Figure 4.

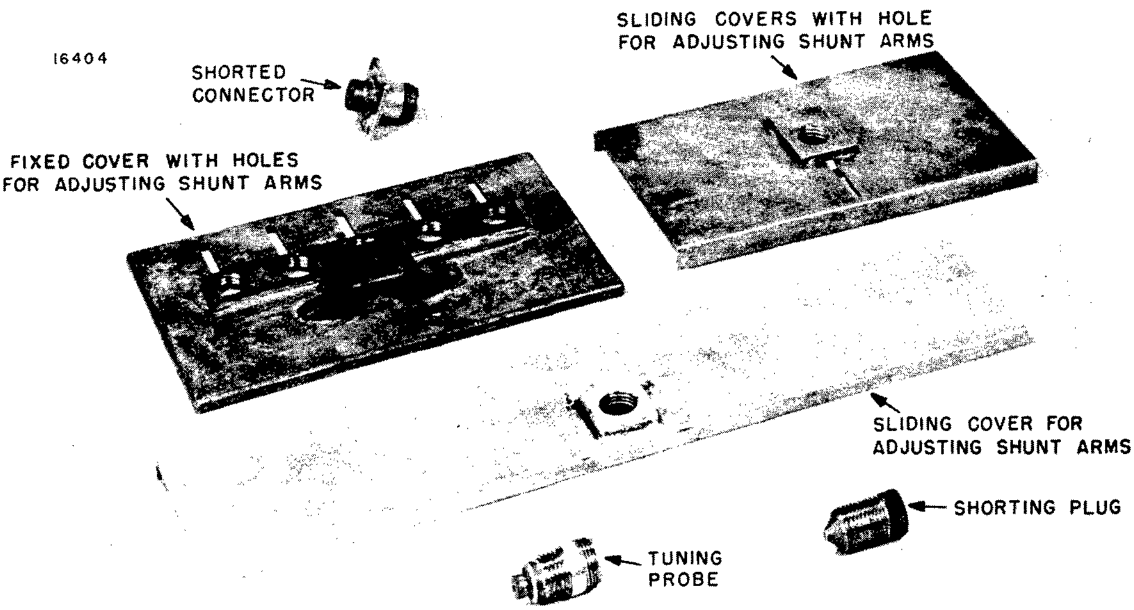


Figure 3 - Accessories used for adjusting filter components in the box

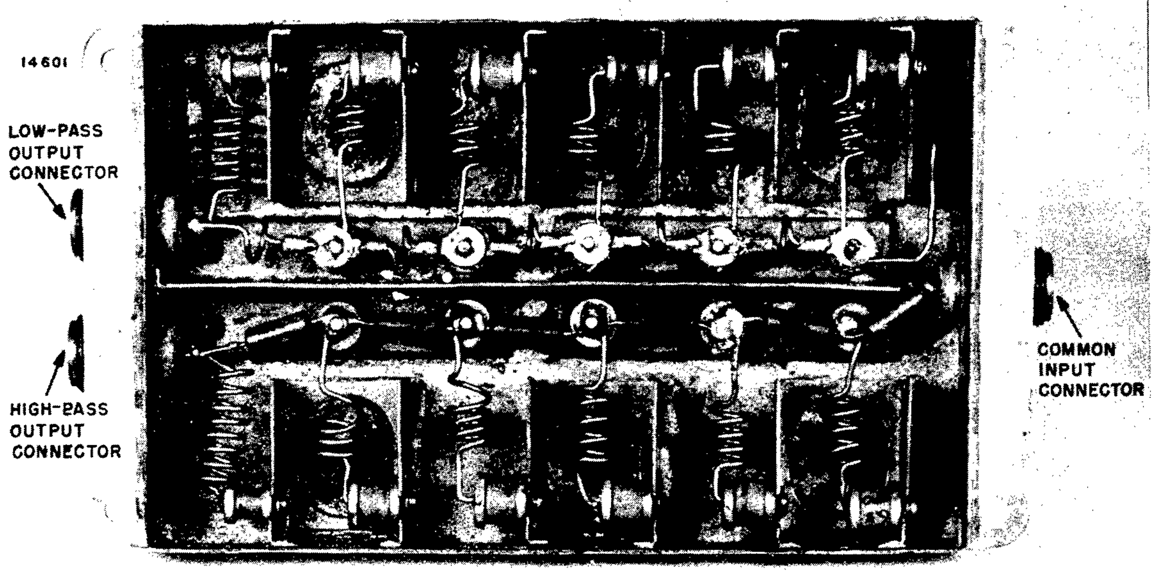


Figure 4 - Complementary filter using techniques of previous filters

Determination of Series Arm Capacitance

A single π section with $m = 0.42$ was built. The value of the series arm capacitor was then varied until the best VSWR characteristic for the desired passband was obtained. The results were unsatisfactory, since the best VSWR characteristic obtained for this single section was worse than that desired for the complete filter. It appeared, therefore, that a more careful study of distributed effects was necessary, particularly in relation to the series arm capacitors.

It was suspected that inherent series inductance might be great enough to cause the series arms to be series resonant either within or slightly above the desired passband of the filter. This would cause the effective value of the series arm capacitance to vary greatly over the operating frequency range and to be decidedly incorrect in the vicinity of the desired cutoff frequency (225 Mc).

A typical capacitor, nominally $14.3\mu\mu$f, was investigated. It was connected between two standoff terminals in the filter box. One end was shorted to the fixed cover by the shorting plug (Figure 3). The other end made contact with the special tuning probe. Again, the slotted line was used to determine the resonant frequency, which was found to be about 367 Mc. Although the inductance in this circuit includes that of the plug, the probe, and the return path in the box, as well as that of the capacitor under test, a good approximation for the residual inductance of the capacitor is about three-fourths of the total measured. If this is so, the resonant frequency of the series arm would be about $367\sqrt{4/3} = 424$ Mc. The effective series capacitance of a $14.3\mu\mu$f Ceramicon capacitor at 200 Mc would then be $18.4\mu\mu$f, and at 400 Mc it would be $130\mu\mu$f.

This evidence showed that a workable filter could be made either if the series inductance of the series arms were reduced or else the filter were redesigned to some configuration which purposely includes this parameter. Such a configuration is a type of double m derived filter. Since adjustments on double m derived sections are more critical than for single m, it was decided to attempt the former solution.

Reduction of Series Arm Inductance - The reduction in series arm inductance was attempted by several means. The first consisted simply of making the junctions on the standoff insulators in the original box more massive by soldering a disc on each terminal. The Ceramicon capacitor was then soldered between the two discs and the effect was to reduce the length of the leads to about 1/32 inch outside the plastic or ceramic case and substitute the massive disc for the 1/2 inch to 5/8 inch lead otherwise required. This method was tried before an attempt was made to measure resonant frequency. As a matter of fact, the figures on resonant frequency were obtained with the capacitor mounted between two such discs.

Second Version Using Stripped Ceramicon Series Arm Capacitors

Design and Construction Procedure - The second method consisted of making use of Ceramicon capacitors (Figures 5 and 6) which had their outer protective casings carefully removed. The small-diameter leads were clipped off completely and the capacitors were soldered into specially made brass lugs. For this filter a new box was made to house only the high-pass filter. It was necessary to stagger the shunt arm coils on either side of the axis of the series arms because the length of the series arms was reduced from 1-1/16 inch to 7/16 inch while the shunt arm compartments had to be at least 3/4 inch wide.

