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SFD Report No. 32-IDR-2
January 1964

DEVELOPMENT OF A Ku-BAND CROSSED-FIELD AMPLIFIER

by
John McBride
Fred Feulner

Second Interim Development Report
for period
30 September 1963 to 31 December 1963

Contract NObsr-89517
Index No. SR-0080301 ST9391

NAVY DEPARTMENT
BUREAU OF SHIPS, ELECTRONICS DIVISION

S•F•D laboratories, inc.
Union, New Jersey

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Approved by R. La Plante

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ABSTRACT

This is the second interim engineering report on a Ku-band crossed-field amplifier development program. Two tubes were constructed and tested during this period. A detailed account of the results obtained from these two tubes is presented in this report. The development of mechanical techniques as they apply to the fabrication of the Ku-band amplifier and design changes which were indicated by the data of these two tubes are also included.

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1.0 PURPOSE

The purpose of this contract is to develop a Ku-band crossed-field amplifier in accordance with Contract NObsr-89517.

The contract requires that S-F-D laboratories, inc., furnish one Ku-band crossed-field amplifier with the following parameters.

1.	Frequency (center)	16 Gc
2.	Bandwidth (instantaneous)	1600 Mc (at 3 db points)
3.	Power input	1 kw (min)
4.	Power output (peak)	100-150 kw
5.	Power output (average)	150 watts
6.	Pulse length	3 μsec (max)
7.	Efficiency	30-40%
8.	Gain	20 db (nominal)

2.0 INTRODUCTION

At the conclusion of the first quarter, fabrication of the first Ku-band amplifier was near completion. A brief review of the program up to that point is presented here and is followed by a summary of the work of this quarter.

The electrical and mechanical design of the first tube was completed. Much of this design was based on scaling a proven X-band slow wave circuit. Cold test equipment was received early in this quarter and was set up for linear circuit measurements and matching transformer studies. Dispersion curves, which describe the electrical behavior of the amplifier slow wave circuit, are obtained from linear circuit measurements. Experience has shown that these data accurately correspond to that of the cylindrical circuit of the completed tube. Cold test results at this time indicated that the circuit incorporating the design dimensions possessed the desired operating characteristics and therefore this circuit was used for the first two tubes.

Several matching transformer designs were evaluated. A ramp type transformer which exhibited a return loss of 23 db to 25 db over the required frequency band was selected for the tubes of this program. These return losses correspond to a VSWR of 1.15 to 1.12 respectively. The matching transformer studies were made with various waveguide-transformer assemblies and a brass cold test model of the amplifier.

Magnetic field studies were conducted with the amplifier pole pieces on an electromagnet. Gaussmeter readings indicated that the necessary values of magnetic field (7500-8500 gauss) occurred below the saturated portion of the B-H curve.

Certain tube parts were ordered early in this quarter. The remaining parts, the dimensions of which depended upon cold test measurements, were ordered as soon as these values were known.

The hot test set was assembled and working properly. A photograph and details of this equipment were included in the First Interim Development Report.

Construction of the first tube, K33E, was delayed due to machining and brazing difficulties. However, the experience gained on the first tube led to a much improved second tube. The first Ku-band amplifier, K33E, was completed and tested early in the second quarter. K33E performed very well delivering a peak power output of 100 kw at 16.8 Gc using a drive signal of 5 kw which is a gain of 13 db.

The second tube, L18E, operated over a 900 Mc band with a gain in excess of 20 db. Here of course, the drive signal level was the required 1 kw.

Cold testing of linear circuits was resumed in the second quarter when it became apparent from the hot test results of L18E that a circuit modification would have to be made in order for the amplifier to conform to frequency requirements. The extent of the modification was determined and is being incorporated into future tubes of this program.

Efforts have been directed toward the construction of a refractory metal vane tip anode in that the amplifier power levels involved may cause overheating of the anode vane tips, especially with a 3 μsec pulse and result in arcing. Techniques to accomplish this are nearly perfected and planned for use in future tubes.

