Numerical calculations of (14) have been carried out on a Univac computer. In order to simplify the programming, the derivatives of cylinder functions and cylinder functions of negative order have been replaced by cylinder functions of positive order [see (31)].

The amplitude and phase of the electric field have been plotted in Figs. 4 and 5. For certain values of the parameters, a, k/μ, β_2 this exact solution yields also a spiral wave. It is interesting to note that except for high values of k/μ either the amplitude or the phase of the electric field is an odd function of the scattering angle ϕ, so that the scattered field is always asymmetrical.

Discussion and Conclusions

The foregoing discussion shows that the scattered field from a ferrite cylinder is in most cases asymmetrical about the direction of incidence. The direction of maximum field strength depends on the dc magnetization of the ferrite. By a suitable arrangement of several cylinders, as shown in Fig. 6, the scattered field can be concentrated in one direction. Here the phases of the scattered waves are in phase with the incident wave in the desired direction and 180° out of phase in the opposite direction. With a cyclic application of the magnetic dc field the field pattern is rotated. In order to distort the field as little as possible under this rotation a large number of scatterers should be used.

Because of the abrupt phase change for certain values of the deflection angle, it seems possible to obtain a narrow beam of a few degrees. The large variations of the amplitude, however, will result in strong sidelobes.

For the design of such an antenna the scattering pattern of the ferrite cylinder has to be measured. Then the time function of the magnetic dc field, which gives the desired antenna pattern, has to be determined.

The advantage of such an electronic scanning antenna is the lack of mechanical parts and the weightless rotation which allows much higher scanning speeds than with a mechanical system.

Acknowledgment

The author wishes to express his sincere appreciation to Prof. B. Davison for suggesting the problem and to A. E. Misek, of the Computing Center of Case Institute of Technology, for obtaining the numerical results of (14). He would, also like to thank Dr. J. R. Wait, National Bureau of Standards, for the information that this problem has also been treated by V. V. Nikol'skii in *Radiotekhnika i Elektronikha*, vol. 3, pp. 756–759, 1958 (in Russian).

Phase Adjustment Effects on Cascaded Reflex Klystron Amplifiers*

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Summary—**Reflex klystrons (type 2K25) were used as regenerative amplifiers for the X-band. Two 2K25 reflex klystron amplifiers were cascaded with a coupling circuit which contained a variable phase shifter. The effect of the phase adjustment was investigated in comparison with another coupling scheme which did not contain the phase shifter. The phase adjustment in the coupling circuit gave the amplifier system high gain (more than 50 db max.), and a reasonably low noise figure (8 db–17.5 db). High sensitivity was obtained. Proper phase adjustment of the two stage reflex klystron amplifier could give more than twice the gain in db of the single stage amplifier because of the regenerative feedback between stages. The linearity and dynamic range were considerably improved by the phase adjustment. But the frequency bandwidth became narrow (2 mc), and improvement in stability and directivity was not significant.**

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Introduction

It has been shown that ordinary reflex klystrons are usable as microwave regenerative amplifiers.[1–6] In order to obtain high gain, it is natural to think about cascading the reflex klystron amplifiers. This is, however, a rather complicated problem, because a part of the amplified power reflects back and forth between

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stages. Phase adjustments of the power fed back between stages have strong influence upon the amplifier performance. In this paper, the phase adjustment effects are described for various kinds of coupling networks of the cascaded 2K25 reflex klystron amplifiers operated in the 9000 mc band.

The reflex klystron amplifier is essentially a one port amplifier. Some types of parametric amplifiers and maser amplifiers are also one port amplifiers. Therefore, the data obtained by investigation of cascading method of the reflex klystron amplifier may suggest an interesting reference to cascading maser or parametric amplifiers.

Phase Adjustment Effects on Amplifier Performance

A schematic diagram of the cascaded 2K25 reflex klystron amplifier is shown in Fig. 1. Two reflex klystron amplifiers are coupled by a coupling network which has a variable phase shifter.

