Crystal Channel Filters for the Cable Carrier System * †

By C. E. LANE

SINCE the channel selecting filters used at the terminals of the twelve-channel cable carrier system are the principal filters in the system this paper is concerned primarily with these. Their importance is evident from the fact that they represent over one-third of the cost of the system terminals.

Many new features appear in these channel filters. The most outstanding is the use as filter elements, along with inductance coils and condensers, of plates cut from crystalline quartz. It is for this reason they are called "crystal filters." In addition, however, the inductance coils, some of the condensers, and also the filter assemblies have in them new features. Only after a number of years of laboratory experimentation with filters using crystal elements, studying their advantages and limitations, was the cable carrier system planned to use such filters.

There are twelve channel filters which transmit the lower side bands derived from the modulation of the speech signals with carrier frequencies spaced 4 kilocycles apart from 64 to 108 kilocycles. An insertion loss frequency characteristic which applies for each of the twelve filters is shown in Fig. 1. Regarding a 10 db loss increase as the cut-off as compared with transmission at 1000 cycles, the voice-frequency band for a single-carrier link, largely determined by the characteristics of the channel filters, extends from approximately 150 to 3600 cycles. For five links the band extends from about 200 to 3300 cycles. This is a 600 or 700 cycles wider frequency band than the present three-channel open-wire carrier system. The maximum delay distortion in the transmission band of each of the filters is about 0.4 millisecond. As many as ten of these filters may appear in tandem in the longest talking circuits. The total delay distortion in such cases would then not exceed 4 milliseconds. This is not objectionable since the average listener can not observe the effect of delay distortion unless it exceeds about 10 milliseconds. A representative filter schematic is shown in Fig. 2. The condenser shown by the dotted line at the left is used only in the two lowest frequency filters to obtain

* This is a companion paper to other papers covering different parts of the twelve-channel cable carrier system.

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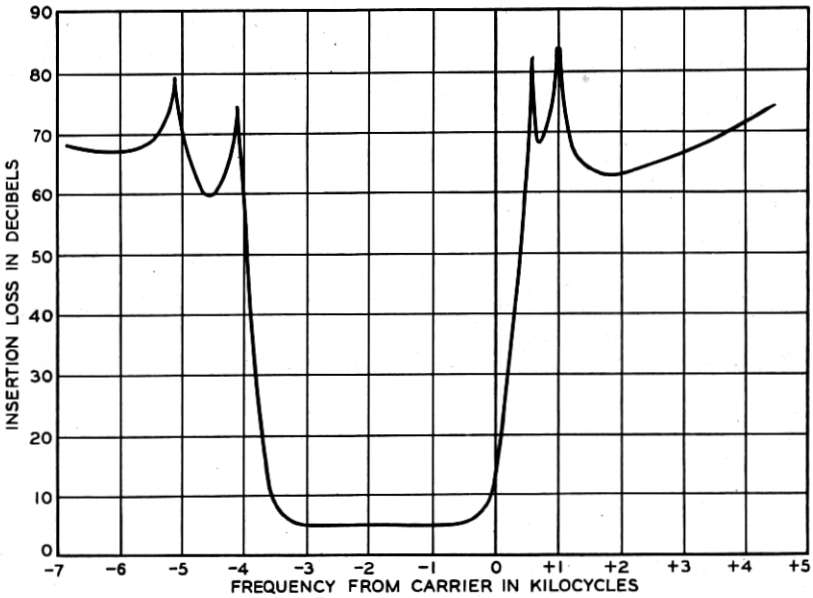

Fig. 1—When plotted in cycles removed from the carrier frequency, the insertion loss frequency characteristics of each of the twelve crystal channel filters are for all practical purposes identical.

