THE DESIGN OF AN 885-MEGACYCLE TELEVISION TRANSMITTER

by

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TABLE OF CONTENTS

INTRODUCTION

The purpose of this thesis was to continue the work in the development of a suitable design of an 885-megacycle experimental television transmitter. Kenneth E. Fultz began the work on this project and most of the work which followed was based on the results and conclusions from his thesis.

The transmitter was to be crystal-controlled in order to maintain frequency stability and the output was to be modulated. These requirements dictated the use of space-charge control tubes. For the most part, the design was based on theory since transmitters utilizing this type of tubes which will operate in the 1000-megacycle region have not been developed extensively.

Previous work on this project has shown the need for efficient tank circuits and has suggested the use of shorted sections of flat-element transmission lines.[1] A considerably lower characteristic impedance is obtainable with flat-element lines than is possible with parallel wire lines. Since the tank is capacitively loaded by the tube's interelectrode capacitance, lowering the characteristic impedance increases the electrical length of the line and improves the efficiency of the tank.

The procedure followed was to design and construct the final amplifier first since tank circuit requirements are more

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[1] Kenneth E. Fultz, "Design of an 885-Megacycle Television Transmitter," Unpublished Master's Thesis, Kansas State College, 1950.

rigorous at the higher frequencies. Once a suitable circuit was found for the final amplifier, the same type of circuits could be used for the amplifiers at the lower frequencies.

Included in this thesis are the design calculations for the second doubler, intermediate, tripler, and final amplifiers. Also included are the construction data and experimental results.

FINAL AMPLIFIER

Selection of Tubes

Screen-grid, beam-power, and pentode tubes have a definite advantage over triodes since in most cases they can be operated as cathode separation amplifiers without neutralization. Triodes, when used at ultra-high frequencies, must be operated as grid-separation amplifiers to provide the necessary isolation between the plate and grid circuits. The advantage of cathode separation, in comparison to grid-separation circuits, is that the required driving power is less,and hence greater gain per stage is obtainable. The disadvantage of pentode, beam-power, and screen-grid tubes is that they are, in general, more expensive than triodes.

An example of a beam-power tube which will probably operate satisfactorily at 885 megacycles is the 4X150A. According to the RCA Tube Manual, this tube has full power output at 500 megacycles. The power output at higher frequencies would be less but should give satisfactory results at 885 megacycles.

Triodes which are useful in the 1000-megacycle region are of the disk seal type commonly known as "lighthouse tubes". These tubes are particularly well suited for grid-separation construction since the plate and cathode connections are on opposite sides of the grid plane.

Because the cost was an important factor in the design of the transmitter and high-power output was not required, the more inexpensive 2C43 lighthouse tubes were chosen in preference to the 4X150A.

Selection of Final Tank Circuit

As previously noted, well designed tank circuits are highly important. Many of the various forms of cavity resonators were considered since they are ideally suited for microwave use. Because the electromagnetic fields involved are wholly internal, there is no coupling to adjacent objects and no energy lost by radiation. However, cavities do not lend themselves readily to push-pull operation because of the mechanical difficulty of tuning and coupling. Push-pull operation in the final stage was desired because it gives greater power output unless parallel operation is used, and eliminates the necessity of a plate bypass condenser. In order to use a push-pull circuit and to simplify construction, flat-element transmission lines were selected.

Tank Circuit Tuning

Tuning of the flat-element lines may be accomplished by several methods. A variable capacitor placed across the high-impedance end of the tank has been the most popular method. The additional capacitive loading has the effect of reducing the physical length of the tank and a consequent reduction of efficiency. Because of the difficulty of providing efficient tank circuits in the 1000-megacycle region, capacitive tuning is not recommended.

A variable shorting bar provides a tuning method which maintains the physical length of the line as long as possible. However, contacts with losses may result, and mechanical construction is more difficult.

Since, for a given physical length, the electrical length of the line is a function of the characteristic impedance, varying the characteristic impedance provides another method of tuning. The characteristic impedance is lowered by the presence of a metal plate parallel to the tank. As the plate is brought closer to the tank, the resonant frequency is increased. Tuning by this method has the advantage of eliminating all r-f contacts while the physical length of the tank is kept long enough to maintain highest efficiency. This method of tuning was used in the first model.