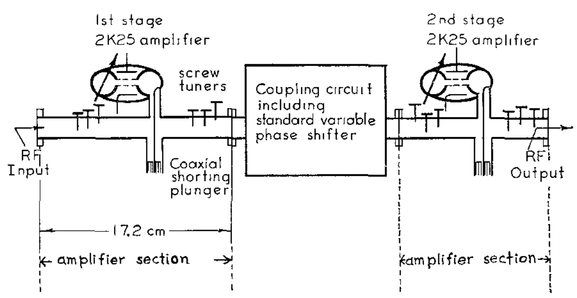

Fig. 1—Cascaded 2K25 reflex klystron amplifier.

In order to have positive feedback, the power fed back must be approximately in phase with the input power or with the electron beam power delivered to the circuit. The phase of the positive feedback can be controlled by the phase shifter.

When the electron beam power is too large, the tube will start oscillating instead of amplifying. The electron beam power can be reduced by the phase shifter, since it controls the phase of the feedback, and hence oscillation can be stopped.

When the tubes are in the amplifying condition, the phase shifter can be used to control the phase of the feedback to obtain optimum gain. Therefore, gain of the amplifier is adjustable by means of the variable phase shifter.

Phase adjustment of the feedback circuit of the cascaded reflex klystron amplifier also affects noise, stability, linearity, and bandwidth as in the case of an ordinary feedback amplifier. If the phase is adjusted so that the amplifier is approaching a near-oscillation condition, generally, the amplifier has high gain, but is noisy, unstable, and has a narrow bandwidth.

Saturation of the cascaded reflex klystron amplifier is mainly caused by both nonlinearity of the electronic impedances of the amplifier tubes, and extenal circuit impedance. But these electronic and circuit impedances can be controlled by the phase adjustment of the feedback circuit. Then, the linearity, or dynamic range of the cascaded reflex klystron amplifier is adjustable using a variable phase shifter in the coupling circuit.

Thus, phase adjustment in the coupling network affects the gain, bandwidth, noise figure, stability, sensitivity, and linearity of the cascaded reflex klystron amplifier.

Phase Adjustment Effects on Gain

When operated at high gain, the gain of a regenerative amplifier of this type is extremely sensitive to very small changes in the impedance presented to its input and output terminals. To obtain reasonable stability and accurate measurement of gain, it was necessary to isolate the input and output of the amplifier system with ferrite isolators. The amplifier system was preceded by a series assembly of a ferrite isolator and several attenuator pads. System stability was achieved by this along with another isolator, and an attenuator pad assembly which was placed before a superheterodyne receiver, which measures gain. This isolator had two effects. The first was the isolation of the amplifier system from load impedance variation, and the second was the prevention of local oscillator disturbance to the amplifier system. The output of the amplifier system was indicated by the output meter of the superheterodyne receiver.

To determine its gain, the amplifier system was replaced by a waveguide section through the use of waveguide switches. The attenuator of the test oscillator was then adjusted to obtain the same output meter reading that was achieved with the amplifier system. The difference between the attenuator readings in the two cases was considered to be the system gain.

Phase characteristics of gains of various kinds of cascaded 2K25 reflex klystron amplifiers are shown in Fig. 2. Curve I shows a phase characteristic of a phase shifter coupled amplifier tested at 9362 mc. Two reflex klystron amplifiers are coupled by a variable phase shifter. As was considered in the previous section, gain was sharply dependent on phase, and regions of oscillation and amplification appear alternately with an increase in phase shift. The oscillation regions are indicated by the shaded areas in Fig. 2. In the case of curve I, the oscillation was critical and it was a near-oscillation condition in the shaded regions. The phase margin, which is the phase shift necessary to keep the gain within 3 db of the optimum gain, was 4° for this amplifier.

Curve II in Fig. 2 shows a phase characteristic of an isolator-phase shifter coupled amplifier tested at 9365 mc. Two 2K25 reflex klystron amplifiers were coupled with an isolator and a phase shifter. In this case, a practical isolator is being considered, that is, the isolation is not perfect. If the isolation were perfect, the phase