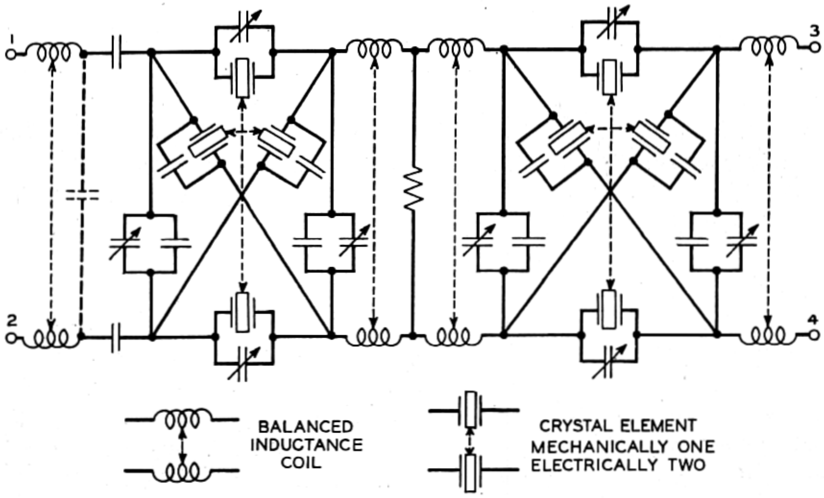

Fig. 2—The schematic circuits of each of the twelve filters are the same except for the addition of the condenser shown by the dotted lines which appears only in the two lowest frequency filters.

an impedance transformation internal to the filters and thereby permit the use of crystals of practical thicknesses for these filters. However, the equivalent circuit for each of the twelve filters is the same. In the system the filters work in parallel at one end and between terminating impedances of 600 ohms. The two condensers appearing in the series arms at the left end of the filter schematic are used in obtaining satisfactory operation of the filters in parallel and otherwise might be omitted provided the inductance at this end was made smaller at the same time.

Figure 2 indicates the separate physical elements and the manner in which these are connected in the filters. In considering the performance of the filters the crystal elements are replaced by their equivalents, an inductance and capacitance in series, shunted by a second capacitance as shown in Fig. 3. Also, the condensers in

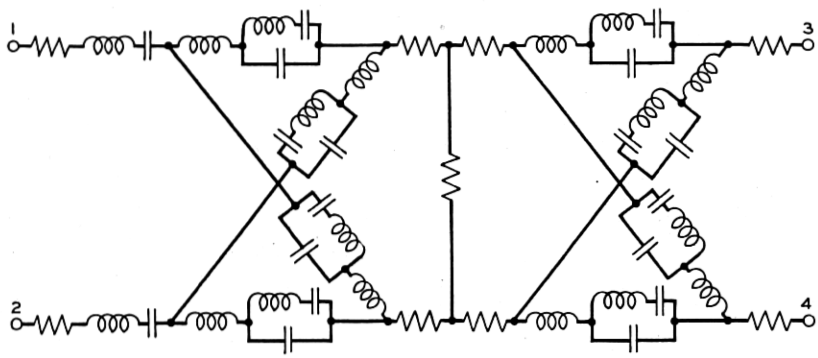

Fig. 3—The schematic circuits of the filters are each equivalent to two lattice sections with a resistance pad between them, resistances at each end and at the paralleling end a coil and condenser which resonate at the mid-band frequency.

shunt across the filter are shown inside the lattice combined with the direct capacitance of the crystals and the inductances are relocated in series in each lattice arm. In making this conversion, however, the effective resistance of the inductance coils are, for reasons which will appear later, shown remaining outside the lattice. Also the capacitances and the portion of the inductance which are used solely for purpose of paralleling are left outside the lattice. The basis for the conversion from Fig. 2 to Fig. 3 is shown in Fig. 4.

Before considering further the filter as a whole, the nature of the crystal elements and the reason for using them will be considered. It is common knowledge to those familiar with the performance of electrical wave filters that the energy loss unavoidably associated with inductances imposes limitations upon the filter characteristics obtainable. Capacitances may be designed so that the energy dissipation is small and negligible as compared to that in the inductances. With ideal reactance elements entirely free from dissipation, filters might be designed for any band width with as little loss in the band as wanted and at the same time frequencies might be rejected outside the band by any amount desired, no matter how near such frequencies