Construction of Final

The plate tank consisted of two 1/16-inch brass plates 3 inches wide, 2-1/4 inches long, and spaced 3/8 inch. The tube's plate leads were connected rigidly to the tank by clamps made from 1/4-inch brass plate. Tuning was adjusted by a movable brass plate pivoted at the shorted end of the tank.

The cathode tank was similar to the plate tank. Two-inch lines were used with 1/4-inch spacing, giving a width to spacing ratio of 8 which is the same as the width to spacing ratio of the plate tank. In the first construction the cathodes were connected rigidly to the cathode tank. Because the plate and cathode connections were both clamped rigidly, tube breakage resulted. The cathode clamps were replaced by phosphor bronze fingers to provide enough freedom of alignment to prevent tube breakage.

The grid-leak condenser consisted of a 4 x 5-inch plate separated from the grid plane of the shield box by a .010-inch Teflon sheet. Originally the grid connection was made by the grid disk contacting the condenser plate. Due to the difficulty of maintaining good grid contact, grid fingers were necessary to provide spring tension on the grid disk. Brass shim stock, .005 inch thick, was found to be suitable for the grid fingers.

Modulation of Final

When plate modulation is used with grid-separation circuits, the modulating voltage must drive the plate negative on the trough of the modulation cycle if 100 per cent modulation is to be obtained. This is because the driving power supplies a portion of the output, and therefore the plate voltage must be negative in order to reduce the output to zero.

An experimental class C amplifier was built for the purpose of determining the linearity of the modulation when the plate voltage is negative. This amplifier used a 6J5 triode and operated at a frequency of 1 megacycle. From the results of this experiment, the output voltage was found to be proportional to the plate voltage.

Design of Final Class C Amplifier

The following design was calculated by the approximate method developed by Terman.[1] Since the tubes were manufactured by General Electric, the tube ratings and plate characteristics were taken from a General Electric pamphlet on lighthouse tubes. The ratings for the 2C43 are 12 watts maximum plate dissipation, 500 volts maximum d-c plate voltage, 55 milliamperes maximum cathode current.

From the plate characteristics, the minimum plate voltage and the maximum grid voltage were chosen as 100 and 20 volts, respectively. The maximum space current is 198 milliamperes and the maximum grid current is 91 milliamperes.

Assuming α equal to 3/2, and a plate current angle equal to 160 degrees, the d-c component of the space current is .25 x 198, or 49.5 milliamperes. The peak value of the fundamental component of space current is .425 x 198, or 84.1 milliamperes.

With an amplification factor of 48, the grid bias required for a plate supply voltage of 450 volts is 14 volts. The calculated grid current angle is 108 degrees. The d-c component

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[1] Fredrick E. Terman, Radio Engineering, 3rd ed. (New York: McGraw-Hill), 1947, p. 374.

of the grid current is .151 x 91, or 13.8 milliamperes, and the fundamental component of the grid current is .285 x 91, or 26 milliamperes.

The power input to the plate is 16.1 watts and the power developed in the plate tank is 10.2 watts. The plate dissipation is 16.1 - 10.2, or 5.9 watts.

The above calculations are for one tube. For two tubes in push-pull the plate power output is 20.4 watts and the driving power required is 2.86 watts. The d-c grid current is 27.6 milliamperes and the d-c plate current is 71.4 milliamperes at the crest of the modulation cycle. The grid-leak resistance required is 507 ohms and the loaded plate-tank impedance is 24,000 ohms.

Plate Tank Design

The following design calculations were based on the relations given by Parker.[1] A flat-element line 3 inches wide and spaced 3/8 inch was used for the plate tank. The 2C43 grid-to-plate capacitance equals 1.7 micromicrofarads. For push-pull operation the plate-to-plate capacitance is .85 micromicrofarad and the reactance at 885 megacycles is equal to 212 ohms. From the given line dimensions, the calculated characteristic impedance is $377 \times \frac{3/8}{3}$, or 47.1 ohms. The required length of the line in electrical degrees is equal to the arc tangent $\frac{212}{47.1}$, or 75.5 degrees. Since a wavelength at 885 mega-

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[1] B. E. Parker, "VHF Tank Design," Radio and Television News, 43:8, January, 1950.

cycles is 13.35 inches, the length of the line is $\frac{75.5}{360} \times 13.35$, or approximately 2-7/8 inches. Because of the difficulty of calculating accurately the effect of the plate lead and tube clamp inductances, the actual line length was determined experimentally and found to be 2-1/4 inches.