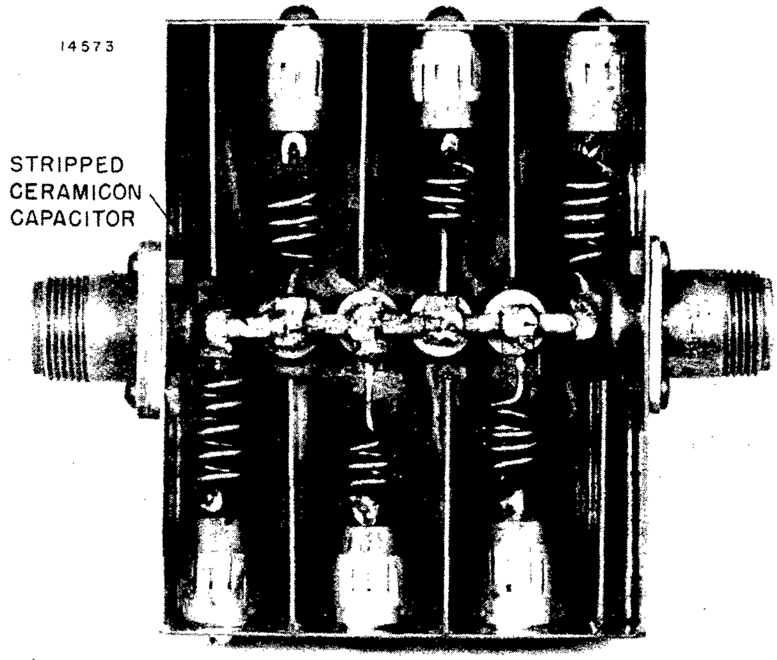


Figure 5 - High-pass filter with stripped Ceramicon series arm capacitors

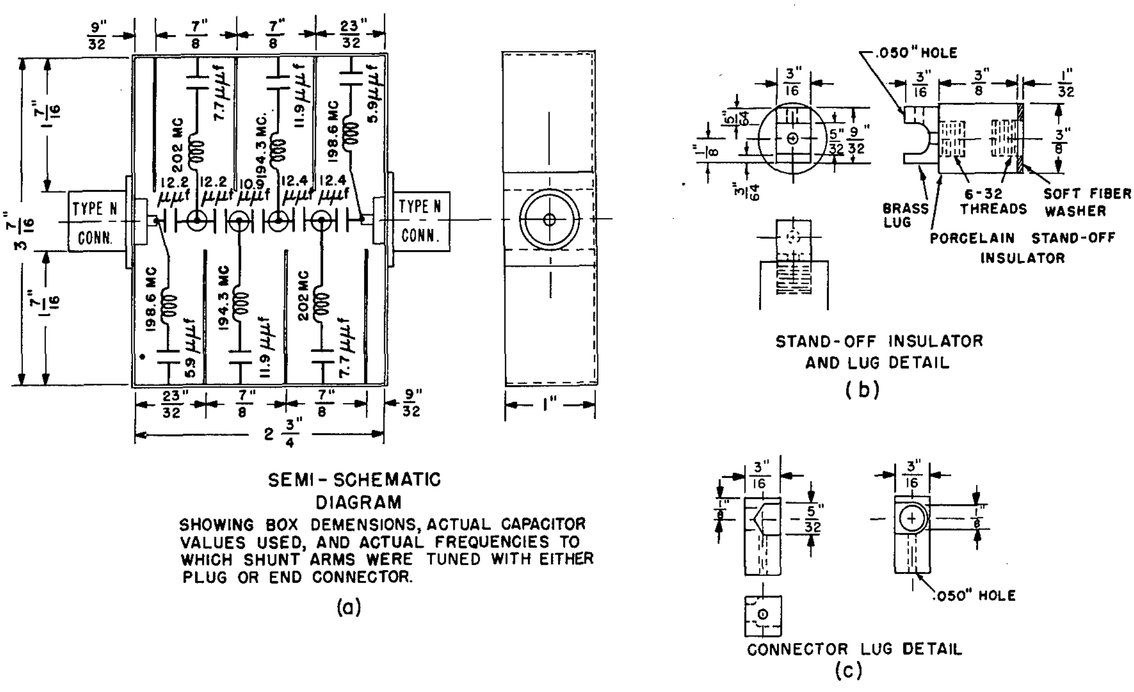


Figure 6 - Construction details of high-pass filter using stripped Ceramicon series arm capacitors

The inductance of a series arm capacitor under these conditions can be computed approximately by replacing it with a conductor having the same dimensions. The inductance at 200 Mc is

$$L = 0.00508\ell\,(2.303\log_{10}\frac{4\ell}{d} - 1 + 0.0008)\ \mu h \qquad (1)^{3}$$

where ℓ = length in inches = $\frac{7}{16}$ inch, and d = diameter in inches = $\frac{1}{8}$ inch.

Then

$$L = 0.00365\ \mu h.$$

The resonant frequency is therefore 685 Mc and the effective values of the nominal 14.3-$\mu\mu$ h capacitor is 15.8 $\mu\mu$f at 200 Mc and 21.7$\mu\mu$f at 400 Mc.

It is possible, moreover, to find the value of a capacitor required to give the correct equivalent capacitance at the critical frequency from the following formulas:

$$C_0 = \frac{C_\omega}{1 + \omega^2 L C_\omega} \qquad (2)$$

$$C_\omega = \frac{C_0}{1 - \omega^2 L C_0} \qquad (3)$$

C_0 = the dc capacitance of the capacitor in farads,

L = the inherent inductance of the capacitor in henries,

ω = angular frequency at which capacitance is desired in radians per second, and

C_ω = the capacitance in farads at angular frequency ω.

These equations show that a nominal capacitance of 13.2$\mu\mu$f becomes 14.3$\mu\mu$f at 200 Mc and rises to 18.8$\mu\mu$f at 400 Mc. Fortunately this estimate is on the pessimistic side; the massive lugs will actually cause the inductance to be somewhat lower than the computed value and hence the frequency of self-resonance will be higher than the estimated value.

Increasing Resonant Frequency of Series Arms - In any event it can be seen that unless these frequencies are high enough it will be impossible to obtain a satisfactory filter on this design basis. Furthermore, it is to be expected that some variation of the effective value of capacitance with frequency must be accepted and therefore the actual filter will only approximate the theoretically designed filter over a band of frequencies.

To raise these self-resonant frequencies still further, filter sections were combined in such an order that the theoretical value of each of the series arm capacitances was a minimum. It was necessary to use at least two sections of $m = 0.3$; therefore these sections were alternated between sections of $m = 0.42$ so that the series arms would have the smallest possible theoretical capacitance.

Offset Tuning of Shunt Arms - Tests carried out on a filter using the stripped Ceramicon capacitor technique in a filter consisting of a single $m = 0.3$ internal section between two $m = 0.42$ terminating sections, showed that the VSWR in the passband was greately improved.

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3 Terman, F. E., "Radio Engineers' Handbook," p. 49, New York, McGraw-Hill, 1943

The actual cutoff frequency, however, was too high. Probable causes of this trouble were twofold. Heretofore, both the inductance of the tuning probe and the mutual inductance between adjacent series arms of the filter had been ignored. The former has the effect of causing the resonant frequency to be higher after the probe is removed because its inductance was part of the tuned circuit. The latter introduces an inductance in the shunt arm that is essentially negative. Thus both effects cause the operating resonant frequency of the shunt arm to be higher than the frequency to which it is tuned by the slotted line and probe technique.

It was found that by tuning the $m = 0.3$ shunt arm to a lower frequency, the effective cutoff frequency was shifted in the desired direction. For this particular filter the amount of offset required was of the order of 1-1/2 to 2 percent.

Subsequently a complete high-pass filter was made using the stripped Ceramicon technique and the offset-shunt-arm tuning. The performance characteristics were good. However, in the process of soldering the series arm capacitors into the special lugs, the caps tended to separate from the capacitors so that it was not possible to rely on the capacitance remaining constant. Furthermore, the Ceramicon capacitors could not be adjusted to exact values, and it was not practical to check through large numbers of such capacitors to obtain precise values.

Despite the difficulties involved in the use of these capacitors, they made possible a much smaller filter than any capacitor subsequently used and therefore would be desirable in future design if their shortcomings can be overcome in a production model.

Third Version Using RCA Toothpick Series Arm Capacitors

A second type of capacitor, the RCA Toothpick capacitor was used in the third version. This capacitor consists of two flat copper leaves separated by a thin sheet of mica and sandwiched between two thicker sheets of mica. The whole assembly is clamped together by a strip of brass. These capacitors were used because they were small, had broad flat leads (for low inductance), and could be adjusted in value by loosening the clamp and sliding the leaves.

It was necessary to design another filter box and a special support for these capacitors. The support was made of a milled block of polystyrene designed to minimize the capacitances from the junctions to ground (Figures 7, 8, and 9).

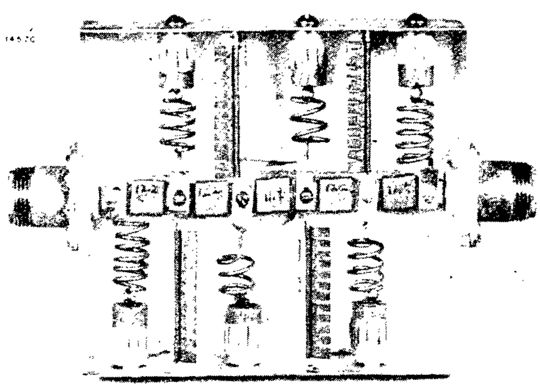


Figure 7 - High-pass filter using RCA Toothpick capacitors for series arms

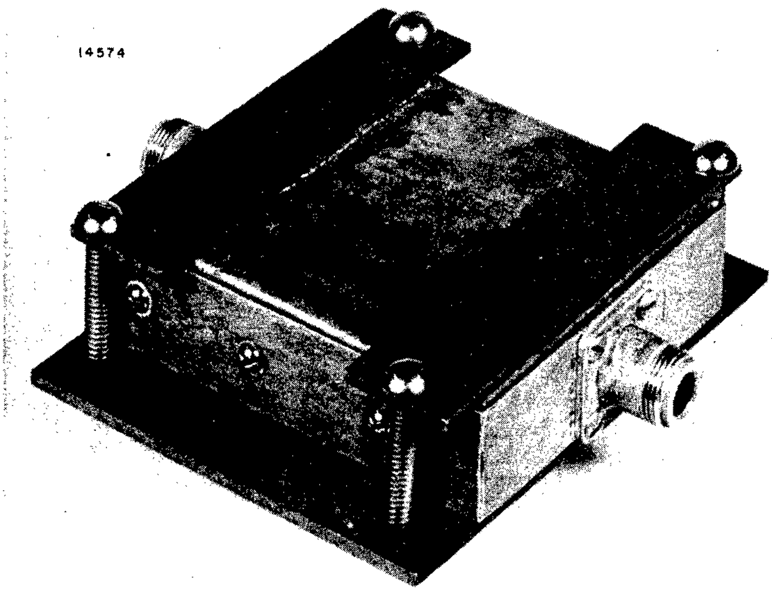


Figure 8 - Closed view of high-pass filter using RCA Toothpick capacitors for series arms