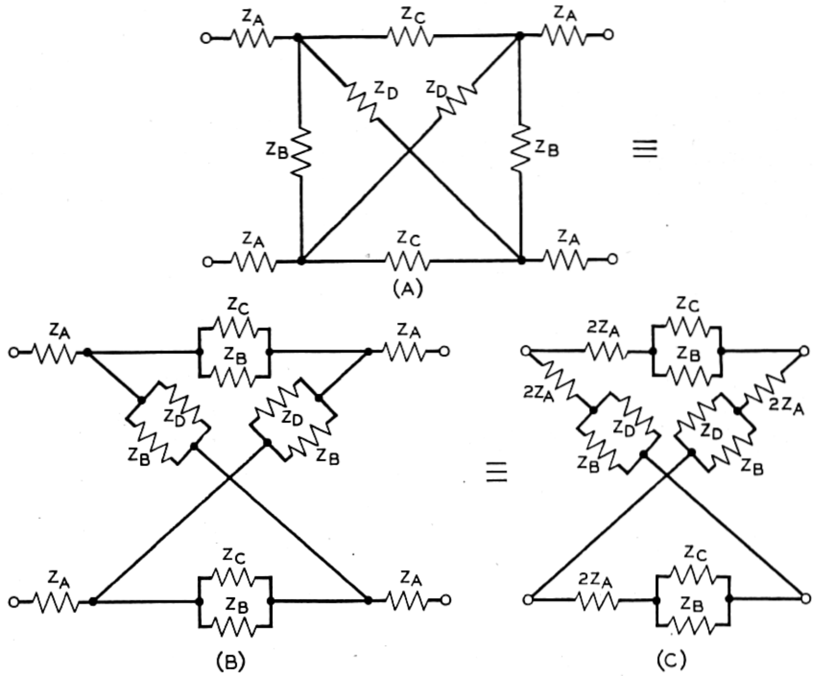

Fig. 4—It does not alter the transmission properties of a network such as shown in Figure 4A to remove the impedances in shunt and outside the lattice and replace them by impedances of equal magnitude in shunt across each lattice arm nor by removing the impedances in series with the lattice and replacing them by series impedances inside the lattice of twice the magnitude of those removed.

were to the edges of the transmitting band. Of course the sharper the filter cut-offs, other requirements being the same, the more complex the filter structure would be even neglecting dissipation. The greater the dissipation in the filter elements, the greater the loss in the transmitting range of the filters and the greater the number of cycles required for this loss to rise from the relatively low and uniform loss in the transmitting band to the high loss wanted outside the band. In the design of channel filters for carrier systems, the presence of dissipation in the filter elements is costly in that the channels must be spaced farther apart than would otherwise be necessary, thereby wasting frequency space. At the same time the loss to transmitted frequencies must be made up for by amplification. The amount of dissipation in a reactance element is measured by the ratio of the effective resistance component of its impedance to the reactance component at any frequency. The reciprocal of this ratio is called the Q of the reactance and hence is a measure of efficiency or freedom from dissipation. In the design of inductances in the form of wire wound coils, it is generally not practical to obtain Q's much in excess of 200 or 300 at any frequency. The quartz crystal element used in the filters as previously stated is equivalent electrically to a two-terminal reactance consisting of an inductance and capacitance in series shunted by a second capacitance. For the Q of the inductance in the equivalent circuit of the crystal element a value of 15,000 or more can readily be obtained. It is for the purpose of utilizing this high Q inductance and obtaining the benefits therefrom that crystal elements are used in these filters.

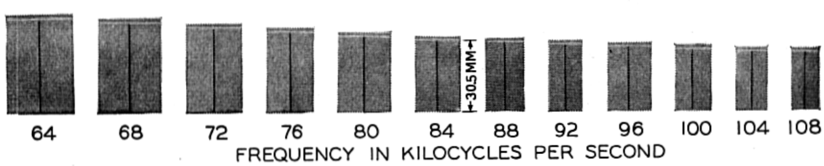

Fig. 5—The length of the crystal elements used in the different filters varies about inversely as the frequency of the filter band location.