Since the characteristic impedance of the cathode line is equal to the characteristic impedance of the plate line, the physical length of the line should be approximately the same. The physical length, determined experimentally, was 2 inches.

Testing of Final Amplifier

The final amplifier was tested with a variable frequency oscillator tuned to 885 megacycles. Adjustment of the plate and cathode tank gave no indication of resonance. A check made with a loop soldered to a pilot lamp indicated that the cathodes were being excited in parallel rather than in push-pull. Extending the outer conductor of the coaxial cable from the shield box to the tank shorting bar remedied this trouble.

Adjustment of the tuning by varying the characteristic impedance did not have sufficient range to tune through resonance. This apparently was due to the large width to spacing ratio of the tank circuits, and consequently the edge effects were slight. This method of tuning was discarded in favor of the sliding shorting bar method which gave satisfactory results.

The aluminum shield box was temporarily constructed by bolting only at the corners. In the process of testing it was discovered that by pressing the unbolted joints the power out-

EXPLANATION OF PLATE I

Close-up of the final amplifier with the shield partially removed.

PLATE I

put was considerably increased. After bolting all joints securely, the final amplifier seemed to work satisfactorily. However, no power measurements were made since sufficient driving power was not available.

TRIPLER AMPLIFIER

After the testing of the final a tripler was constructed similar to the final. Push-pull operation was chosen because of the required driving power for the final and the simplicity of tank circuit construction. The tubes employed were the 2C40 lighthouse triodes.

The plate tank was identical to the plate tank of the final and the cathode tank was identical to the final cathode tank except that the length was increased to 8½ inches to give quarter-wave resonance at 295 megacycles.

Class C Design

The tripler class C design, based on RCA Tube Manual characteristics, was computed by Fultz.[1] The important design quantities applied to push-pull operation are as follows:

d-c plate current equals 22 milliamperes
d-c grid current equals 11.6 milliamperes
power delivered to the plate tank equals 3.72 watts
cathode driving power equals 1.72 watts
loaded plate-tank shunt impedance equals 96,800 ohms
grid-leak resistance equals 3625 ohms
grid bias equals 42 volts

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[1] Kenneth E. Fultz, "Design of an 885-Megacycle Television Transmitter," Unpublished Master's Thesis, Kansas State College, 1950.

Testing of Tripler

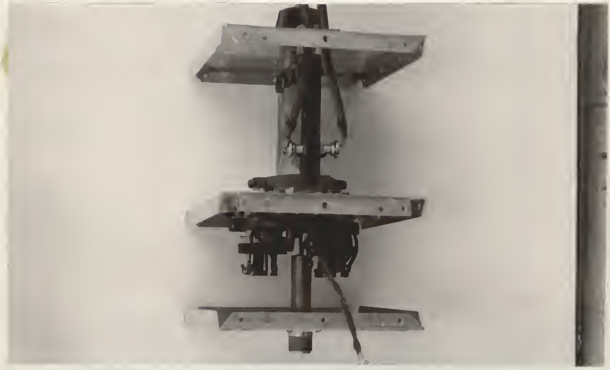
The tripler amplifier was tested by supplying the driving power from a laboratory oscillator. When the plate and cathode tanks were tuned to resonance, oscillation at the plate frequency resulted. Apparently the feedback was through the tubes since adequate shielding was provided. The cathode line was one quarter of a wavelength long at the input frequency but it would be approximately three quarters of a wavelength at the plate frequency. Due to the existence of this higher mode, the cathode tank offered a high impedance to energy fed back from the plate circuit. To remedy this difficulty, the cathode line was replaced by a lumped-inductance tank circuit. The coil, wound with 3/16-inch copper tubing, had three turns with an outside diameter of 1 inch and a center-to-center spacing of 9/16 inch. The filament leads were placed inside the copper tubing and brought out at the center tap to remove the r-f voltage. After replacing the cathode tank, the tripler had no tendency to oscillate.