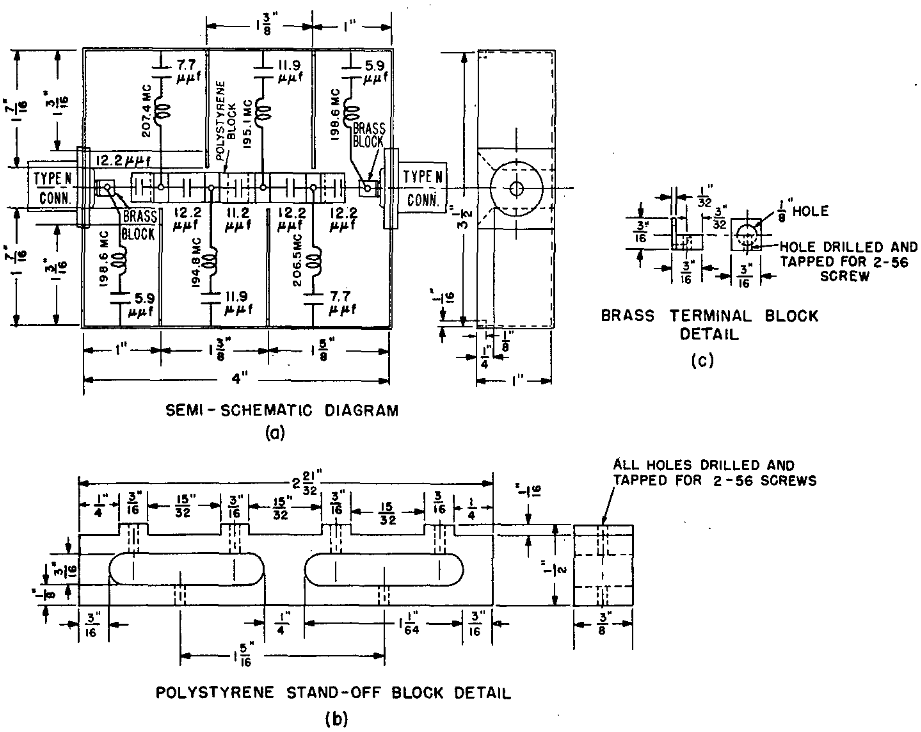


Figure 9 - Construction details of high-pass filter using RCA Toothpick capacitors for series arm capacitors

A filter using these capacitors for the series arms was built and tested. Use was made of a Q-meter to adjust the series arm capacitance at about 120 kc. The inherent inductance of one of these series arms was determined by computing the inductance of a flat conducting strip 1/2 inch long, 3/16 inch wide, and 0.010 inch thick. This inductance was then used in Equation (2) to find the value of a capacitor that would give the correct effective value at 300 Mc. Internal shunt arms were tuned to about 2.5 Mc below the design frequency. The terminating shunt arms were tuned to the actual design frequency, since no tuning probe was necessary for these.

It was found in this filter that much higher attenuation in the stop band could be obtained by using copper finger contacts to make good electrical contact between partitions and the box cover. They were therefore used on all subsequent filter designs.

The results of electrical tests on this filter were satisfactory, but for mechanical reasons, it was not acceptable. When the unit was subjected to vibration, the series arms changed values. It is felt, nevertheless that because of the good electrical characteristics obtained, an attempt might well be made to produce for future designs a more stable type of flat plate capacitor with broad flat leads. Perhaps printed circuit techniques might be applicable in a production model.

Final Version Using Centralab Type 854 Series Arm Capacitors in a "Stick"

Construction Procedure - In the final version of the high-pass filter, the same type of capacitor (Centralab type 854) as was already used for the shunt arms was employed for the series arms (Figures 10 and 11). This capacitor is a hollow cylinder, 3/8 inch both in diameter and length, with a web across the center so that the two plates are as two cups bottom to bottom. A 3/8-inch extension was required to permit the use of an adjusting sleeve. Therefore, it was necessary to design a longer shield box to accommodate the change in length.

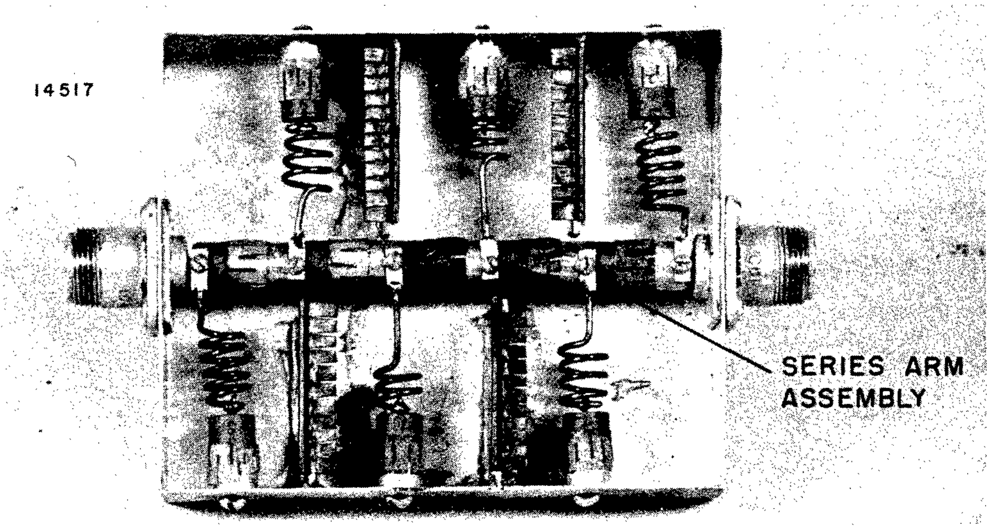


Figure 10 - High-pass filter using Centralab type 854 capacitors as a solid "stick" with adjusting sleeves for series arms

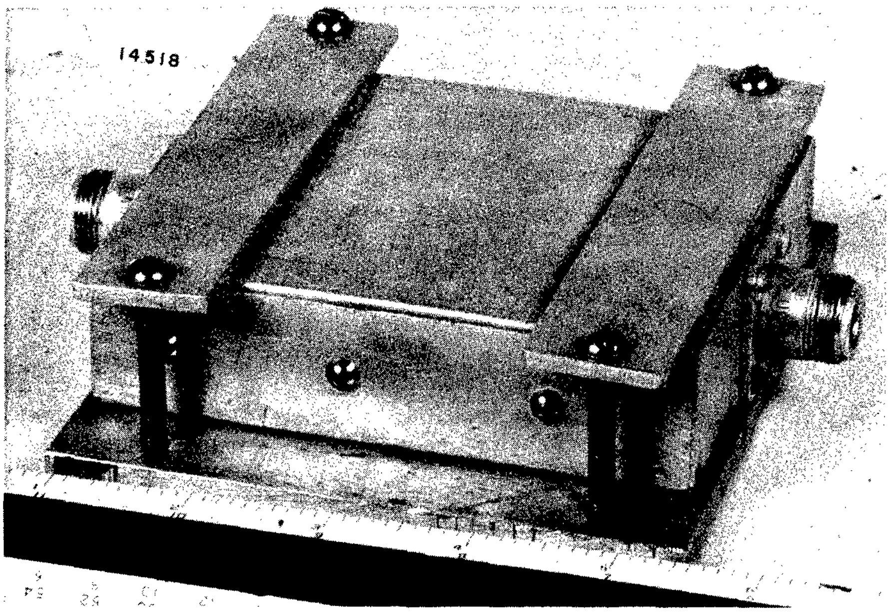


Figure 11 - Closed view of high-pass filter using Centralab type 854 capacitors for series arms

In assembling the series arms, adjacent capacitors were connected together by means of brass cylinders (Figure 12b), 3/8 inch in diameter and 3/8 inch long, having 1/4-inch diameter extensions on both ends to fit into the cups of the capacitors. Thus, the complete series arm assembly (Figure 10) was a "stick" of alternate brass cylinders and capacitors. A cap (Figure 12c and d) on each end of the "stick" was force-fitted onto the 1/8-inch diameter extensions of the center conductors of the two input connectors.

The adjusting sleeves were slid into place after the "stick" was assembled and the capacitance of each section was then adjusted with the aid of a Q-meter at 120 kc. Care was taken to reduce error by always connecting the part of the "stick" with the greatest extension to the ground side of the Q-meter terminals. Short leads (3/8 inch) were used and arranged to keep the "stick" as far as practicable from the Q-meter case. One end of each brass cylinder had a hole drilled and tapped for a 2-56 screw to permit attachment of the shunt arms which were fitted with special lugs (Figure 12e).

The values of the series arm capacitor adjustments were determined by computing the inductance at 200 Mc of a rod 3/8 inch in diameter and 3/4 inch long. The value of nominal capacitance was then chosen so that the correct value of effective capacitance would be obtained at 300 Mc in each case (Equations 2 and 3).