The filter schematic in Fig. 2 shows crystal elements in each filter section; the two in the lattice arms and the two in the series arms in each case are identical. Electrically there are four crystals in each section but for reasons of economy and for convenience in handling and adjusting the crystals those in corresponding arms are physically one. This is possible since the filter is a balanced structure and the two like crystals vibrate in unison. Figure 5 is a photograph which shows a representative double crystal element taken from each of the twelve filters. The four crystals in the lowest frequency filter range from 40.2 millimeters to 41.8 millimeters in length and those in the highest frequency filter from 23.8 to 24.3 millimeters. The thickness of the crystals in all four of the lowest frequency filters are 0.63 milimeters, in the next four filters 0.82 millimeters, and in the highest frequency filters 1.1 millimeters. Uniformity in thickness is maintained as far as practicable since it contributes to economy in manufacture of the crystal. Within the range using the same crystal thickness the impedance and frequency differences, called for by the design of the different filters, can be provided by variations in width and length of the crystals. The ratio of width of the crystals to their length ranges from about 1/2 to 4/5.

The major surfaces of the crystals are plated with a thin layer of aluminum deposited by an evaporation process. This plating is divided along the center line lengthwise of the crystals to form the two

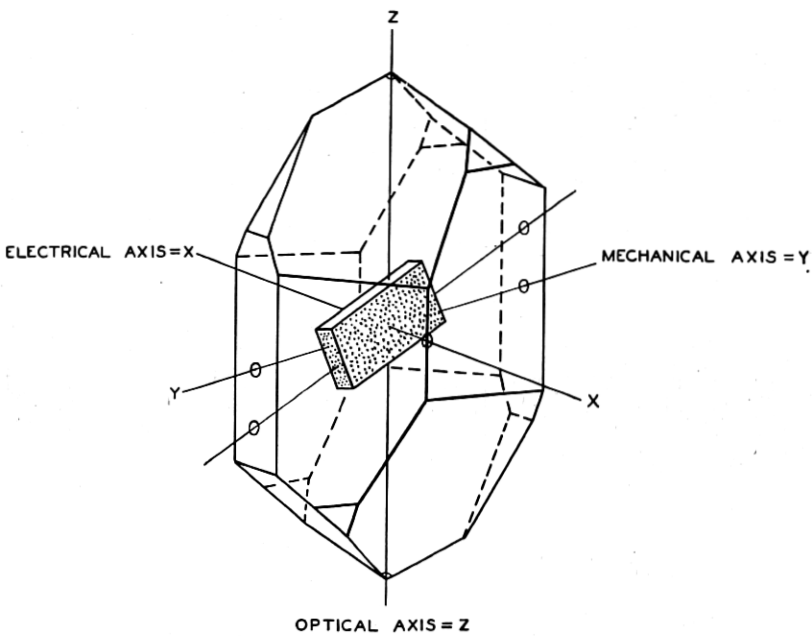

Fig. 6—The crystal elements are out with their major surfaces perpendicular to the electrical axis of the natural quartz, with their side surfaces making a small angle with the mechanical axis, and with their end surfaces making a small angle with the optical axis.

electrically independent crystals. Since the crystals vibrate longitudinally with a node across the middle, they are clamped at this node in mounting. Figure 6 shows the orientation of the crystal plates with respect to the natural axes of the quartz from which they are cut. The plates are cut as accurately as is practicable to the dimensions computed making a small allowance in length and then the crystal is finally adjusted in an electric circuit by grinding the end of the crystal until the resonant frequency falls within five or ten cycles of that desired.

Considering again the filter schematic as a whole (Fig. 3) and neglecting the dissipation in the crystals and condensers, the filter may be regarded as made of two lattice filter sections having ideal reactance elements, that is, elements free from dissipation. The location of the effective resistance of the coils outside the lattice, for purpose of performance analysis, shows how at the end of the filter these resistances may be regarded as part of the terminating impedance between which