Only a small dip in plate current was observed when tuning through resonance. This was thought to be due to insufficient drive since reducing the drive on a tripler reduces the third harmonic component of the plate current. In order to be certain that the tripler would work if sufficient driving power were available, a standpipe oscillator was altered to take a type N coaxial fitting and was then used to drive the tripler. This new source of driving power gave a larger dip in plate current and power output was observed with a pilot lamp.

EXPLANATION OF PLATE II

Close-up of the tripler amplifier with the shield box partially removed.

PLATE II



SECOND DOUBLER

Description

At this point it was evident that the tripler amplifier would require more driving power than was available from the second doubler of the transmitter previously constructed. Therefore the second doubler was redesigned to give greater power output. The new second doubler used two 2C40 lighthouse triodes in a push-push circuit. This design would require more driving power than was available from the first doubler; however, an intermediate amplifier could be used between the first and second doublers. Using an intermediate amplifier between the first and second doublers was chosen in preference to placing an intermediate amplifier between the second doubler and the tripler because better tubes are available for use at the lower frequency.

The push-push doubler used a quarter-wave shorted flat-element transmission line for the plate tank. A tuning condenser, consisting of a 1-inch disk secured to a 1/4-inch bolt, was placed between the tubes at the open end of the tank.

Since the output was single-ended, it was necessary to construct a plate bypass condenser. A brass plate 2-3/4 x 6 inches, separated from the plate tank by a sheet of Teflon .010 inch thick, formed the plate bypass condenser.

The cathode tank used a 3-turn lumped inductance similar to the cathode tank of the tripler with a 15-micromicrofarad variable condenser for tuning.

Class C Design

General Electric tube characteristics were used for the class C design of the 2C40 push-push doubler. The minimum plate voltage was chosen as 75 volts and the maximum grid voltage as 9 volts. At this point on the plate characteristic curves, the plate current and grid current are 70 and 67 milliamperes, respectively. For an assumed plate-current angle of 120 degrees, the d-c component of space current is 26.4 milliamperes, the fundamental component is 47.9 milliamperes, and the second harmonic component is 36.3 milliamperes.

The bias voltage required for a plate-supply voltage of 350 volts and an amplification factor of 36, is 36.1 volts. For a calculated grid-current angle of 74 degrees, the d-c component of grid current is 7.36 milliamperes and the second harmonic component is 12.8 milliamperes.

The above design conditions are for one tube. For two tubes operating push-push, the power developed in the plate tank is 3.7 watts and the cathode driving power is 2.16 watts. The required loaded tank impedance is 10,200 ohms.

Plate-Tank Design

The plate tank used a 3-inch brass plate spaced 3/8 inch above the grid plane. The characteristic impedance calculated by the equation given by Parker is 47.1 ohms.[1] The grid-to-

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[1] B. E. Parker, "VHF Tank Design," Radio and Television News, 43:8, January, 1950.

plate capacitance of the 2C40 is 1.3 micromicrofarads. The maximum capacitance of the 1-inch disk tuning condenser spaced 1/8 inch above the grid plane is 1.4 micromicrofarads.[1] The combined capacitance of two tubes in parallel and a mid-range tuning capacitance of .7 micromicrofarad has a reactance of 163 ohms. The required electrical length of the line to give resonance is 73.9 degrees. At a frequency of 295 megacycles, the physical length of the tank is 8.21 inches.

Testing of Second Doubler

The second doubler was tested as a separate unit with the excitation supplied from a laboratory oscillator. No changes were made on the doubler; however, an optimum value for the plate voltage was found to be approximately 125 volts. This indicates the tank circuit efficiency to be low.[2]

Next, the second doubler was used to drive the tripler with the doubler excited by the laboratory oscillator. This proved to be unsuccessful. There was no measurable power out of the tripler.

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[1] Federal Telephone and Radio Corporation, Reference Data for Radio Engineers. (New York: McGraw-Hill) 1940, p. 90.

[2] Kenneth E. Fultz, "Design of an 885-Megacycle Television Transmitter," Unpublished Master's Thesis, Kansas State College, 1950.

