Manufacture of Quartz Crystal Filters

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Quartz crystal filters used in modern carrier systems present new problems in manufacturing technique. In the assembly and testing of the filters and in the production of component crystals, coils and condensers, special factory facilities are required for accurate measurement of frequency and control of atmospheric conditions. The manufacture of quartz crystal plates in particular combines several fields of applied science, including crystallography, precision grinding, vacuum technique and high frequency electrical measurement. Inductance coils and fixed and variable condensers for use in crystal filters must consistently meet advanced requirements, especially in regard to stability. The assembly of these components into filters resembles the manufacture of radio receivers, differing mainly because of smaller quantity requirements. Testing equipment must permit rapid shop adjustment and test of the completed filters with laboratory precision.

Introduction

ELECTRICAL wave filters employing quartz crystals [1] are used extensively in broad band carrier systems [2, 3] recently introduced into commercial service. Such crystals exhibit the property of piezoelectricity; that is, an electrical voltage applied to the terminals of a crystal causes a mechanical distortion of the quartz, and vice versa. Because of this interrelation a plate of quartz, at frequencies near its mechanical resonance, behaves electrically like the coil and condenser combination shown in Fig. 1. The series inductance and capacitance

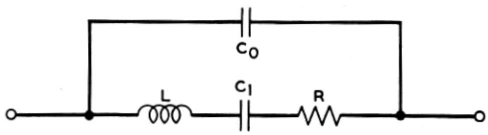

Fig. 1—Equivalent circuit of a quartz crystal plate. Elements L, C_1 and R are associated with the piezo-electric property and mechanical resonance of the crystal, while C_0 represents capacitance between the electrodes.

represent the mass and elasticity of the plate, respectively, while the shunt condenser represents the capacitance between faces of the crystal. The damping of such a plate may be made very low, giving a ratio of reactance to resistance (commonly termed Q) of 15,000 or

[1] Numbered references are listed at end of paper.

higher, as compared with a practical limit of 300 for coils. Stability of resonance frequency and compactness of dimensions are two further respects in which quartz crystals surpass the best coils and condensers available.

Filters designed to utilize these properties generally consist of one or more crystal plates, plus such condensers, inductance coils and resistances as may be required to give the desired overall performance. The principal types used in the Bell System operate at frequencies ranging from 40 to 600 kilocycles and transmit bands varying from 5 cycles to 6 kilocycles in width. Physical dimensions range up to $3 \times 5 \times 16$ inches.

Unusual manufacturing requirements are imposed by the nature of these filters and of the systems in which they are used. Adjusting tolerances and stability requirements, for example, range from $\pm$ 20 to $\pm$ 200 parts per million on crystals and on coil-and-condenser circuits used in crystal filters. Transmission losses must be measured to accuracies of the order of $\pm$ .03 db at 100 KC. To insure stability of adjustment during service life, component apparatus must be protected against dust and excessive humidity. Methods of assembly and testing must be adaptable to a variety of types of filters, one of which, the channel filter,[4] is manufactured by the Western Electric Company in quantities of 1500 to 5000 per year, while the others range from 10 to 1000 per year. Long service life must be assured by proper choice of materials and technique.

In order to satisfy such requirements special manufacturing procedures are necessary. In reviewing these features it will be convenient to consider first those methods or facilities which are used in several or all stages of the manufacture of crystal filters, second the methods employed in producing component apparatus for such filters—particularly crystals, coils and condensers—and finally the technique of assembling and testing the complete filters.

General Facilities

A primary requisite in the adjusting and testing of both crystals and crystal filters is the precise measurement of frequency. The equipment used for this purpose includes a standard frequency generator containing a 100 KC crystal oscillator. This generator normally maintains a frequency accuracy of about 1 part in 2,500,000 operating under the control of the Bell System master frequency standard in New York, but will remain accurate within 1 part in 1,000,000 even though the master signal is interrupted for as much as 24 hours. Three sub-harmonics of 100 KC, namely, 100 c.p.s., 1000 c.p.s. and

10,000 c.p.s., are distributed to all test positions. Oscillators supplying the individual test sets are provided with cathode ray oscilloscopes, by means of which they can be synchronized with any multiple of the three standard frequencies. To set up an odd frequency not coinciding with any multiple it is necessary to interpolate dial readings between two synchronized points.

Control of atmospheric conditions also plays an important part in the manufacture of crystal filters. The temperature coefficient of frequency of the crystals most commonly used is about 15 parts per million per degree Fahrenheit. For some filters, in order to secure uniform performance throughout the temperature and frequency ranges encountered in service, these crystals must be adjusted within tolerances as small as 40 parts per million. Fluctuations of as little as 2° F., in such cases, must be taken into account during the adjustment of the crystals. In addition, crystals, coils and condensers are all sensitive to the effects of excessive humidity. To minimize such difficulties, the assembly and testing of these components and of the filters in which they are used are carried out in air conditioned rooms controlled at 75° ± 2° F. and approximately 40 per cent relative humidity.

Crystals

Of the several component parts used in crystal filters, the first to be considered in detail are logically the quartz crystals themselves. Their properties of low loss and high stability are primarily responsible for the unusual performance of filters in which they are employed.