3.0 MECHANICAL TECHNIQUES

Tolerances of the order of plus or minus 0.0005 inch and less must be adhered to in the machining and assembly processes. Techniques which work so well at X-band were modified to accomodate the Ku-band structure. As work progressed on the fabrication of the first tube, it became evident that these techniques would have to be further refined. There was delay in the completion of the first tube due to these difficulties. This is not unusual. Where new type devices are concerned, time should be allowed to develop those mechanical techniques peculiar to the individual project.

Two tubes were constructed during this period. Most of the mechanical problems were resolved in the construction of the first tube, K33E. The choke supported interdigital line has multiple brazes which tend to cause an increased insertion loss for the circuit. Obviously circuit losses must be minimized. The experience with this type circuit has pointed up the need for small and even fillets at every braze joint and a high temperature, low resistance brazing material must be used - the high temperature because of the successive brazing steps in the assembly process and the low resistance to limit the power dissipation on the circuit. Relatively large, irregular and rough surface fillets not only contribute heavily to these losses but are also points of reflection for the growing wave on the circuit. Brazing techniques which involve critical oven time and temperatures and precise jigging arrangements were developed for this program. Insertion loss of K33E at 16.8 Gc was 4 db. At this frequency the second tube, L18E, had an insertion loss of 2.3 db.

Another problem which became evident after the first machining step of K33E was anode vane distortion. This was corrected with an accurate twin spline type tool which, when fitted through the circuit structure, would properly realign the vanes. Modifications of this tool are used throughout the assembly process to insure continued line up. Anode vane distortion can cause reflections and does cause a variation in phase shift through the circuit.

Methods were developed whereby waveguide-transformer assemblies would be brazed in a manner to insure exact line up of the transformers with the coupling slot of the tube body. Previous work with this type of tube has shown that, if a misalignment of the transformer occurs at the output, reflections are set up which can lead to instability when operating at or near the limit of stable gain.

An inspection of the second tube, L18E, revealed none of the abovementioned defects.

4.0 OPERATING PERFORMANCE

Extensive testing of the first tube of this program, K33E which is shown in the photograph of Figure 1, produced encouraging results. The required peak power output of 100 kw was obtained at 16.8 Gc using a drive signal of 5 kw which is a gain of 13 db. The other parameters during this test were 70 watts average power, pulse length of 1.4 μsec and 26% efficiency. These data are significant in that they demonstrate, with the first test vehicle, an amplifier peak power output of 100 kw at Ku-band. Continuing with this test, the drive signal was reduced to 2 kw and the amplifier peak power output was 77 kw, a gain of 15.86 db. Further reduction of the drive signal to the minimum required power level of 1 kw resulted in a gain of 16.25 db where the peak power was 42.3 kw.

Data were obtained at 100 Mc steps over the band with a 5 kw and a 2.5 kw drive signal. Between 16.0 Gc and 16.8 Gc, the gain varied from 9 db to 13 db. In this frequency range, tube K33E would not lock at a 1 kw drive level.

At frequencies below 16.0 Gc tube performance was very poor. Here the tendency toward oscillation was the strongest. The reduced tube performance in the lower half of the required frequency band was attributed to the mechanical problems as previously mentioned. Also, some thought was given to improving tube performance at the lower frequencies by modifying the slow wave circuit. Available data at this time did not clearly reveal the exact nature of this change; therefore, a change in the circuit design was not considered for the second tube.

The most pressing problems were to construct a tube which mechanically would be an improvement over K33E and to define an interaction space dimension that would permit the amplifier to lock at a 1 kw drive signal over a wide band. Both of these problems were solved as shown by the performance data of tube L18E.

