# CONSIDERATIONS IN KLYSTRON DESIGN FOR MICROWAVE RELAY SYSTEMS

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## INTRODUCTION

When a new relay system is being considered, there are many decisions to be made about the type of system and the tube to generate the power. A system which employs a klystron power mixer has many advantages. One of them being that all video amplifiers are eliminated except one at each of the terminals. Furthermore, there are no modulation processes that cause amplitude non-linearity in any of the repeaters. Also, experience has demonstrated that klystrons for this service can be very long lived giving tens of thousands of hours life.

Since the power mixer frequently does not already exist, the Relay Systems Engineer has to deal with hypothetical tubes which he may later want to have developed and produced. Early decisions concerning the tube are very important and false ideas at this point can cause considerable delay and expense. The object of this paper is to help the Relay Systems Engineer anticipate the klystron for his system by giving him some rules of thumb, some data on a proven tube of standard design and sufficient understanding of klystron characteristics to indicate what will happen when deviations are made from the standard design. Limits will not be emphasized since many variations are possible by suitable compromises, and new inovations tend to extend the limits even further. It is rather intended to present a specific design from which variations may be considered. Obviously, this paper will not replace the Tube Engineer.

The tube which has been chosen for illustration is the Sperry SAC-19, a two cavity klystron which has performed well in a 6000 Mc. system developed by the Philco Corporation. An external view of the SAC-19 type klystron is shown in Figure 1. The tube is supported by 1-1/2 x 3/4 inch waveguide flanges giving a straight through appearance. Four of the eight screws and nuts for semi-fixed tuning are shown on the side. A finned collector is provided to give effective cooling with 25 cubic feet per minute of air.

This tube and system have already been described in the literature, so their characteristics will be reviewed only briefly.[1,2]

## THE POWER MIXER TYPE SYSTEM

A simplified block diagram of a repeater in this type of system is shown in Figure 2. Frequency modulated signals are received from the previous repeater and mixed in a crystal mixer with power from a stabilized local oscillator. The oscillator is a SAC-19 which is stabilized in the feedback loop by a high Q invar cavity. The 75 Mc. difference frequency is amplified and mixed again with the output from a second local oscillator to give a second intermediate frequency of 115 Mc. This signal containing the 20 Mc. band of intelligence is amplified up to the power level where it can modulate the beam voltage of the SAC-19 mixer. Most of the r.f. power from the first local oscillator is used to drive the first cavity of the mixer klystron. The signals are mixed and amplified to a 1-1/4 watt-level for beaming to the next transmitter on a frequency which is shifted 40 Mc. from the incoming signal.

A more complete block diagram of the actual system is shown in Figure 3* which includes an antenna switch for reversing the direction of transmission and reception, filters for increasing the discrimination between the output and input signals and to remove more of the unwanted sidebands, and terminating equipment for receiving or initiating video intelligence if desired.

The oscillator and mixer are shown with their associated circuit components in Figure 4*. The high Q invar stabilizing cavity in the oscillator feedback circuit receives a portion of the oscillator power from an antenna coupled phaser. Also shown is the probe monitor connection. The small knob on the side adjusts the attenuator to give optimum drive.

Mixing is accomplished with a klystron by modulating the beam voltage at an intermediate frequency of up to 125 Mc. and at the same time driving the input cavity from a constant frequency microwave source. There is an r.f. phase delay of several cycles within a klystron which is determined by the length of time it takes electrons in the beam to travel from the first gap to the second gap. Modulation of the beam velocity at intermediate frequencies varies the r.f. phase delay within the tube and thus produces

*These illustrations made available through the courtesy of W.H. Forster and the Philco Corp.

## GAIN

When a tube is used as an oscillator as in the system of Figure 2, it is important that it also have sufficient gain. Any variation in the output circuit that affects the power output as previously discussed, affects the gain in the same proportion. However, variations can be made in the input circuit which will affect the gain without affecting the power output or the bandwidth of the tube as a mixer. In general, the gain is higher for high voltage tubes and tubes designed for lower frequency.