INTERMEDIATE AMPLIFIER

Since the second doubler did not have sufficient power to drive the tripler, an intermediate amplifier was constructed to amplify the output of the second doubler. The intermediate amplifier made use of an 832A dual beam-power tube in a push-pull cathode separation circuit. According to the manufacturer's ratings, the 832A gives full power output at 200 megacycles. The operating frequency of this stage was 295 megacycles which is well above 200 megacycles. However, this tube gave good results and supplied sufficient power for driving the tripler amplifier.

The plate tank was made from 1/4-inch brass rods 5 inches long and spaced 7/8 inch apart. Coarse adjustment of the tuning was accomplished by a semi-fixed shorting bar. A small trimmer condenser, tapped down 3½ inches from the open end, was used for vernier adjustments.

An attempt was made to use a parallel wire section for the grid tank but due to the capacity loading of the tube, quarter-wave resonance was not possible. A flat-element loop, formed from a copper strip 3/4 inch wide and spaced 3/8 inch, proved to be satisfactory. A ceramic trimmer condenser placed near the closed end of the loop provided the tuning adjustment.

The design of the intermediate amplifier was based on the typical operating conditions given by the RCA Tube Manual. The screen-dropping resistor used was 7200 ohms, the grid-leak resistor was 10,000 ohms, and the cathode-bias resistor was 300 ohms.

EXPLANATION OF PLATE III

Fig. 1. Top view of the doubler amplifier with the cover removed.

Fig. 2. Bottom view of the doubler amplifier with the cover removed.

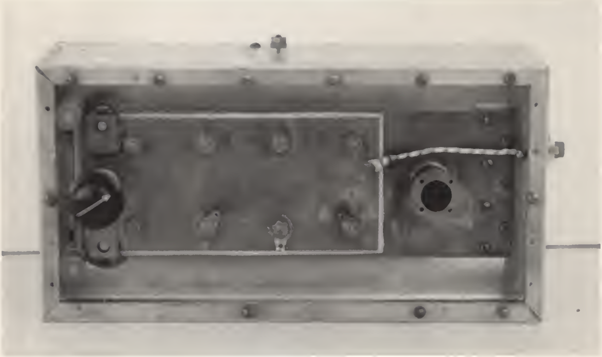

Fig. 1.

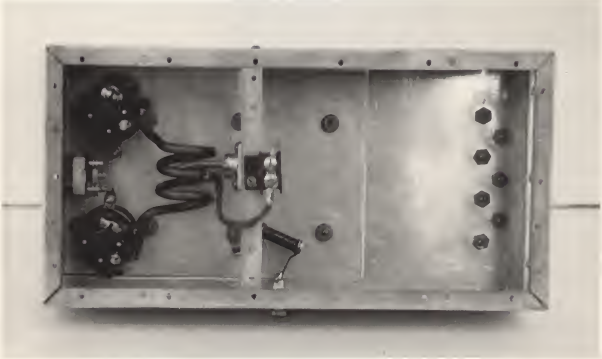

Fig. 2.

OVERALL TRANSMITTER PERFORMANCE

Testing of Transmitter

The next step was to test all of the amplifiers together. A test oscillator using one section of an 832A tetrode, was built for the purpose of supplying the excitation for the second doubler. The test oscillator, second doubler, intermediate, tripler, and final amplifiers were temporarily mounted on a masonite panel for testing. From this experiment the power output of the final was estimated at 1.5 watts. However, the grid current of the final indicated the driving power to be too low. The lack of drive was thought to be due to insufficient coupling. The coupling could have been increased by tuning of the coupling loops but this would have the disadvantage of increasing the number of resonant circuits coupled together as well as complicating mechanical construction. For these reasons the coupling loops were replaced by variable taps on the tanks.

Coupling between the Tripler and Final

Since the output of the tripler and the input of the final are balanced circuits, shielded twin lead would be ideal. However, two coaxial cables will serve the purpose as well. The outer conductors were grounded to the shield boxes at each end and the inner conductors were tapped to opposite sides of the tripler plate and the final cathode tanks. This method of coup-

EXPLANATION OF PLATE IV

Fig. 1. Top view of the intermediate amplifier showing the plate tank.

Fig. 2. Bottom view of the intermediate amplifier showing the grid tank and coupling loop.

Fig. 1.