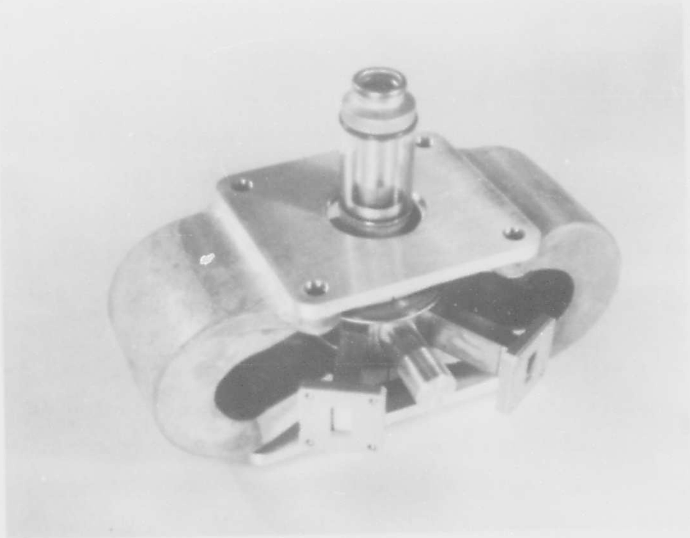

FIGURE 1 THE FIRST Ku-BAND CROSSED-FIELD AMPLIFIER, TUBE K33E

Encouraging results marked the testing of the second tube, L18E. The newly designed interaction space enabled the tube to lock at the required 1 kw drive signal over a 1500 Mc band, that is from 16.0 Gc to 17.5 Gc. The gain exceeds 20 db over a 900 Mc band (16.6 Gc to 17.5 Gc) and between 16.0 Gc and 16.5 Gc, the gain varies from 13 db to 19 db.

A test was performed using constant current operation. Experiment has shown that gain can nearly be constant with frequency over a wide bandwidth provided dc power input is supplied by a line type modulator. Such power supplies tend to function in a manner similar to a constant current generator and apply to the load whatever voltage is required. Here the amplifier average current was constant at 9.5 ma and the drive signal was 1 kw. The gain varied 0.5 db over a 900 Mc band, that is from 20.3 db to 20.8 db and the 900 Mc band extended from 16.6 Gc to 17.5 Gc. Tube voltages during this test ranged from 14.3 kv to 15.0 kv, and tube efficiencies were 30% to 35%. These results are represented in the graph of Figure 2. It is quite obvious from this graph that there is no cyclic variation of gain with frequency. Although the amplifier seems to work too high in frequency and performance cannot be fully measured, it appears to have the requisite bandwidth. Corrective steps are discussed in the next section.

In another test, tube L18E delivered a very impressive peak power output of 195 kw at 16.7 Gc using a drive signal of 5 kw which corresponds to a gain of 15.9 db. Average power at this frequency was 90 watts with an efficiency of 38%.

A photograph of tube L18E is shown in Figure 3. The tube is set on the electromagnet with the input and output connected to the waveguide system of the hot test set. Also shown in the photograph is a VacIon® pump appended to the amplifier which permits the tube to be pumped and pressure monitored while operating.