Natural deposits in the earth constitute the sole source of supply of quartz crystals, since no practical method of producing them synthetically has been developed. "Raw" crystals suitable for use in filter manufacture must be unusually large and free from flaws. The principal source is Brazil, the bulk of the quartz being brought in by native prospectors to trading posts and shipped to this country via Rio de Janerio and other coastal cities. The crystals usually range between 3 and 10 pounds in weight, with occasional pieces reaching 100 pounds.

The raw quartz passes through successive stages of inspection and selection, commencing at the trading post and culminating in careful examinations before and during the cutting operations. A concentrated beam of light from an arc lamp (see Fig. 2) is used in locating internal flaws, which generally appear as small bubbles and inclusions of foreign matter. Quartz takes two distinct forms, left-hand and right-hand, having opposite piezo-electric polarities. Portions of raw crystals containing both forms are not usable. This condition, called

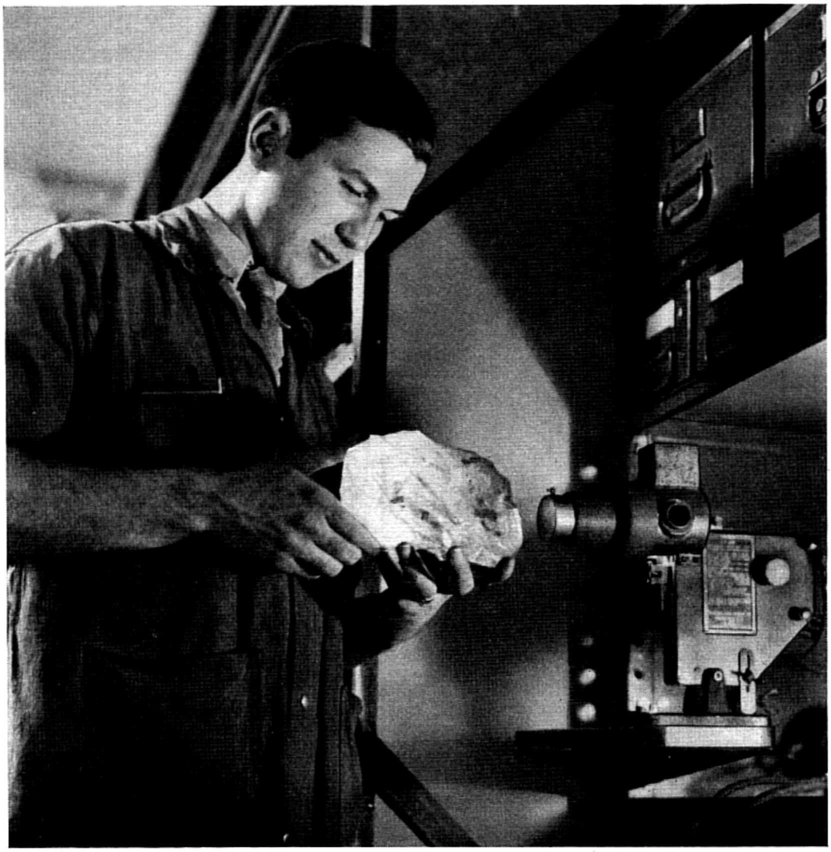

Fig. 2—Inspection of quartz crystals. An arc light beam aids in the detection of internal flaws.

"twinning," appears as shown in Fig. 3 when observed with polarized light.

For use in filters, quartz must be cut into rectangular plates properly oriented with respect to the electrical, mechanical and optical axes of the crystal, as shown in Fig. 4. A polariscope and an X-ray spectroscope are used in locating these axes to an accuracy of $\pm$ 0.25 degree. For the majority of applications the plate is cut in the plane of the mechanical and optical axes, with the long dimension set at an angle of 18.5° from the mechanical axis. This orientation eliminates secondary resonances in the completed crystal and makes the primary resonance frequency relatively independent of slight errors in orientation. For applications requiring a low coefficient of resonance frequency versus

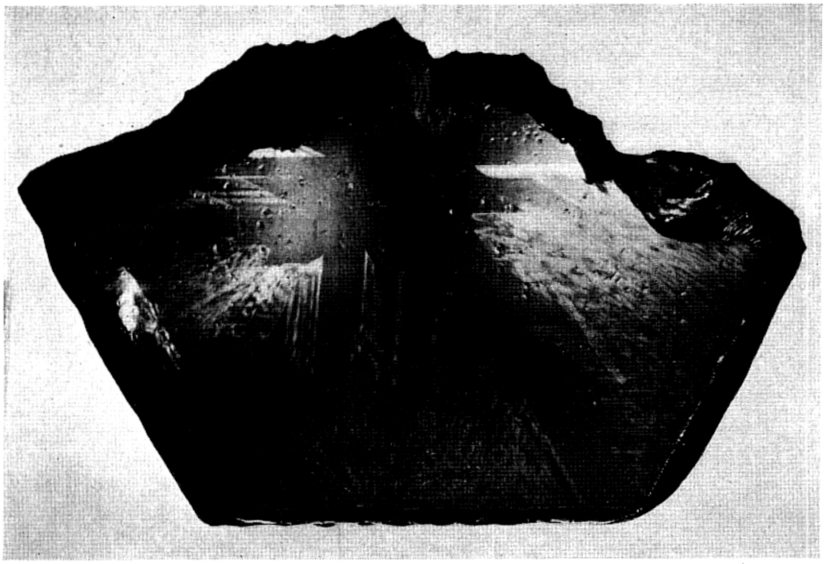

Fig. 3—Right and left-hand twinning in quartz as seen by polarized light.