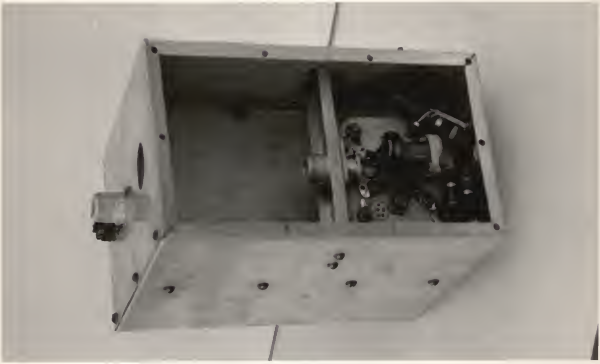

Fig. 2.

ling improved the performance but still more improvement was made by removing the cathode tank of the final and connecting the transmission line directly to the cathodes. The length of the transmission line must be an integral multiple of half wavelengths. In this model one wavelength was used.

After the change in coupling, the measured power output was 4 watts, which is far less than expected from calculations. However, even though the cathode driving power was greater than before, it was still insufficient.

In order to increase the cathode driving power of the final without disrupting the cathode tuning, a type ATP-5 surplus radar jammer was used to excite the tripler at 885 megacycles instead of 295 megacycles. This gave the required excitation for the final and the power output measured was 8-1/3 watts. The power output expected from calculations was approximately twice this value.

Analysis of Final Amplifier Performance

An attempt was made to determine the nature of the losses of the final amplifier from the tube characteristics and the measured d-c voltage, direct currents, and the r-f power output. The grid current was 42.6 milliamperes, the grid-bias voltage was 15.8 volts, the plate current was 79 milliamperes, the plate-supply voltage was 320 volts, and the power output was 8-1/3 watts.

Values for the minimum plate voltage and the maximum grid voltage which will give the above d-c relations are 100 and 16 volts, respectively. By extrapolation of the General Electric plate characteristics, the maximum plate current is 154 milliamperes and the maximum grid current is 120 milliamperes. For a bias voltage of 15.8 volts, the plate-current angle is 140 degrees. The d-c component of space current is .223 x 274, or 61 milliamperes, and the fundamental component is .39 x 274, or 107 milliamperes.

For a calculated grid angle of 120 degrees, the d-c grid current is 20.8 milliamperes and the fundamental component of grid current is 33.7 milliamperes. The d-c plate current is 61 - 20.8, or 40.2 milliamperes, and fundamental component of plate current is 107 - 33.7, or 73.3 milliamperes.

The power developed in the plate tank by two tubes in push-pull is 16.1 watts and the required load impedance is 12,000 ohms. Since the measured power output was 8-1/3 watts, the plate tank efficiency is 51.8 per cent.

The unloaded impedance of the tank is given by the relation $\frac{R_L}{1 - n}$, where R_L is the loaded impedance of the tank, and n is the tank efficiency. From the above relation the unloaded impedance is 24,900 ohms. This result indicated the unloaded tank impedance to be approximately equal to the required loaded tank impedance of 24,000 ohms calculated in the class C design.

These results were verified by unloading the plate tank and increasing the plate-supply voltage to the design value. The measured d-c plate and grid currents were approximately equal to the design values. This indicated the final amplifier was operating as designed with all of the plate power dissipated in the plate tank. Therefore the unloaded plate-tank impedance must be approximately 24,000 ohms.

CONCLUSIONS

The choice of tubes for use in the 1000-megacycle region is highly important. The author recommends the use of tetrode, beam-power, or pentode tubes when possible despite their extra cost. The reason for this is the greater power gain obtainable with grounded cathode circuits. The advantage of tubes which are capable of large power gains is that fewer stages are required, and therefore the overall efficiency is greater since fewer tank circuits are required. However, in any case, the tank-circuit design and coupling between stages are of extreme importance. The experimental results obtained with flat-element transmission lines indicated that the losses were too great to give good class C operation, although in comparison to parallel wire lines, the electrical length of the flat-element lines was much longer because of the lower characteristic impedance. For frequencies of the order of 300 megacycles and lower, the flat-element lines will give satisfactory results. Since flat-element lines were too inefficient at 885 megacycles, the next alternative is cavity resonators.

Although considerable emphasis has been placed on the tank circuits, the coupling between stages is equally important. If coupling loops are used, they must be tuned to provide the necessary coupling. A variable tap on the tank or a variable capacitance coupling offers a more simple and efficient method of coupling. Also the tank circuits should be placed adjacent to each other to eliminate the transmission lines between stages and thus reduce the number of resonant circuits coupled together.