The terminating shunt arms were adjusted to resonate at 198.6 Mc. The other shunt arms were adjusted initially to about 2.5 Mc below the design resonant frequency, and finally, by trial and error for the best VSWR and attenuation characteristics. The resulting VSWR and insertion loss characteristics were as shown by the "a" curves of Figure 13.

Plastic-Filled High-Pass Filter - The arrangement of the series arm capacitors into a solid "stick" had a serious shortcoming. The capacitors were made of a ceramic material and were too brittle to withstand much stress or shock. One solution was to fill the box with a casting dielectric resin. This method used the technique and materials specified by

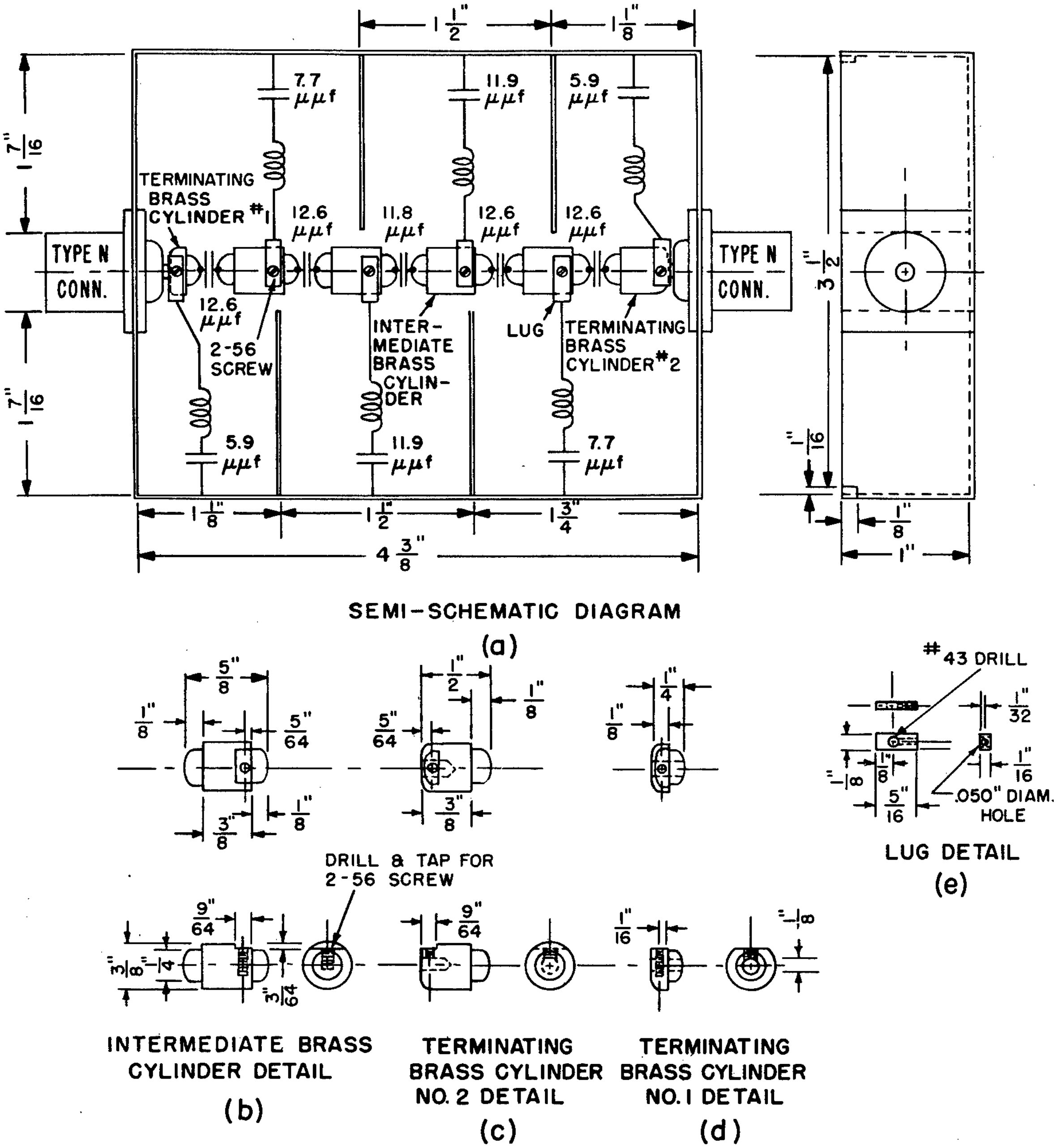


Figure 12 - Construction details of high-pass filter using capacitor "stick"

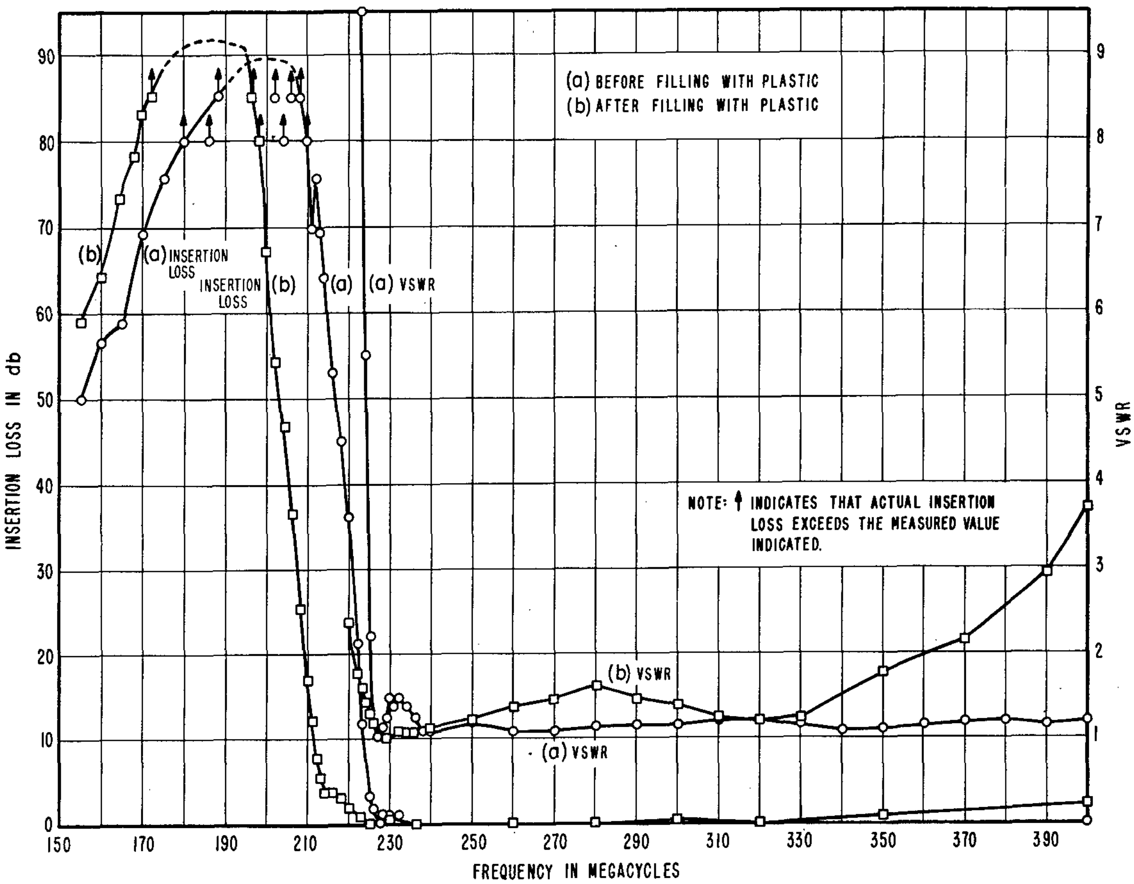


Figure 13 - High-pass filter, VSWR and insertion-loss characteristics, series arms made into a "stick" of Centralab type 854 capacitors with adjustable sleeves

NBS Technical Report 1149.[4] The material used has a dielectric constant and dissipation factor very nearly the same as polystyrene.

The effect upon the characteristics of the filter caused by filling with this resin is shown by the "b" curves of Figure 13. It may be noted that the whole insertion-loss curve is displaced toward the low frequency side when the dielectric is added. There is also a relatively slow increase in insertion loss as frequency decreases between 225 and 214 Mc, and somewhat greater insertion loss between 320 and 400 Mc. A similar translation in the VSWR curve is caused by the addition of dielectric, with a decided increase in VSWR in the range 320 to 400 Mc.

A check of the shunt arm resonant frequencies indicated that the dielectric had lowered these from their previous values. This was to be expected since the distributed capacitances of the coils would be changed by the addition of dielectric; in fact, the order of magnitude could be predicted. In addition, the experimental results seemed consistent with a reduction of the "Q" of the circuits owing to increased dielectric loss in the surrounding medium.

[4] Weinberg, M., "The Preparation of NBS Casting Resin," National Bureau of Standards Technical Report 1149, 16 Oct. 1947

From the effect produced, it is possible to determine the frequency to which each shunt arm coil should be resonated in air so as to obtain the proper value when it is imbedded in this dielectric. The method assumes the change in resonant frequency to be due to a change in the distributed capacitances of the coil. This assumption is valid since the change in the dielectric constant surrounding the coil is of the order of 170 percent, whereas the effective dielectric constant of the capacitor changes but very little.