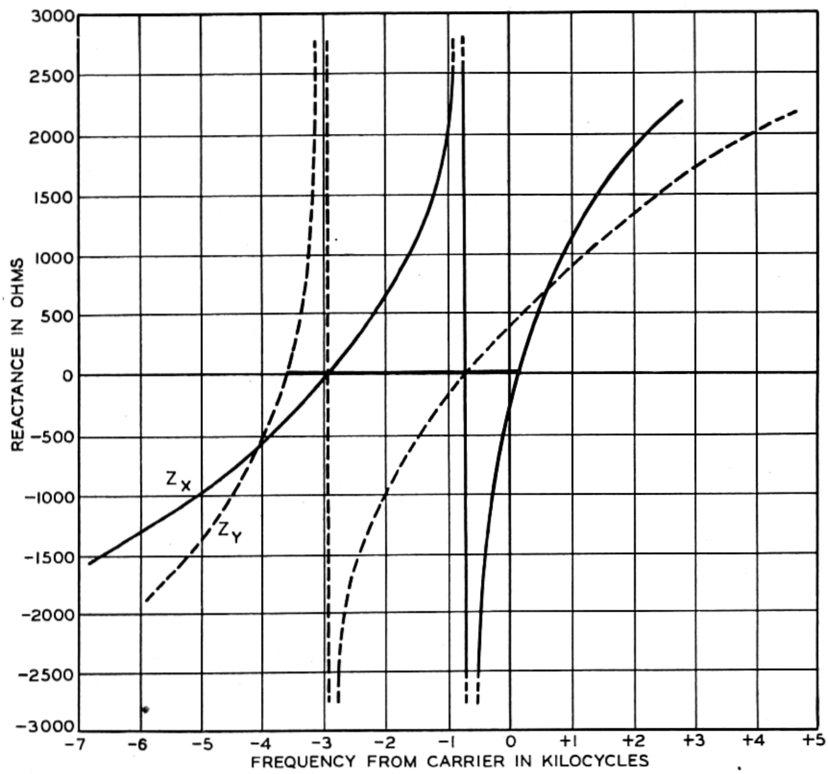

Fig. 7—In a lattice filter section transmission occurs for frequencies where the impedances for the two arms of the lattice are of opposite sign and attenuation peaks of very high loss occur where the impedances cross.

the filter works, and how between the filter sections the resistances may be combined with a shunt resistance to form a resistance pad which matches the image impedance of the two filter sections. The effect, then, of the coil resistances is primarily to provide a flat loss over the entire frequency range and does not affect appreciably the shape of the loss characteristic furnished by the reactance inside the lattice sections.

In considering the performance of lattice type filter sections, it is common practice to sketch together the frequency reactance curve of the two lattice arms Z_x and Z_y. This is done for one of the filter sections and is shown in Fig. 7. In the frequency range where the two curves are of opposite sign the filter transmits, and where they are of