temperature, plates are cut with their long dimension 5° from the mechanical axis. Tolerances in cutting and grinding to thickness, length and width prior to calibrating are of the order of .001 mm., requiring the use of technique similar to that employed in the manufacture of gage blocks. A few standard thicknesses, ranging from .020 to .060 inch, are used for most crystal plates. Lengths vary from 0.5 to 2.0 inches while widths range from 0.15 to 1.5 inches. Because of unavoidable waste in the cutting and grinding operations and the rejection of quartz containing flaws, only a small portion of the material entering the cutting room finds its way into finished plates.

Up to this point the cutting and grinding are purely mechanical operations, directed toward securing prescribed physical dimensions. During final adjustment and in service, however, the crystal plate must be connected as an electrical element. Electrodes are provided by coating the major surfaces of the plate with aluminum, using a process of evaporation and condensation in a vacuum, similar to that employed in the silvering of telescope mirrors. If the plate is to be used in a balanced filter section which requires a pair of crystal elements of the same frequency, as is frequently the case, the plating on each face is then divided in half along the longitudinal axis. This division, one-hundredth of an inch wide, must have a d.c. insulation resistance of at least 100 megohms to insure proper operation in some types of crystal filters.

Preliminary tuning is accomplished with a fixture, simulating the final holder, which grips the plate at the center by four contact points, one on either side of the division in the plating of each face. These

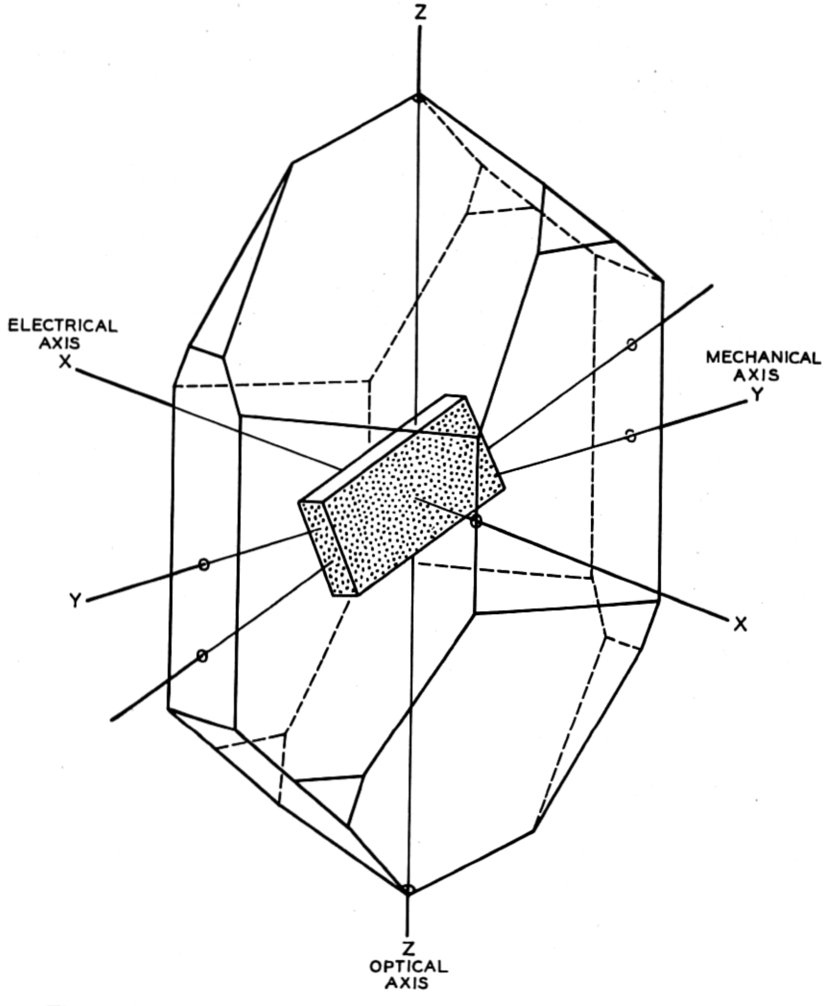

Fig. 4—Orientation of a typical quartz plate with respect to its electrical, mechanical and optical axes.

contacts introduce very little damping, since the mode of vibration normally employed is longitudinal, with maximum amplitude at the ends of the plate and a node at the center. The test set-up normally used consists of two oscillators with a meter arranged to read the difference between their frequencies. One oscillator is controlled by the crystal plate being tuned and operates at its resonance frequency; the other is controlled by a standard crystal of the desired frequency. Starting 100 to 200 cycles low, the plate is ground on the ends until its frequency approaches that of the standard.