In a parallel resonant circuit, the effective inductance L_{eff} at a frequency, f, is

$$L_{eff} = \frac{L}{1 - (f/f_0)^2} \qquad (4)$$

for $f < f_0$ where f_0 is the resonant frequency and L is the dc inductance. Increasing the shunt capacitance decreases the resonant frequency and thus causes the effective inductance of the coil to be increased at any particular frequency.

In the present case, however, the change in resonant frequency is small. Therefore adequate compensation should be obtainable by simply tuning the shunt arms in air to a frequency greater than the original air-tuned frequency by an amount equal to the difference in resonant frequency before and after filling with dielectric.

Although this last procedure has not been tried, it is believed that with a little further experimentation a dielectric-filled filter can be made to work satisfactorily.

Use of Flexible Low-Inductance Leads Between Centralab Type 854 Series Arm Capacitors - Another method of overcoming the fragility of the "stick" of series capacitors was used in the complementary filter. Cylindrical brass pieces of 3/8 inch outside diameter as shown in Figure 19, page 19, were soldered into each end of a Centralab type 854 capacitor and the adjusting sleeve was set in place and adjusted to obtain the correct value of capacitance. A flexible lead made of a strip of 0.010-inch copper, 1/4 inch wide, was then attached to each end so as to minimize series inductance. Yet the "stick" was no longer solid and each junction from series arm to shunt arm was made at a polystyrene standoff post as shown in Figures 18 and 19, pages 18 and 19. Although this method is still relatively crude in the experimental model, it could be easily improved in a production model.

If capacitors of sufficient accuracy can be obtained, the adjusting sleeves of the series arms could be eliminated and the length of the high-pass filter could be considerably reduced. Tests indicate that the series arm capacitors should have values within $\pm 0.2\,\mu\mu f$ of the finally determined value.

LOW-PASS FILTER DEVELOPMENT

Construction Procedure

The procedure for adjusting the shunt arms of the low-pass filter was essentially the same as that used for the high-pass filter. The chief practical difficulty lay in finding a reliable means to adjust the series arm coils to the desired inductance. The first method tried, one which seemed to be the simplest, consisted of tuning a shunt arm in place to its desired resonant frequency by means of the tuning probe and slotted line and then adjusting a series arm coil to resonance at a frequency computed from the presumably already known values of the combination. Although great care was taken to be sure that the shunt arm values did not change during the connection of the series arm, and although the method took into account the probe inductance, a trial with coils adjusted by this method was not successful. It is believed that neglecting the mutual inductance between the two coils increased the errors in the adjustment.

Method for Adjusting Low-Pass Series Arms

After several unsuccessful attempts the following method produced satisfactory results. A Centralab type 854 capacitor with silvered disc caps on both ends was modified by drilling and tapping the end holes for 6-32 screw threads, the same type screw as that used for the porcelain standoff insulators. This capacitor was then substituted for one of the standoffs. A straight piece of wire, equal in size to that used for the coils, was connected between the capacitor and the next adjacent standoff with 6-32 screws and washers arranged so that the screws were screwed into the standoff and capacitor as far as they would be when the filter was completely assembled. Care was taken that the wire would be as far above the bottom of the box as the center of the series arm coil would be in the assembled filter.

The resonant frequency of this circuit was measured. The length of the straight part of the conductor and the diameter of the conductor were measured and from these its inductance was computed. The capacitance of the capacitor was measured by the substitution method on a Q-meter at 120 kc.

From the computed value of inductance and the measured resonant frequency it was possible to estimate the residual inductance of the test setup. The straight wire was then replaced by a series coil. This was resonated at a frequency determined by the same capacitance in series with the residual and coil inductances. To reduce mutual coupling, each coil was wound with its axis at right angles to the axes of both the filter and the shunt arms.

The coils were also wound on as large a diameter as practicable (0.275 inch inside diameter) and with as large a spacing as was consistent with good adjustment properties. This tended to keep distributed capacitance low. With too small a diameter or too closely spaced windings, this procedure was unsuccessful.

After the series arm coils were carefully adjusted by this method, it was found possible to adjust the shunt arms by trial and error to produce satisfactory characteristics for the filter. The complete low-pass filter (Figures 14 and 15) was then built and its VSWR and insertion-loss curves were plotted (Figure 16).

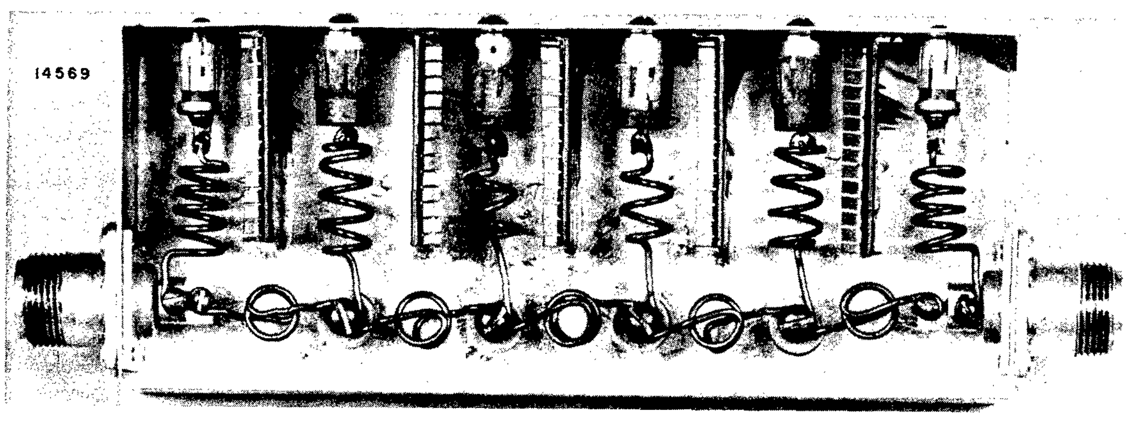
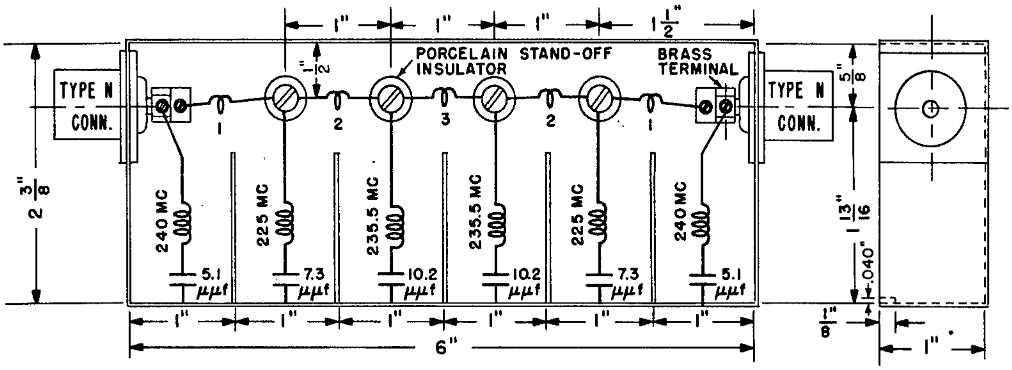
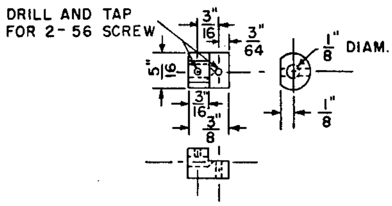


Figure 14 - Low-pass filter



SEMI-SCHEMATIC DIAGRAM
(a)



BRASS TERMINAL DETAIL
(b)

Figure 15 - Construction details of low-pass filter

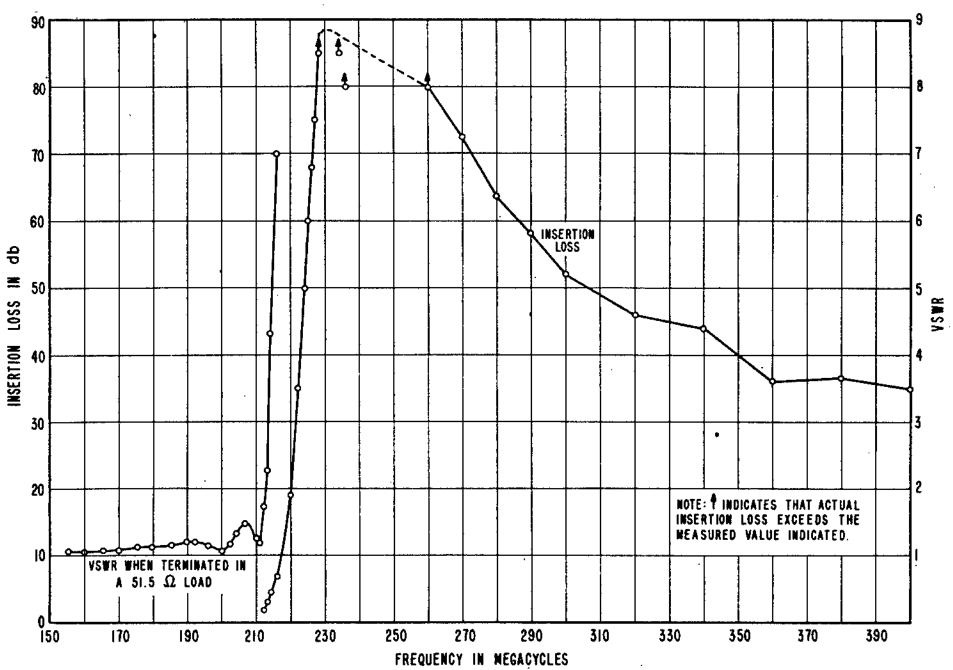


Figure 16 - Low-pass filter, VSWR and insertion-loss characteristics

COMPLEMENTARY FILTER DEVELOPMENT

The complementary filter (Figure 17) consisted of two separate boxes—the same size and shape as the final version of the high-pass unit, except for the omission of an input connector on the low-pass filter box—bolted together at the corners back to back. Common holes were drilled for the standoff insulators and the lead from the input connector to the low-pass side.