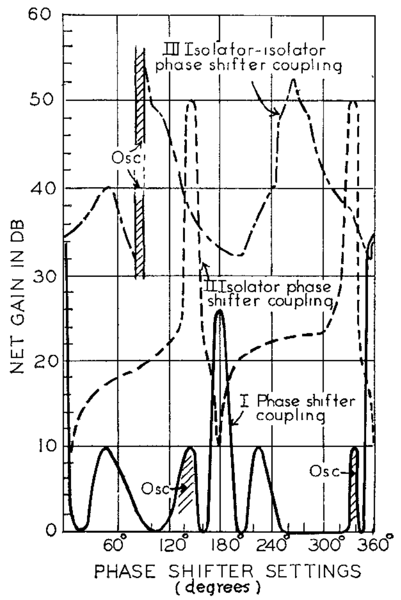

Fig. 2—Phase characteristics of the cascaded reflex klystron amplifiers.

shifter would have no effect on over-all behavior of the amplifier, because no feedback would exist. On the other hand, a practical isolator allows significant feedback to occur because of imperfect isolation. The isolator used in this experiment had 0.5 db forward loss and 30 db backward attenuation at the operating frequency. As a matter of fact, curve II shows that the gain of the amplifier depends upon the phase shifter settings. The phase shifter controls the phase of the power fed back between stages even though there is an isolator. The phase margin was 3°, and was very small, but, because of the isolator, the amplification region extends over a considerable range of the phase shifter setting.

Curve III in Fig. 2 shows a phase characteristic of an isolator-isolator-phase shifter coupled amplifier tested at 9359 mc. This amplifier was formed by coupling two reflex klystron amplifiers with two isolators followed by a variable phase shifter. In this case, the isolation was increased but phase adjustment still had strong influence upon gain. According to curve III, the phase margin was 20°, and the region over which amplification took place was larger than either of the two amplifiers mentioned before. Phase-sensitivity was decreased by increasing the isolation, and the isolation made the realization of higher gain through phase adjustment easier.

Effects of Phase Shifter on Frequency Characteristics

The use of a phase shifter in a coupling network of a cascaded reflex klystron amplifier usually makes the system frequency sensitive, because the phase shifter itself is one of the most frequency sensitive parts of the system. The frequency sensitivity is caused by the inevitable physical length of the phase shifter. In other words, the phase shifter makes the system narrow band. For example, when two reflex klystron amplifiers were coupled directly without using the phase shifter, the bandwidth was 6 mc for 30-db gain. On the other hand, bandwidth of the phase shifter coupled amplifier was 2 mc for 43-db gain.

An example of the frequency characteristic of a phase shifter-isolator coupled amplifier is shown in Fig. 3. For comparison, the frequency characteristics of the individual stages are also plotted. The total gain was not equal to the sum of the gains in db of the individual stages because of the feedback. The effect of the negative feedback can be observed at the edges of the selectivity curve where the total gain is less than that of the individual stages. The over-all bandwidth was 2 mc. A somewhat higher gain than that shown in Fig. 3 can be obtained, if the circuit constants are very carefully adjusted.

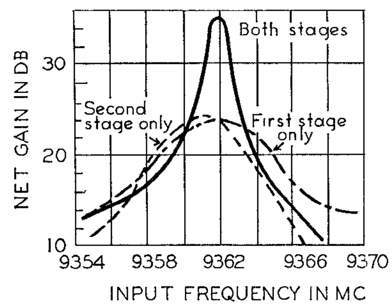

Fig. 3—Frequency characteristics of phase shifter-isolator coupled amplifier.

Phase Adjustment Effects on Noise Figures

Phase adjustment of the feedback circuit of a regenerative amplifier can control the noise of the system. In the case of the cascaded reflex klystron amplifier, similar effects were observed. Noise figures of various kinds of cascaded reflex klystron amplifiers are listed in Table I. The experiment showed that any reflex klystron amplifier system which employed the phase shifter in the coupling network generally had a considerably lower noise figure than the other kinds of amplifiers which did not have the phase shifter in the coupling network. As was considered in the early part of this paper, this result can be explained as follows. Improper phase of feedback may make the amplifier system noisy due to proximity to the near-oscillation condition. This improper phase is corrected by the variable phase shifter.