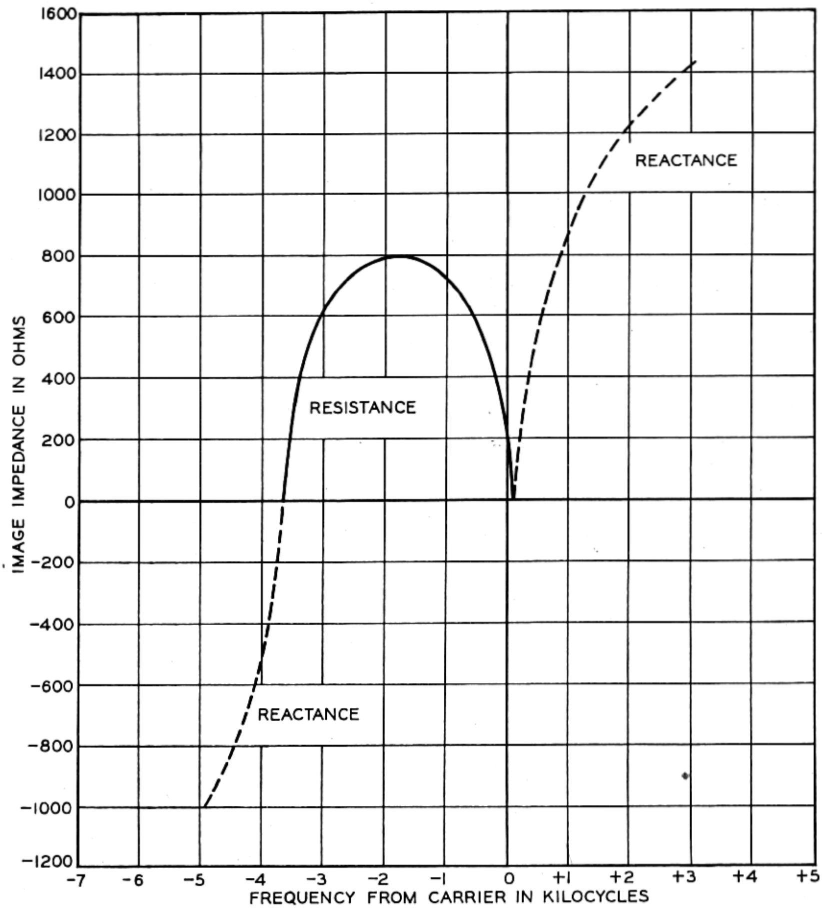

Fig. 8—The large reflection losses occurring within the transmission band of the filters and near the edges of this band has the effect of narrowing the width of the transmission band.

the same sign there is attenuation. At the point where the two curves intersect there are attenuation peaks of very high loss. The reactance curves of Fig. 7 are for the filter section accountable for the pair of attenuation peaks shown in the filter characteristic which are the closer to the edges of the transmitted band. For the other section the cross-over points of the two reactance curves are farther away from the band, since this section is responsible for the outer pair of attenuation peaks. The design of the filters consisted in determining values for the inductance coils, condensers, and crystals, such that the reactance curves of the lattice arms of the filter passed through infinity and intersected with each other at the desired frequencies and, at the same time, in determining the impedance level for all of the elements such that the filters would have the right image impedances.

The curves of Fig. 7 would seem to indicate a somewhat greater band width for these filters than shown by the insertion loss characteristic of Fig. 1. The reason for this can best be explained by referring to the image impedance of one of the filter sections as shown in Fig. 8. Within the band the image impedance is, of course, a pure resistance which varies with frequency. It is about 800 ohms at mid-band frequency and falls rapidly to zero near the edges of the band. Assuming the effective resistance of the coils, which is about 100 ohms, as belonging to the terminating impedances, the filter sections actually work between impedances of about 700 ohms. This means that large reflection losses occur at each end of each filter section near the edges of the transmission band where the image impedance of the filter is very small. It is these reflection losses that are responsible for the actual transmission band being much narrower than it would be with the filter sections terminated in their actual image impedances. The filter sections are designed with 800 ohms image impedance at mid-band frequency instead of 700 ohms to make the band flatter and somewhat wider than it would be otherwise.

When a number of band filters are operated in parallel it is generally necessary to connect across the paralleled end a two-terminal network to correct for the distortion that would otherwise be present in the highest- and lowest-frequency filters in the group. A circuit of the network used for this purpose with the channel filters is shown in Fig. 9.

The filters employ crystal elements in order to obtain abrupt discrimination between wanted and unwanted frequencies and at the same time to secure low and uniform loss in their transmitting bands. This characteristic must not only be obtained at the time the filters are assembled and adjusted but must be maintained throughout the service life of the filters and not appreciably affected by temperature variations. This imposes severe stability requirements upon the elements used in the filters. The crystal elements themselves are very stable when properly designed and once adjusted will retain at a given temperature their frequencies of resonance within one or two cycles seemingly indefinitely. Their temperature coefficient is only about twenty-five parts per million per degree centigrade, which is not objectionable.

The obtaining of inductance coils and condensers that were adequate in stability for use in conjunction with the crystals required considerable development effort. The inductance coils were required to have not only a high degree of stability with respect to temperature and time but also a high ratio of reactance to effective resistance, low modulation, and at the same time be small in size. Air core coils might have been designed for the purpose but they would have been quite large. The coils used are of the toroidal type wound on about one and three-fourths inch rings of molybdenum-permalloy. To reduce eddy current losses the cores are made of very fine powder and then annealed to reduce hysteresis losses. The particles are mixed with insulating

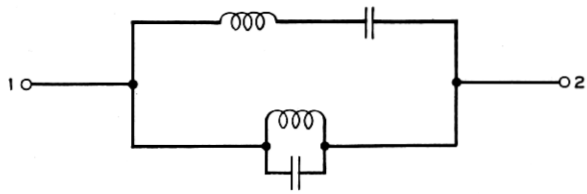

Fig. 9—A two-terminal reactance network is connected in shunt across the filters at their paralleling end to improve the characteristic of the highest and lowest frequency filters.

material and formed into rings by extremely high pressure. The inductance of the coils has a temperature coefficient of less than 40 parts per million per degree centigrade. The cores of the coils for the higher-frequency filters are wound with finely stranded wire to help secure good Q's (about 225). Because of the high impedance of the coils called for by the filter design, care is taken to make the capacitance between the windings and the core and between the windings and the case as low as practicable and also to make stable all such small capacitances as must be present.