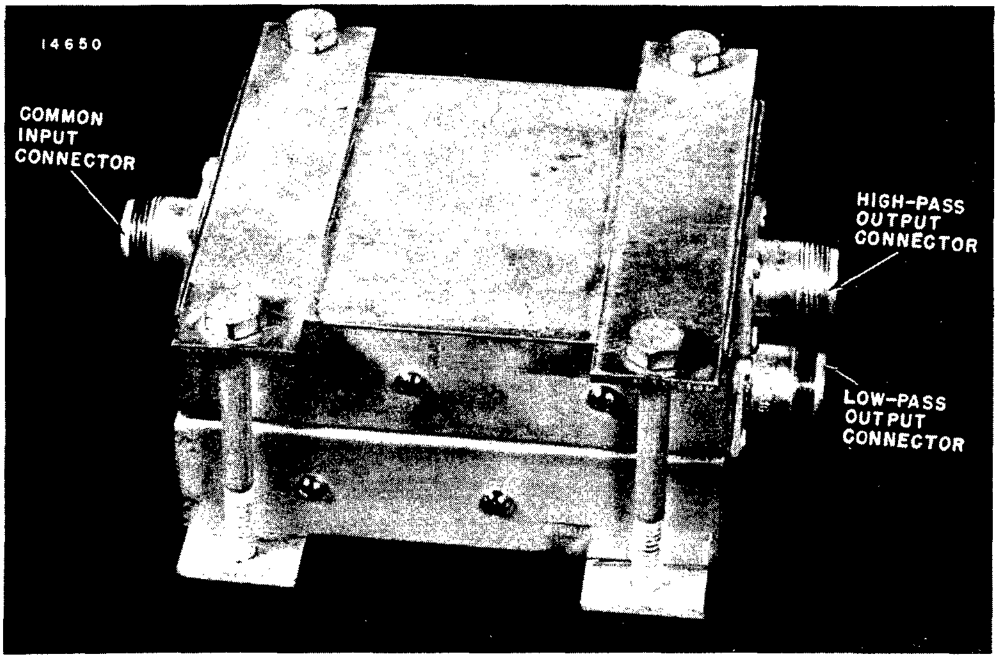


Figure 17 - Complementary filter

The high-pass side (Figures 18 and 19) was built with adjustable Centralab type 854 capacitors for its series arms with flexible leads (as described previously).

The arrangement of components of the low-pass side (Figures 20 and 21) was modified in the complementary model with respect to the separate low-pass filter to allow for the different shape of box. The series arm coils followed a zigzag pattern and the shunt arms were then placed alternately on opposite sides of the series arms, as in the high-pass section.

Adjustment of the components of the complementary filter followed the techniques developed earlier.

The curve of VSWR versus frequency at a temperature of 25°C for the complementary filter, when both outputs are terminated in 51.5 ohms, is shown in Figure 22. It can be seen that the VSWR in the high-pass band is greatest at the low end of the band (2.1 at 212 Mc).

The curves of insertion loss at temperatures of +25°C, -38°C, and +60°C are shown in Figures 22, 23, and 24. At +25°C the maximum insertion loss for the high-pass section in its passband is 1.6 db at 225 and 226 Mc. For the low-pass section in its passband the maximum is 1.9 db at 212 Mc. Throughout the rest of both transmission regions the loss

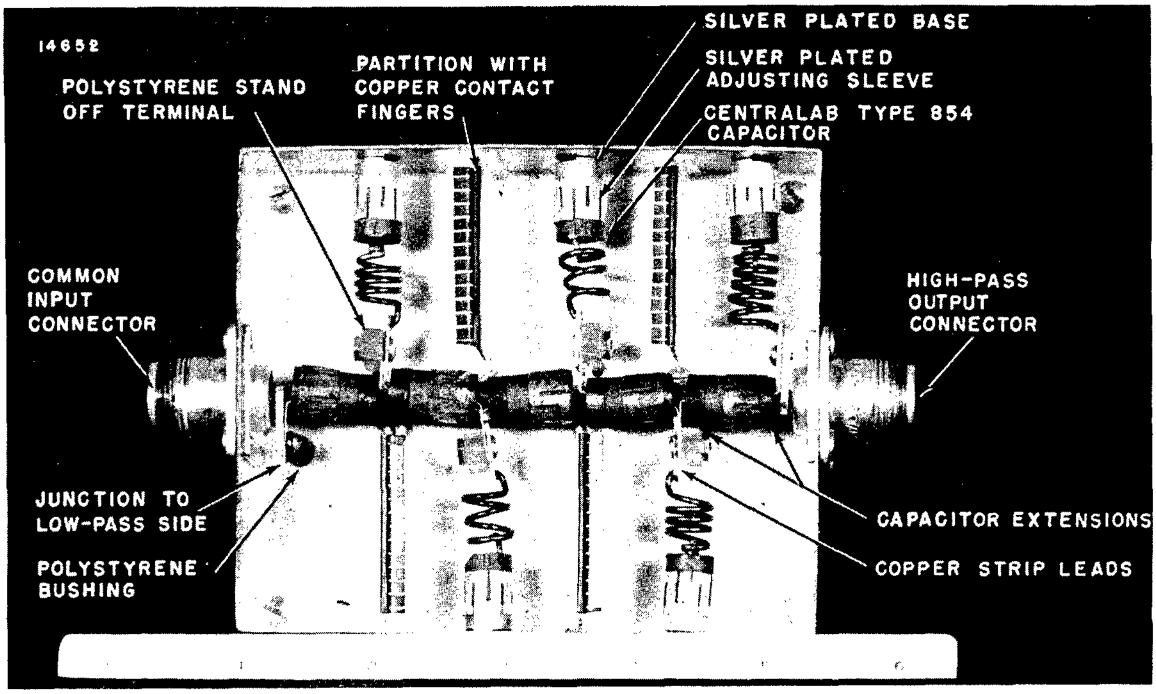


Figure 18 - High-pass side of complementary filter

is less than 1.2 db and is less than 0.5 db over more than 60 percent of each passband. For the high-pass section the minimum insertion loss in the stop band is over 50 db and the maximum is over 85 db with over 70 db at 212 Mc. For the low-pass section the minimum insertion loss in its attenuation region is 40 db with a maximum of 85 db and is more than 75 db at 225 Mc.

From the curves of insertion loss at -38^{0} C and at $+60^{0}$ C in Figures 23 and 24, it can be seen that the insertion-loss characteristics change somewhat with extreme temperatures. The most important changes in these characteristics are the increases in insertion loss at the critical ends of the passbands, i.e., the low end of the high passband and the high end of the low passband. The worst change of this sort is the increase in insertion loss at 225 Mc from 1.6 db at 25^{0}C to 2.4 db at $+60^{o}$C, an increase of 0.8 db.