TABLE I
Noise Figures of Cascaded Reflex Klystron Amplifiers

Types of Amplifiers	Noise figures (db)
Direct coupled	28
Isolator coupled	26
Phase shifter coupled	16
Isolator-*phase shifter* coupled	8
Phase shifter-isolator coupled	17.5

Phase Adjustment Effects on Stability

The stability, that is the gain fluctuations with time, of various kinds of cascaded reflex klystron amplifiers were examined using an automatic output recorder for several hours for each kind of amplifier system. In order to keep the ambient temperature constant, the klystron tubes were mounted within 7×8.5×11.5 cm brass boxes of 2 mm wall thickness. Because of the heat capacity of this scheme, after a one hour warming up period, the environmental temperature of the tube itself remained quite constant. For example, placing a hand on the box or blowing on the box did not affect the gain. In order to avoid instability caused by the power supply, an electronically regulated power supply was used for the anodes of the reflex klystrons, and a battery was used to give stable repeller voltage for each individual tube. The experimental results are listed in Table II. According to this table, when the phase shifter alone

TABLE II

Stability of Cascaded Reflex Klystron Amplifiers

Types of Amplifiers	Number of isolators	Stability, average gain fluctuation db/10 minutes
Direct coupled	0	0.08
Phase shifter coupled	0	0.1
Isolator coupled	1	0.066
Isolator-*phase shifter* coupled	1	0.023
Phase shifter-isolator coupled	1	0.05
Isolator-isolator coupled	2	0.025
Isolator-isolator-*phase shifter*	2	0.00
Phase shifter-isolator-isolator	2	0.02
Isolator-*phase shifter*-isolator	2	0.044

was used in the coupling network, the stability improvement was not significant. On the other hand, when the phase shifter was used together with one or more isolators, the stability was somewhat improved in comparison with a case in which an isolator alone was used.

Phase Adjustment Effects on Linearity

Linearity of the cascaded 2K25 reflex klystron amplifier was improved with the employment of the phase adjustment in the coupling circuit.

Input power versus output power characteristics of two kinds of cascaded reflex klystron amplifiers, namely, the direct coupled amplifier and the phase shifter coupled amplifier, are shown in Fig. 4. In the case of the direct coupled amplifier, since the two reflex klystron amplifiers were connected directly, no phase adjustment was made between the two amplifier sections. The amplifier sections are shown in Fig. 1. In the case of the phase shifter coupled amplifier, the two amplifier sections were coupled with a variable phase shifter, and this was adjusted to give an optimum gain to the amplifier system. The phase shifter coupled amplifier apparently has wider dynamic range and lower noise output level than the direct coupled amplifier.

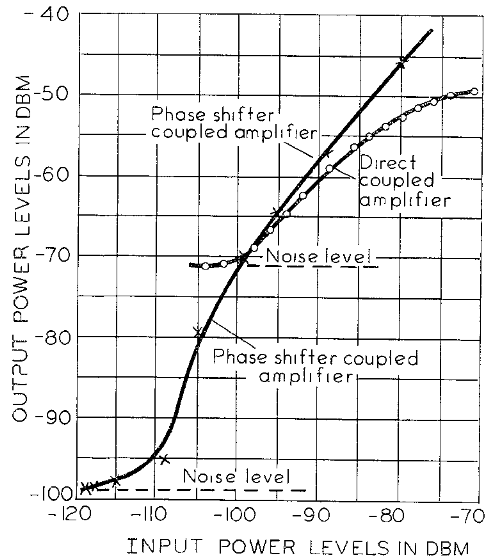

Fig. 4—Linearity of cascaded reflex klystron amplifiers.

Phase Adjustment Effects on Sensitivity

It has been experimentally shown that employment of the phase adjustment in the coupling circuit of the cascaded 2K25 reflex klystron amplifier decreases noise and increases gain. Then, the sensitivity must be increased. In this case, the sensitivity was defined as the minimum detectable input power level in dbm of this amplifier-receiver system. Experimental results showed that the sensitivity improvement of the phase shifter coupled amplifier over the sensitivity of the direct coupled amplifier was 15 db. This can be seen from Fig. 4 if the minimum detectable input signal levels of these two curves are compared.