The plate is then transferred from the fixture to its final holder, shown in Fig. 5. This mounting normally accommodates two plates

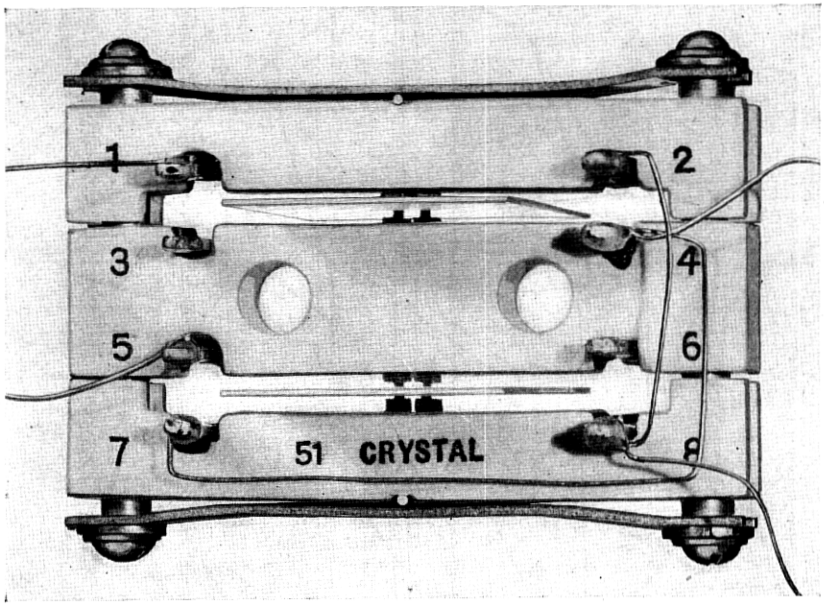

Fig. 5—Crystal plates mounted in holder. The four points at the center of each plate provide electrical contact and mechanical support.

of different frequencies, each supported at its nodal point by contacts projecting from ceramic blocks. The entire assembly is held together by a spring suspension in order to apply uniform pressure at all contacts. To minimize damping, the contacts must be accurately aligned and the quartz plates must be carefully centered upon them.

A final adjustment of frequency is now performed, as shown in Fig. 6. Permissible tolerances vary from $\pm$ 20 to $\pm$ 150 parts per million for different types of crystals. Crystals having the broader tolerances and substantial quantity requirements are adjusted by comparison with a standard crystal, as in the case of preliminary tuning. The test set shown at the left in Fig. 6 is being used for this purpose. The upper and lower panels are the oscillators controlled by the standard and the test crystals, respectively, while the center panel indicates the frequency difference between them. For very accurate work and for periodic checks of the standard crystals it is necessary to use a precision oscillator, shown at the right.

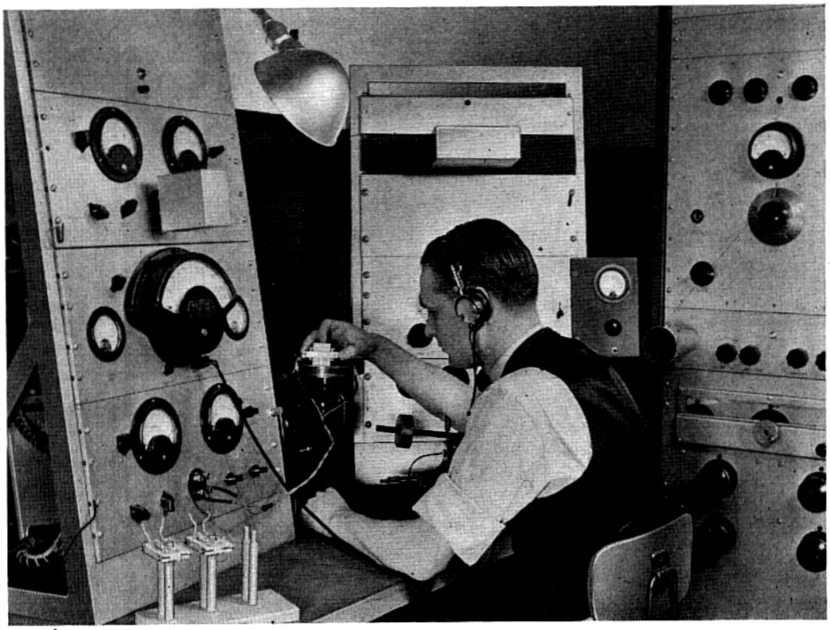

Fig. 6—Final tuning of a crystal plate using a standard crystal (in small box at upper left) for comparison.

Occasionally, in the course of adjustment, plates are carried too high in frequency. In such instances, as a result of the standardization of thicknesses mentioned previously, the plate normally can be salvaged by grinding it to the dimensions of the next higher frequency plate of the same thickness.

Aging occurs in both resonance frequency and effective resistance, as slight strains created in the quartz and in the contacts during adjustment relieve themselves. The greater part of the aging takes place during the first few hours after calibration and nearly all of it during the first week. In general, the frequency rises a few cycles and the resistance drops slightly. Crystals on which the frequency tolerance is approximately equal to the shift due to aging are stabilized by one or more temperature cycles, prior to final measurement of frequency and resistance.