The two extra condensers used at one end of each filter for paralleling purposes are of a high grade mica type. The other condensers are all quite special. The fixed ones, ranging in magnitude from about 7 mmf to 100 mmf, are made by plating short lengths of high grade glass tubing inside and outside with silver. Because of the intimate association of electrodes with the surfaces of the tubes and the low expansion coefficient of the glass used, a condenser is obtained that has a temperature coefficient comparable with that of the coils and crystals. No aging effect has been observed. It will be noticed that four small adjustable air condensers appear in each filter section. These are used to secure precise initial adjustment of the filter capacitances.

To protect the filter elements against moisture, the filters are hermetically sealed in a container made from a rectangular section of seamless brass tubing with closely fitting plates soldered in each end. One end plate carries four metal-glass seal terminals and a nozzle through which dry air is blown after the filter is assembled. The other end plate is provided with a small hole for the escape of the drying air. After the drying operation the hole in the nozzle and the hole in the opposite end of the filter are closed by soldering. The elements that make up the filter are assembled on a chassis which is completely wired and then slid into the container in assembly. Figure 10 is a photograph showing this chassis and the arrangement of the

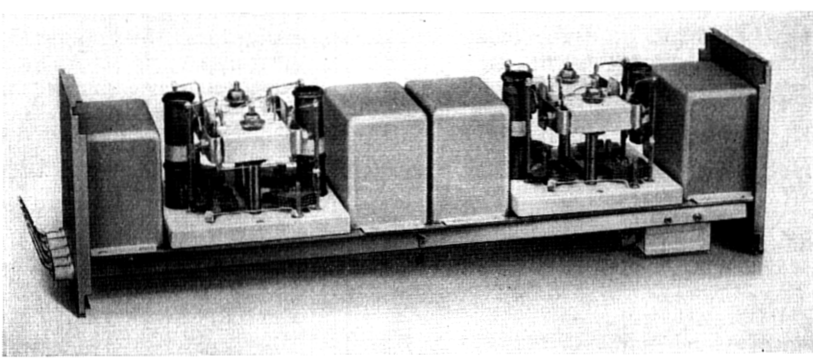

Fig. 10—The filter parts are assembled and wired on a chassis which is slid as a unit inside the filter container.

elements. The elements are located in such a way as to use very short wiring connections which reduce the magnitude of any stray admittances. The wired filter chassis is carefully adjusted by setting the values of the air condenser such that for each filter section the resonance frequencies looking into each end of each section occur where they theoretically should. This compensates for the effect of small capacitances between the filter parts. In the design of the filter parts care is taken to use no material which absorbs moisture readily since such moisture would later be released and raise the relative humidity of the air inside the filter.

If a potential much in excess of about twenty volts is applied across crystal elements at frequencies near resonance, the crystals will break from the mechanical strain of their vibration. The maximum safe voltage across the channel filters at the resonant frequencies of the crystals is considerably greater, however, since at resonance the full voltage does not appear across the crystals. In normal use the voltages across the filters will be very much less than twenty volts.

Other filters forming part of the terminal apparatus are the group modulator and group demodulator low-pass filters, the channel and group carrier supply filters, and the pilot supply filters. The group modulator and demodulator filters are of the low-pass type employing only coils and condensers as elements. The group carrier supply filter is the same in schematic and mechanical design as the crystal channel filters described. The pilot supply filters and the channel carrier supply filters are equivalent in schematic to one section of the channel filters; but of course they are only about half the size and are hermetically sealed in the same manner.

References

For a further discussion of crystal filters the reader is referred to "The Evolution of the Crystal Wave Filter" by O. E. Buckley, *Journal of Applied Physics*, October 1936, and "Electrical Wave Filters Employing Quartz Crystals as Elements" by W. P. Mason, *Bell System Technical Journal*, July 1934.