In a similar way, the phase shifter coupled amplifier showed a sensitivity 15 db higher than that of the isolator coupled amplifier, and 7 db higher than that of the isolator-isolator coupled amplifier. When the phase shifter was used together with one isolator in the coupling circuit, the sensitivity improvement over that of the isolator coupled amplifier was 22 db. When the phase shifter was used together with two isolators the sensitivity improvement over the sensitivity of the isolator-isolator coupled amplifier ranged from 14 to 20 db depending upon the position of the phase shifter in the coupling circuit. These results were obtained experimentally. It would be interesting to know if they can be justified theoretically. This problem may, however, not be easy because the two amplifiers are regenerative and another feedback loop is formed between stages. The phase adjustment effect on gain and noise figure must be calculated before obtaining the sensitivity theoretically.

Phase Adjustment Effects on Directivity

Because of the very nature of the circuit construction of this kind of amplifier, the amplified power is radiated generally in both directions—one part into the load of the amplifier system, and the other part back in the direction of the signal source.

One might expect that the directivity, which is the ratio of the forward power to the backward power from the amplifier system, would be strongly influenced by the phase adjustment of the coupling circuit. But the experimental results showed that the phase adjustment effect was not significant. For example, the directivity of the direct coupled amplifier was 10 db, and on the other hand, the directivity of the phase shifter coupled amplifier was 11 db. The phase shifter setting for optimizing gain was different from the phase shifter setting for optimizing the directivity.

Conclusions

Adjusting the phase of the feedback between the amplifier stages of the cascaded 2K25 reflex klystron amplifier is necessary if more than twice the gain in db of a single stage amplifier is to be obtained. The phase adjustment gives high gain and reasonably low noise figure, and, consequently, high sensitivity is obtained. The use of the phase shifter made the system somewhat narrow band but stable. The linearity and dynamic range of the cascaded amplifier were improved considerably using the phase adjustment, but the effect of the phase adjustment on the directivity was not significant.

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TE Modes of the Dielectric Loaded Trough Line*

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Summary—**The properties of TE modes on a dielectric loaded trough waveguide have been investigated. In the case of the dominant mode of this line (TE_{20}), families of design curves giving the field distribution, guide wavelength, power handling capability, wall losses, and dielectric losses as a function of operating wavelength, waveguide dimensions and dielectric constant are presented. For a loosely bound wave, the losses are comparable to those of conventional rectangular waveguide and the power handling capability is an order of magnitude greater. The apparatus and procedure used to measure guide wavelength, rate of field decay in the transverse direction, and attenuation are described. The measured performance is in close agreement with the theoretically predicted characteristics.**

Introduction

The transmission line to be investigated consists of a rectangular trough structure with a dielectric slab lying on the bottom. A cross section of this line and the coordinate system used in the analysis are shown in Fig. 1. The TE surface wave modes which can propagate in the dielectric loaded trough line have been previously determined in an analysis of the dielectric loaded parallel plane waveguide.[1] A transverse resonance approach has been used by Hatkin[2] to determine some of the characteristics of these TE modes on an infinite dielectric sheet. The dielectric loaded parallel plane waveguide consists of two dielectric loaded trough waveguides lying back to back along the $x=0$ plane with the common conducting plate removed. The above mentioned analysis has shown that the dielectric loaded parallel plane waveguide can support a class of TE modes, whose field structure is similar to the TE modes of rectangular waveguide. These TE modes display either even or odd symmetry about the geometrical plane of symmetry ($x=0$). The even symmetry modes correspond to m being an odd integer and vice versa. It was further shown that if a conducting wall is placed at the $x=0$ plane, all of the even TE modes will be suppressed, but the odd modes will be unaffected. The dominant mode of the resulting trough line (half of the original line) will be the TE_{20} mode.

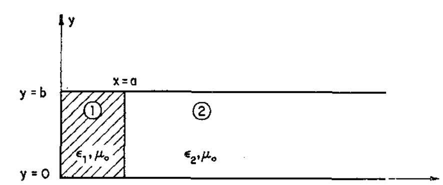

Fig. 1—Cross section of the dielectric loaded trough line. The positive z direction is out of the paper.

The purpose of this extension to the previous work is to present a series of design curves applicable to the trough line. It is recommended that the reader refer to the earlier work for a derivation of the properties of the odd symmetry TE modes.

A dielectric loaded trough line has been built and measurements have been made of the guide wavelength, rate of field decay in the transverse direction and at-

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† Radiation Lab., The Johns Hopkins University, Baltimore, Md.

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