Coils

Inductance coils are used in some crystal filters, particularly the channel filter for the newer types of carrier telephone systems. Since it may be necessary to connect as many as ten such filters in tandem in a long-distance circuit without appreciable impairment of the quality of transmission, the filters must meet exacting requirements not only

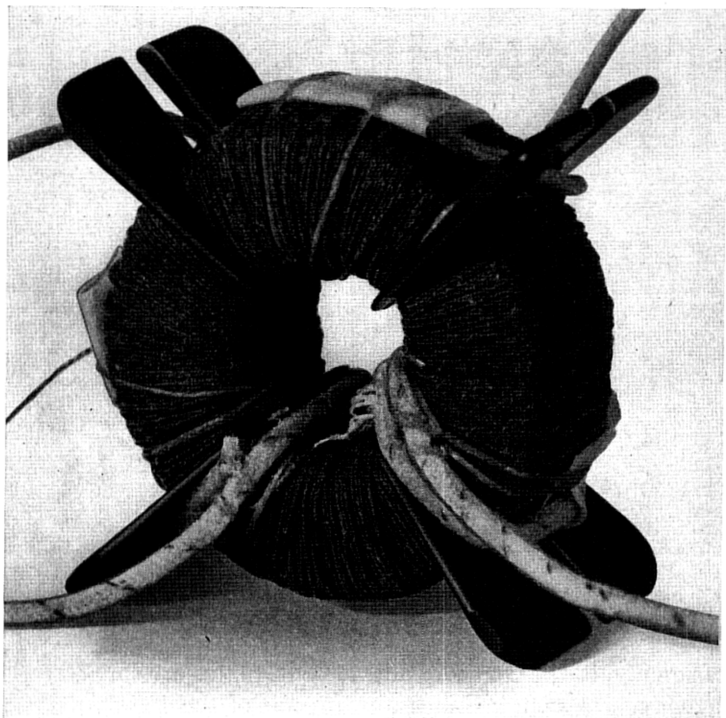

Fig. 7—Toroidal inductance coil used in crystal channel filter, shown before potting.

at the time of their manufacture but throughout service life. Consequently inductance coils used in the filters must exhibit little aging or shift with temperature, either in inductance or in effective resistance. Losses must be kept low in order to meet a Q requirement of approximately 200. The types employed in channel filters range from 25 to 50 millihenries in inductance and from 60 to 120 kilocycles in operating frequency.

Unusual features of design and manufacture are employed to meet these requirements. The coil is essentially a toroidal winding with low distributed capacitance, applied to a permalloy dust core, impregnated and potted in wax. A molded jacket with protruding fins, placed around the core, reduces the capacitance from windings to core and improves the uniformity of the windings. The coils are adjusted to within ± 1 per cent for inductance and 2 per cent for inductance unbalance by removal of excess turns, all adjustments being made at low frequency. Figure 7 shows a coil at this stage of manufacture.

The coil is then potted in a copper can and a cover soldered in place. Final test simulates actual service conditions. The coil is resonated with an external variable condenser at the operating frequency for which it is designed.

Condensers

Nearly all crystal filters contain condensers shunted across the crystal elements. These condensers must meet stability requirements similar to those already mentioned in connection with coils.

One form of fixed condenser, used where small values of capacitance and high stability are required, is illustrated in Fig. 8. Silver is fused

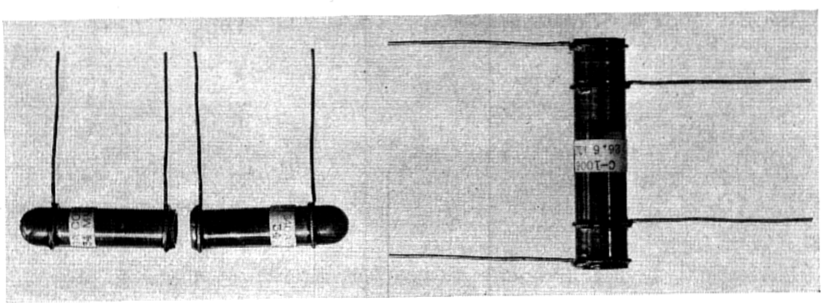

Fig. 8—Silvered glass condensers used in crystal filter applications where high stability is required.

to the inside and outside of a glass tube by applying a coating of silver paste and firing the tube in an oven. A gap is left uncoated on the outer surface near the open end and leads are soldered to the silver on both sides of the gap. The capacitance is then adjusted to the required value, within approximately ± 1.5 mmf., by scraping off a portion of the silver coating. Capacitances up to 80 mmf. are realized by this means. Two condensers may be combined in a single unit, as shown at the right in Fig. 7. The completed condenser is dipped in varnish to protect the silver from corrosion.

Pairs of such condensers, matched to each other within 0.4 mmf., are required in some types of crystal filters. This precision is achieved by manufacturing a quantity of condensers of the correct nominal capacitance and sorting them into close-limit groups after final measurement.