The 2C43 triodes, in a grounded-grid circuit, showed no tendencies to oscillate and required no neutralization. However, the loading of the cathode tank, due to the 500-ohm,grid-bias resistor, lowered the effective grid-to-cathode impedance. Other circuits, with less loading, may require neutralization.

A frequency multiplication of 12 times was required for this transmitter. This calls for two doublers and one tripler. The relative load impedance required for a tripler is approximately 5/3 times the load impedance required for the same tube used as a doubler.[1] Because the difficulty of providing high tank impedance increases as the frequency increases, the tripler should precede the two doublers.

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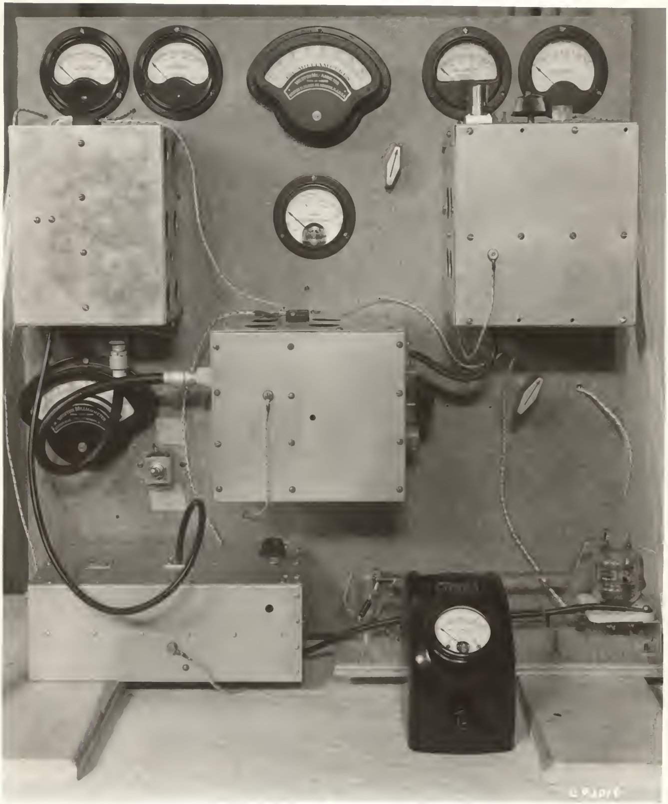
[1] Fredrick E. Terman, Radio Engineering, 3rd ed. (New York: McGraw-Hill), 1947, p. 396.

PLATE V

Front view of the complete transmitter assembly temporarily mounted on a masonite panel to facilitate testing.



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THE DESIGN OF AN 885-MC TELEVISION TRANSMITTER

by

MARVIN CLYDE BURK

An Abstract of Thesis

The Design of an 885-mc Television Transmitter

by

Marvin Clyde Burk

The purpose of this paper was to continue the work of Kenneth E. Fultz in the development of a suitable design for a low-power ultra-high-frequency television transmitter.

The transmitter constructed by Fultz consisted of a crystal-controlled oscillator operating at a frequency of 73.75 megacycles, followed by two doubler amplifiers and one tripler amplifier to increase the frequency to 885 megacycles. The output of the tripler was then amplified and modulated by a plate-modulated final amplifier. The results obtained with this model have shown the need for more efficient tank circuits.

The procedure followed was to reconstruct the final amplifier utilizing shorted sections of flat-element transmission lines in place of the parallel wire lines. The tubes used were the type 2C43 lighthouse triodes in a push-pull circuit. Although sufficient driving power was not available for driving the final amplifier, the results were promising since quarter-wave resonance was possible. With the parallel wire tank of the first model, it was necessary to use three-quarter-wave resonance.

After completion of the final amplifier, the tripler, second doubler, and an intermediate amplifier were con-

structed. The intermediate amplifier was required because the power output of the second doubler was insufficient to drive the tripler amplifier.

The measured power output of the final amplifier was considerably less than the calculated power. Data were taken for the purpose of determining the nature of the losses and it was concluded that the losses of the flat-element tank circuits were too great for good class C operation.