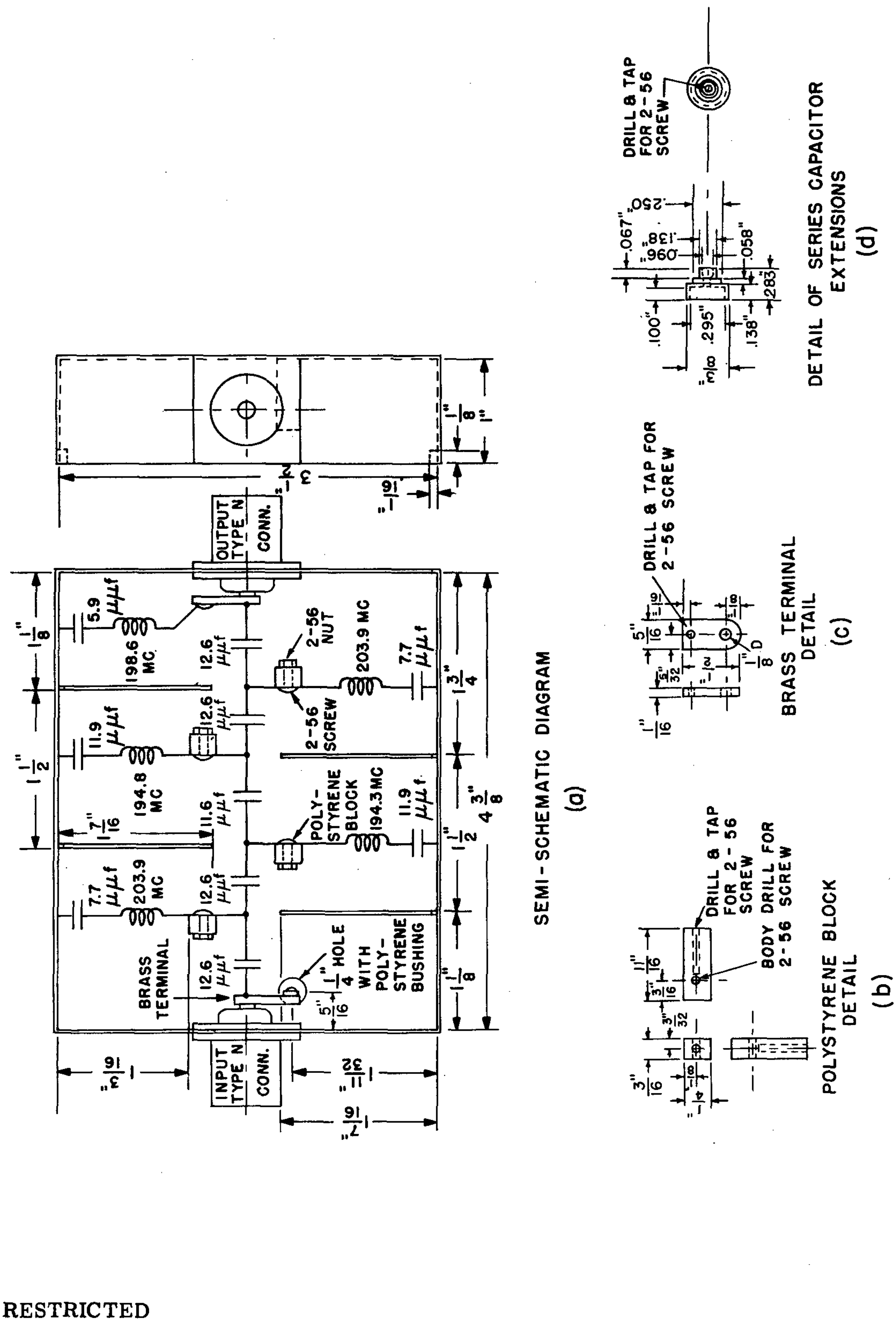


Figure 19 - Construction details of high-pass side of complementary filter

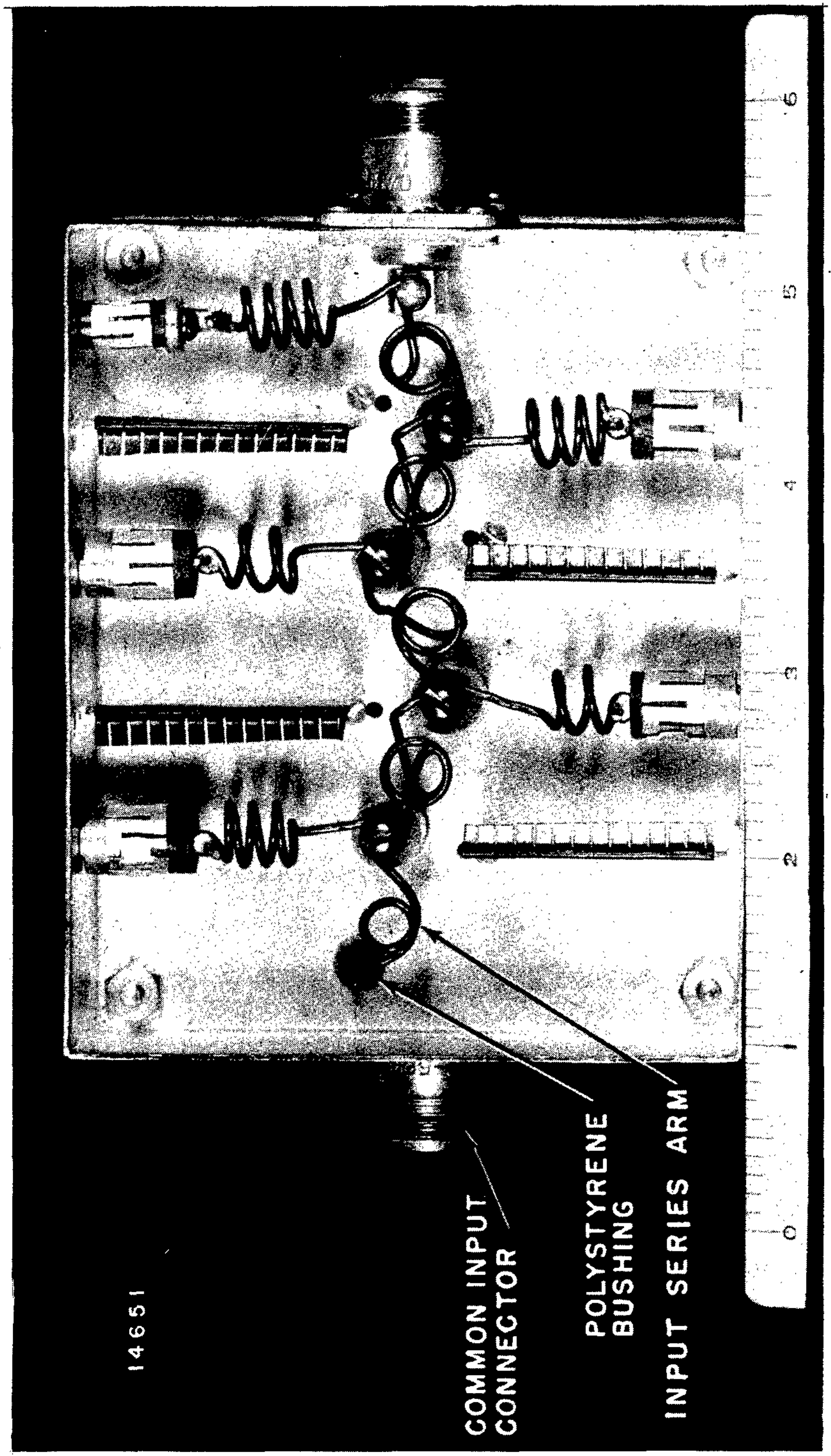


Figure 20 - Low-pass side of complementary filter

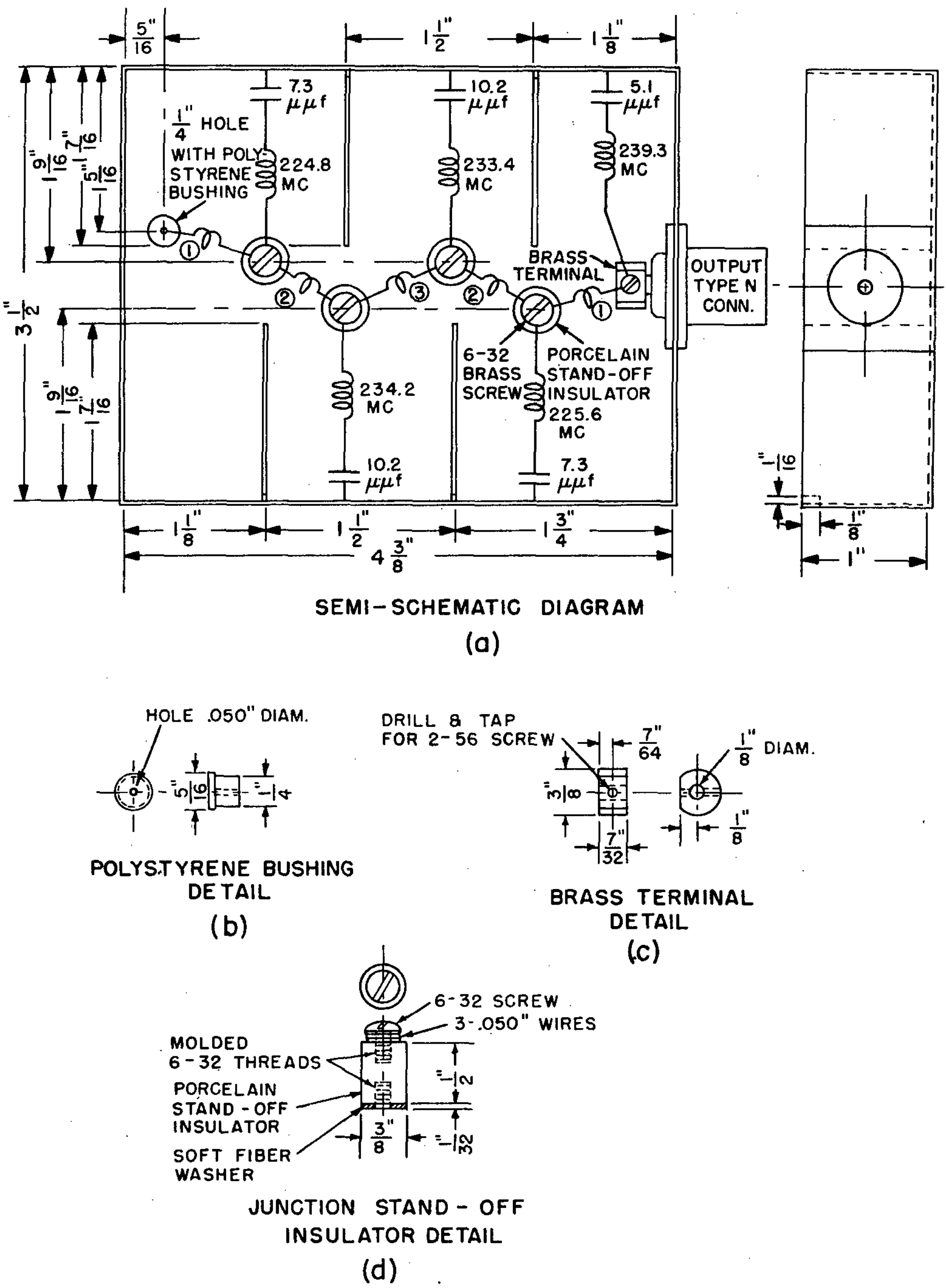


Figure 21 - Construction details of low-pass side of complementary filter

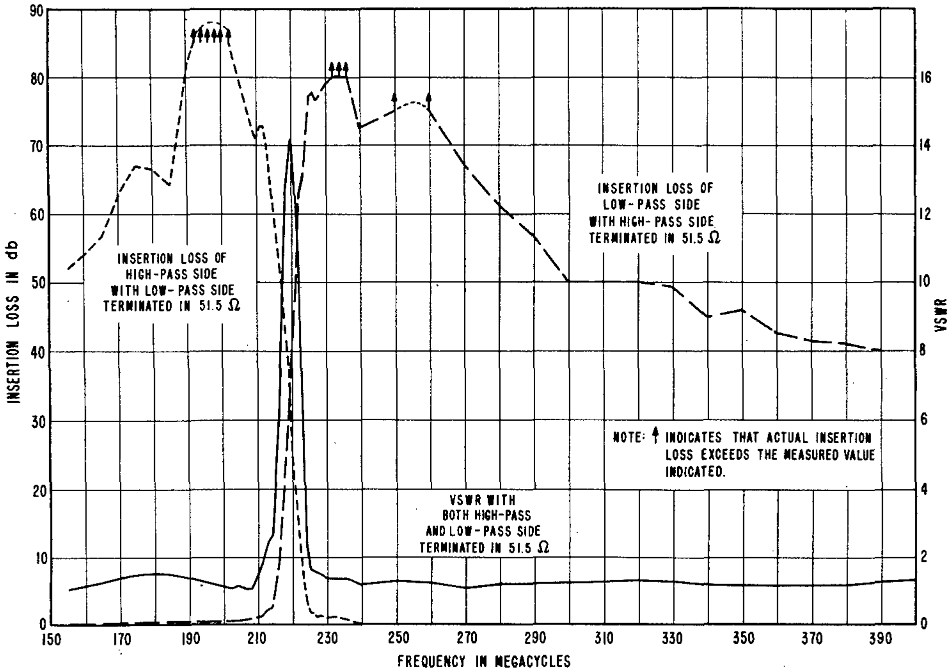


Figure 22 - Complementary filter at +25°C, VSWR and insertion-loss characteristics

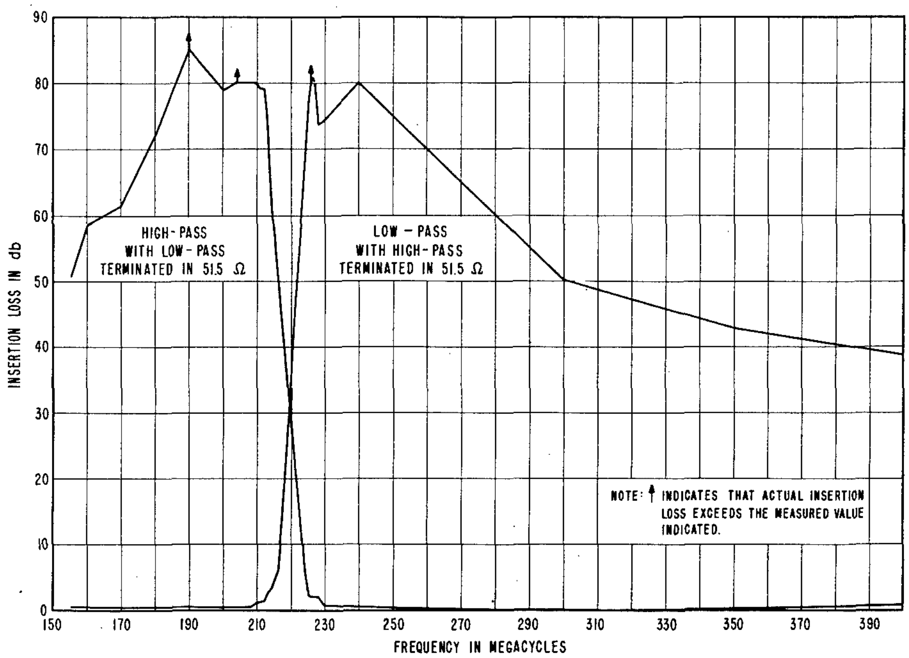


Figure 23 - Complementary filter at -38°C, insertion-loss characteristics

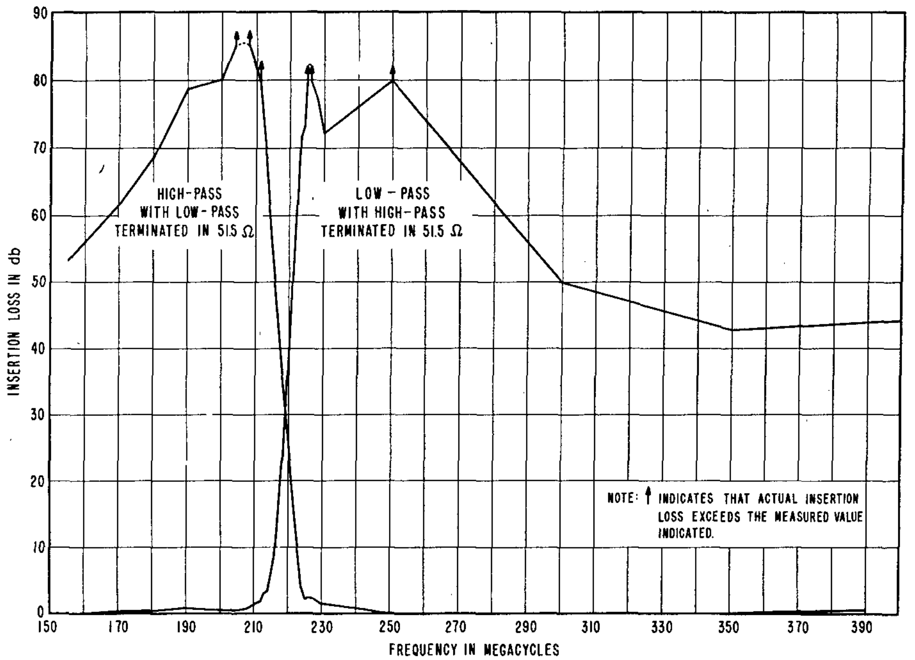


Figure 24 - Complementary filter at +60°C, insertion-loss characteristics

CONCLUSION

The following lumped constant filters have been designed and constructed for nominal 50-ohm termination:

(1) A high-pass filter having an insertion loss of 3.1 db at 225 Mc and greater than 70 db at 212 Mc with less than 2.0 db between 226 Mc and 230 Mc and less than 1.0 db between 230 Mc and 400 Mc.

(2) A low-pass filter having an insertion loss of 1.8 db at 212 Mc and 60 db at 225 Mc with insertion loss of less than 1.2 db between 208 Mc and 155 Mc.

(3) A complementary filter having a high-pass insertion loss of less than 1.6 db at 225 Mc and greater than 70 db at 212 Mc with less than 1 db insertion loss from 234 Mc to 400 Mc; and a low-pass insertion loss of 1.9 db at 212 Mc and greater than 70 db at 225 Mc with less than 1 db insertion loss from 208 Mc to 155 Mc; a VSWR of less than 2 between 211 and 155 Mc and between 225 and 400 Mc when both high- and low-pass sides are terminated in 51.5 ohms of resistance.

Experience with the techniques involved in this study indicates that although the final version of the filters is of small physical size, the ultimate in small size has not yet been reached. Further study of such lumped constant filters may lead to smaller sized filters for these frequencies as well as an extension of the lumped constant technique to frequencies higher than 400 Mc.

RECOMMENDATIONS

It is recommended that the techniques of lumped constant components be used in the design of filters to operate up to 400 Mc where small physical size is an important consideration.

For an application where two equipments of frequency ranges 157 to 212 Mc and 225 to 400 Mc are to be operated from a common antenna, it is strongly recommended that the final version of the complementary filter designed during this investigation be manufactured. It is to be expected that production problems and other considerations may necessitate slight modifications of the present model.

It is also recommended that for large quantity production, consideration be given to the possibility of using printed circuit techniques in the manufacture of the components, particularly the series arm capacitors of the high-pass section.

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