Variable air condensers are used in adjusting the assembled filter. For the channel filter four such condensers are manufactured on a single ceramic base, as shown in Fig. 9, to eliminate unnecessary parts

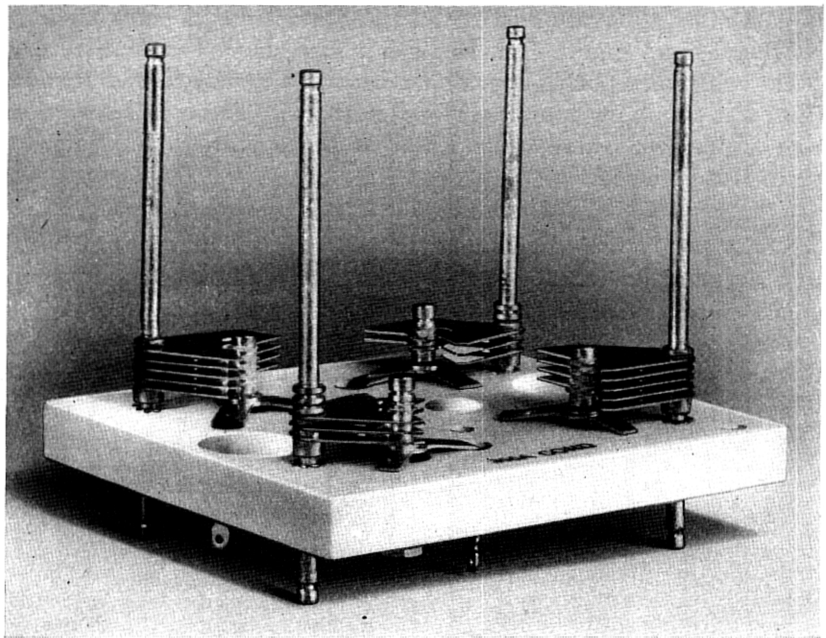

Fig. 9—Four-section variable air condenser.

and reduce assembly cost. The posts supporting the stator plates are extended both upward and downward to serve as convenient terminals for leads from adjacent pieces of apparatus. Freedom from binding is important, since condensers in crystal filters must be adjusted through angles as small as 2 minutes. To insure smooth adjustment the rotor shafts and their bearings are held to close dimensional tolerances and lubricated with petrolatum. Stability is secured by the use of thrust springs providing a substantial holding torque.

Assembly

The foregoing components—crystals, coils and condensers—are assembled into complete filters by methods somewhat similar to those employed in the manufacture of radio receivers, the principal differences arising from smaller volume requirements. The channel filter alone is produced in sufficient quantities (1500 to 5000 per year) to warrant a substantial degree of tooling. Figure 10 illustrates the

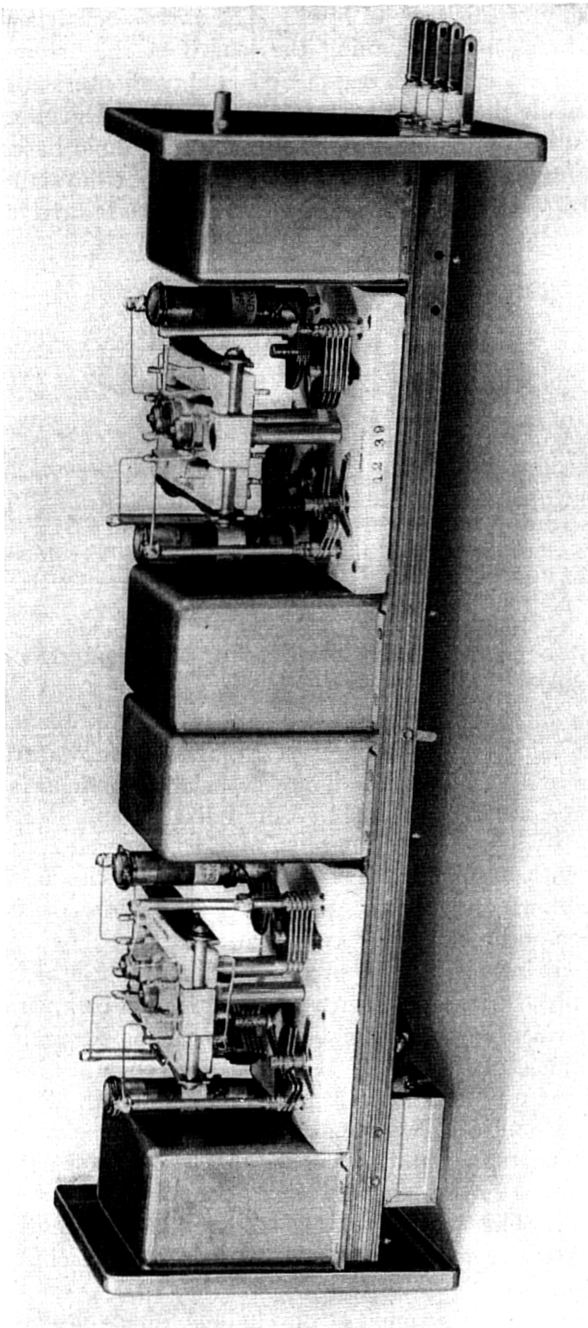

Fig. 10—Internal assembly of crystal channel filter, used in Type *J*, *K* and *L* carrier systems.

internal assembly of this type of filter. The chassis consists of a pair of perforated brass angles running the length of the assembly and spot-welded to a cover at each end. Coils and condensers are riveted to the angles, while the crystal holders are mounted with rubber shock absorbers on studs extending upward from the ceramic bases of the variable condensers. External leads are brought out through copper-to-glass seals to terminals, as shown in Fig. 11, since in final assembly