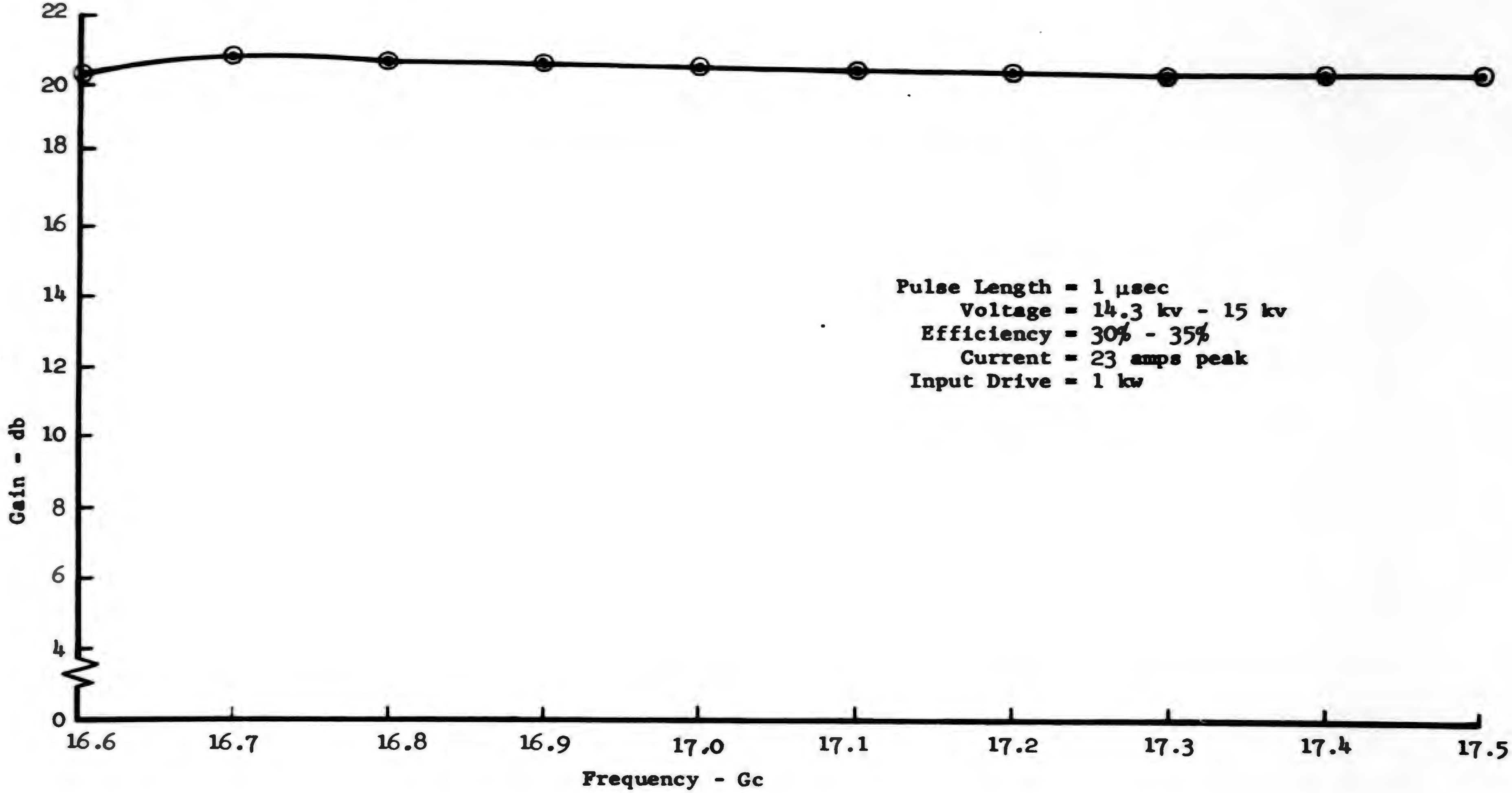

FIGURE 2 GAIN VERSUS FREQUENCY FOR Ku-BAND CROSSED-FIELD AMPLIFIER - TUBE L18E

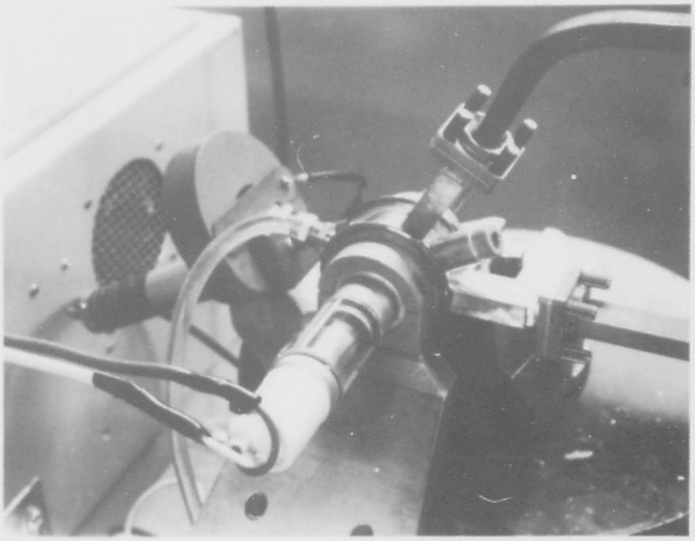

FIGURE 3 TUBE L18E ON THE ELECTROMAGNET AND CONNECTED TO THE WAVEGUIDE SYSTEM OF THE HOT TEST SET

The contract requires that the amplifier be operated at a 3 µsec pulse and a 0.001 duty cycle. Most of the testing of both tubes, K33E and L18E, was performed using a 1 µsec pulse. Subsequent testing of these tubes for a short period of time was made using a 2.7 µsec pulse and a 0.0008 duty cycle to determine that the present cathode-anode-pole piece design was compatible with the required pulse length and duty cycle. Both tubes performed well at this increased pulse length. Future tubes of this program will have refractory vane tip anodes and will be tested at the full pulse width and duty cycle.