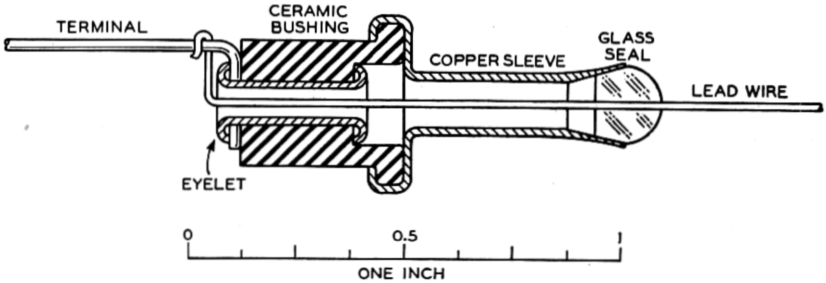

Fig. 11—Terminal used in hermetically sealed filters. The copper sleeve, bonded to the lead wire by means of an insulating glass bead, is soldered into the container of the filter in final assembly.

the filter must be hermetically sealed to protect components from moisture and dust.

In wiring the filter special precautions are taken to prevent foreign materials from being deposited on crystal plates, thereby introducing mechanical damping, and from lodging in variable condensers, where electrical leakage must be avoided. Internal connections are made with bare tinned wire. Rosin flux remaining on soldered connections is washed off with a solvent. Dust and other particles in variable condensers are blown out with air. The filter then undergoes a careful visual inspection and a 500 volt d.c. insulation test.

At this stage it is generally necessary to adjust certain of the filter elements, usually variable condensers, in order to compensate for manufacturing variations in other elements and for parasitic effects such as capacitance of the wiring to ground. A general view of the testing equipment used for this purpose is shown in Fig. 12. One or more of three methods of adjustment are employed, namely, (*a*) transmission loss, (*b*) resonance and (*c*) capacitance. The first and second of these are utilized on the channel filter, the schematic of which is shown in Fig. 13. The two sections are adjusted independently before the resistance pad, seen at the center of the figure, is inserted to connect them.

In transmission loss adjustment of the channel filter, the attenuation

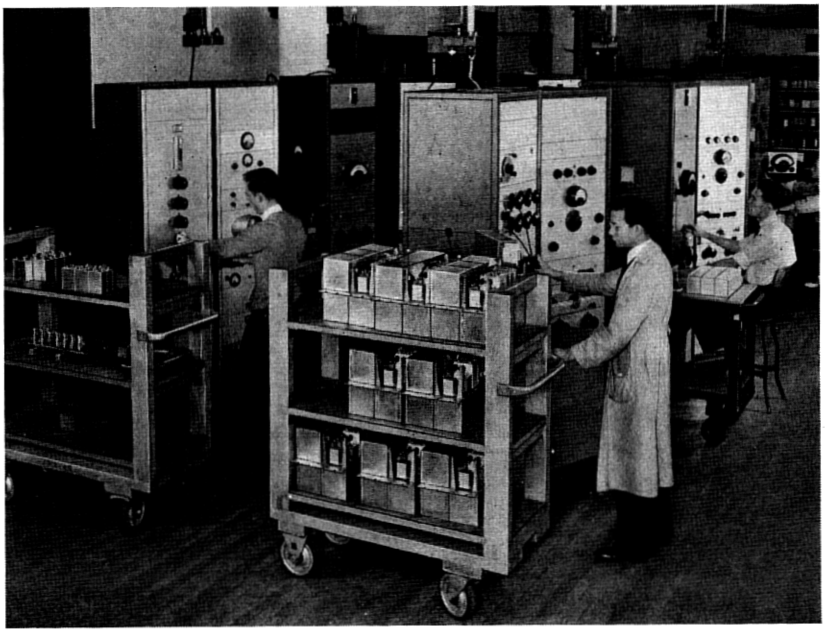

Fig. 12—Filter testing area. The standard-frequency outlets are seen above the test sets.

of each filter section is brought to a peak at a specified frequency. The filter is placed in a test shield simulating its final container. Voltage from a precision oscillator is applied to the input terminals of the section and the voltage at the output terminals is measured with a sensitive detector preceded by a variable attenuator. The condensers designated C_{TL} in Fig. 13 are adjusted with a non-metallic tool until the loss reaches a peak of 50 to 70 db. Each section contributes two such peaks.

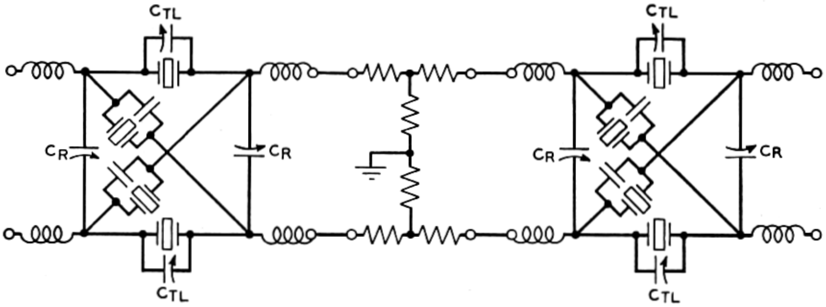

Fig. 13—Schematic of crystal channel filter.