Amplifier performance to date is summarized in the following table and compared to the contract requirements.

Parameter	Contract Specification	Tube L18E
Frequency (center)	16 Gc	≈ 17 Gc
Bandwidth (instantaneous, 3 db points)	1600 Mc	900 Mc (0.5 db)
Power input	1 kw min	1 kw
Power output (peak)	100-150 kw	120 kw
Pulse length	3 µsec	1 µsec
Efficiency	30-40%	30-35%
Gain	20 db	> 20 db

Tests are now being conducted at drive signal levels less than 1 kw. Preliminary results show gains of 23 db to 25 db using a drive signal of 500 watts. Detailed results of these tests will be included in the third and final report of this contract.

5.0 DESIGN CONSIDERATIONS

It has been mentioned that the data of the first tube roughly suggested a design change might be necessary in the slow wave circuit. This point was even more clearly revealed in the data of the second tube. The required gain, peak power and efficiency occur at and above the upper limit of the frequency band. The slow wave circuit must be modified in such a manner that the operating characteristics of tube L18E fall within the required band. Cold test studies were made with various linear circuits to determine the extent of this modification. Two dispersion curves, which describe the electrical behavior of the amplifier slow wave circuit are shown in Figure 4. The curve titled "Original slow wave circuit" applies to the circuit of the first two tubes where the phase shift per section varies from 129° per section at 16.8 Gc to 148° per section at 15.2 Gc. The curve titled "Modified slow wave circuit," the circuit of succeeding tubes of this program, reflects a lower phase shift per section over the 1600 Mc band. The reduction in phase shift per section is approximately 6°. This change should have the desired effect wherein the amplifier band of operation is shifted down in frequency to conform to the contract.

Fabrication of the third tube was delayed in order that this modification could be incorporated in the slow wave circuit. Further, a decision was made to construct a fourth tube which, when completely assembled, would be similar to the third tube but the mechanical techniques employed in its construction would be different. Both tubes, as stated, would have refractory vane tip anodes.

Another modification that would be made in the third and future tubes involves shortening the cathode support assembly and increasing its cross-sectional area. Evidence thus far indicates that at the required power levels, electron back bombardment would