The filter is then transferred to a resonance bridge and the impedance looking into either end of each section, with the opposite end open-circuited, is adjusted to series resonance at a specified frequency by means of the condenser C_R. This adjustment primarily controls the shape of the loss characteristic of the filter in the transmission range. The resistance at resonance is recorded for later reference.

In some types of filters, adjustment must be made to secure the correct absolute capacitance between certain points in the filter rather than to obtain desired attenuation peaks or resonances. A capacitance bridge is employed for this purpose.

In all of these adjustments, test leads connecting the filter to the test set play an important part. Shielding, balance, capacitance to ground, dielectric loss, stability and other characteristics of the leads must be carefully controlled or compensated by adjustments within the test sets in order to meet precision requirements of the order of $\pm$ 0.01 per cent.

After adjustment, in the case of the channel filter, the individual sections are connected through a resistance pad selected to complement the values of resistance measured during resonance adjustment. Uniformity of overall transmission loss, regardless of manufacturing variations in components, is secured by this means.

The completely wired filter is now placed in a copper shell and hermetically sealed with solder, except for an inlet and an outlet vent. In order to remove vestiges of moisture which might affect the crystals or other components during service life, a current of air of less than 3 per cent relative humidity is then passed through the filter for 12 hours and the vents are sealed off.

Final test consists of measurements of transmission loss at a series of frequencies in the transmission and attenuation bands of the filter, using equipment similar to that on which the peaks were adjusted. The variety of product which must be tested with these facilities demands maximum flexibility and minimum set-up time. This requirement is met with plug-in terminating impedances, pads, leads, etc., and with oscillators and detectors tuning continuously over a wide range of frequencies. Several filters of the same type are normally tested simultaneously, all being measured at one frequency before the next frequency is set up. Contact fixtures for particular types are provided when justified by quantity requirements, in order to facilitate the transfer of test leads from one filter to the next.

Transmission loss characteristics of channel filters under various conditions are shown in Fig. 14. The solid curve illustrates a normal filter. The loss in the passband is approximately 5.6 db, with distortion of about 0.25 db over a band 3 KC wide. The peak losses are from 75 to 90 db, with the intervening "valleys" approximately 65 db. The other curves illustrate three types of defects occasionally observed, namely: (*a*) displacement of one attenuation peak caused by

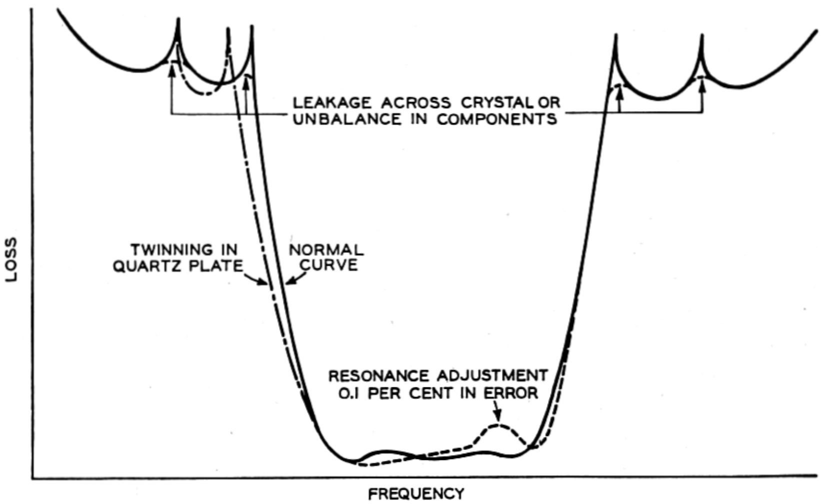

Fig. 14—Insertion loss characteristics of crystal channel filters, showing the effects of deviations from normal conditions.

twinning in one of the crystal plates, (*b*) abnormal distortion caused by a 0.1 per cent error in resonance adjustment, and (*c*) low loss at peaks caused by leakage across a crystal or by components which are inadequately balanced to ground. As an aid to locating the particular components or adjustments which are responsible for such defects, a catalogue of "trouble-shooting" instructions, arranged by classes of filters and types of symptoms, has been compiled.

Cleaning, finishing and labelling constitute the remaining operations on crystal filters. High temperature processes such as vapor degreasing and baking of the finish are inapplicable here because of the nature of the component apparatus in the filter. The surface is scratch-brushed, washed with a solvent and sprayed with aluminum lacquer. Rubber stamps and printers' ink are then used to apply the terminal and type designations.

Conclusion

Crystal filters exemplify the trend toward higher frequencies and higher precision in modern carrier systems. These advances in design have required the development of new manufacturing processes and refined methods of adjusting and testing, and demand increased care and skill in every step. Ten years ago this technique had not reached even the laboratory stage. Today, in the commercial production of crystal filters, it has become commonplace to deal with capacitances expressed in tenths of a micromicrofarad, transmission losses in hundredths of a decibel, crystal dimensions in thousandths of a millimeter and frequency measurements in thousandths of a per cent. The attainment of such precision at moderate shop cost is the primary engineering problem in the manufacture of the higher frequency types of carrier telephone facilities.

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