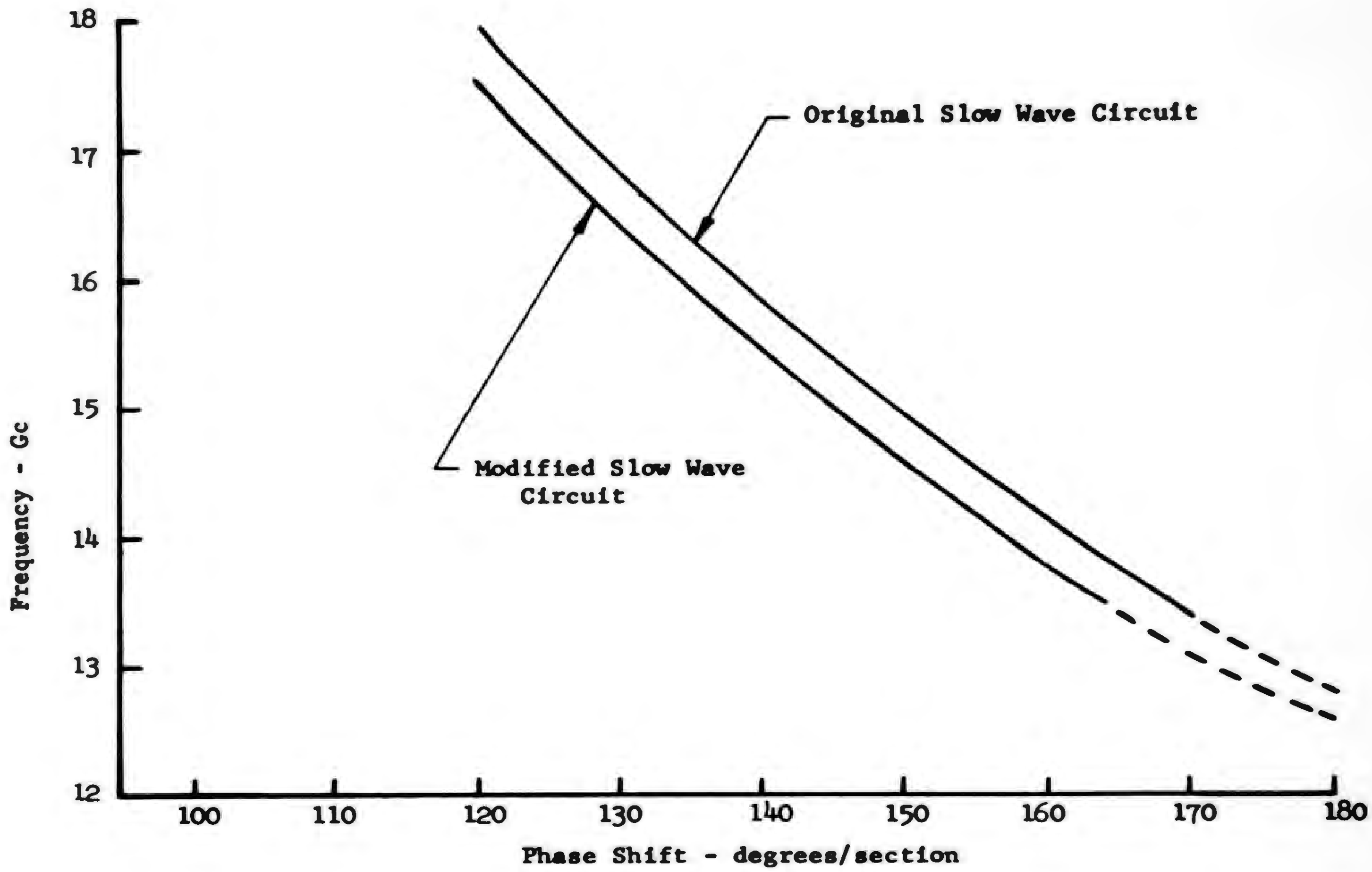

FIGURE 4, DISPERSION CURVES OF THE CROSSED-FIELD AMPLIFIER SLOW WAVE CIRCUIT cause the cathode to operate at a temperature that would exceed its normal operating range. The new support assembly will provide for a reduced cathode temperature and thereby contribute toward a "long life" tube.

The ceramic window assemblies manufactured at S-F-D laboratories and made to the specification set for the Ku-band amplifier, have presented no electrical or mechanical problems. These windows have a very low VSWR (≈ 1.02 to 1.08) over the frequency band, are mechanically strong and are easily wedded to the waveguide transformer assemblies.

The anode structure is such that it readily lends itself to water cooling and a flow rate of approximately 0.3 gpm appears to be adequate for a 100 watt average power output.

Finally, but certainly not of least importance, is the fact that oscillation is present at low voltage levels. Oscillation problems in the X-band amplifier have been solved and in a similar manner, the oscillations in the Ku-band tube can be suppressed.

6.0 CONCLUSIONS

The data presented in this report show the validity of scaling a proven X-band slow wave circuit, consisting of a choke supported interdigital line, to accomodate other frequency bands.

Crossed-field amplifier gains in excess of 20 db, peak power output of nearly 200 kw, efficiencies ranging from 30% to 40% and broad band operation have been attained at Ku-band frequencies. In fact, all of the contract specifications have been accomplished except for the required center frequency and average power. Modifications in design and the application of new techniques in future tubes should correct these two deficiencies.

7.0 PROGRAM FOR THE NEXT PERIOD

Construction of the third and fourth tubes is now near completion. A thorough testing of these tubes will reveal what further modification will be necessary for the fifth tube which will be the final tube of this program. Preliminary work has already begun on the fabrication of the fifth tube. Special emphasis will be placed on all further design changes and testing procedures which will permit the amplifier to operate at the full average power and in the required frequency band.

8.0 MAN HOURS EXPENDED TO DATE

Listed below are the man hours expended during this quarter and the man hours expended to date on the program by the principal engineering personnel and personnel in other classifications:

	Hours This Period	Hours To Date
F. H. Corregan	326	726
J. Drexler	2	18
F. A. Feulner	91.5	150.5
R. La Plante	4	4
J. McBride	305.5	545.5
Misc. Shop & Technical	1416.5	2274.0
Total	2145.5	3718.0

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