## MODULATION REQUIREMENTS

### Modulating Voltage

An important consideration is the amount of peak sinusoidal modulating voltage, $\Delta V_o$, required to give the maximum output at the sideband frequency. This is given by the following approximate equation:

$$\frac{\Delta V_o}{V_o} = 2\frac{\Delta\phi}{\phi} = 2 \times \frac{1.84}{2\pi \times 3.5} = \frac{1}{6} \qquad (1)$$

The mixer output in the first sideband varies as the $J_1$ bessel function of the peak change in phase delay. $\Delta\phi$ so that the optimum $\Delta\phi$ is 1.84. The optimum drift length for power amplifiers of this type is 3 to 4 cycles. The net result is that $\frac{\Delta V_o}{V_o}$ should be about $\frac{1}{6}$ for the optimum peak modulation voltage.

### Modulating Frequency

The modulating frequency is chosen as high as possible to take advantage of the improved carrier rejection by the output cavity. The upper limit for the modulating frequency is determined in part by the capacitance of the gun which is about $7\frac{1}{2}$ $\mu\mu$f in the best klystron tubes and in part by the series lead inductance which causes the SAC-19 to be self-resonant at 400 Mc. An external inductance is usually used in shunt to resonate the modulating circuit. The higher L/C ratios require the least I.F. drive power for a given bandwidth so the gun capacitance is held as low as possible.

### Variation of Characteristics with Frequency

The frequency dependence of bandwidth, power output and gain has been delayed until this point so that their interrelationship can be more clearly shown. In order to establish a framework for reference, the SAC-19 will be assumed as a standard design at 6 Kmc. and scaled over the frequency range from 2 Kmc. to 7 Kmc. The beam voltage and perveance will be kept constant, the load will be kept matched and the linear dimensions will be inversely proportional to the frequency. The three characteristics depend upon frequency and the shunt conductance of the output cavity which also is a function of frequency as follows:

$$P_o \propto \frac{1}{G_{sh}} \qquad (2)$$

$$\text{Gain} \propto \frac{1}{(G_{sh})^2} \qquad (3)$$

$$\text{Bandwidth} \propto \frac{f_o}{Q_L} \propto f_o\, G_{sh} \qquad (4)$$

It is assumed for the purposes of gain calculations that the $G_{sh}$ of the cavity alone without the shunt losses introduced by the beam and the load is proportional to the square root of the frequency. The electronic loading is not simply related to frequency and must be determined in part by experiment.

By using available data on electronic loading and the above cavity losses, the curves in Figure 7 have been plotted with their ordinates normalized to the SAC-19 values at 6 Kmc. The effect of the decreasing $G_{sh}$ as frequency is lowered is easily seen. Bandwidth decreases to about 1/5 at the low-frequency. The power output does not continue to rise indefinitely but stops somewhere short of the theoretical maximum efficiency of 10%. At the lower frequencies especially, there is considerable flexibility of design and the values of the characteristics can be varied to meet specific requirements as previously discussed.

### Three Cavity Klystron Mixer-Amplifier

There are some advantages in the use of three cavity two stage mixer-amplifier klystrons. The principle advantage is the increased gain of two stages which reduces the r.f. drive requirements. Mixing can occur either in the second or the first stage by tuning either the output, or the output and phase modulation of the a.c. beam current at the output gap. Phase modulation sidebands are produced at multiples of the intermediate frequency away from the original radio frequency and on either side. The amount of r.f. current in a particular sideband is identified with the appropriate Bessel function of the peak change in phase delay within the tube. Figure 5. Thus the maximum current in the first sideband is equal to 58% of the current available at the original radio frequency when no modulation is applied, and occurs when the peak sinusoidal phase delay is 1.84 radians. Since the power output is proportional to the square of the current, the output of a mixer tuned to the first sideband is about 1/3 of the output of the same tube as a straight amplifier.

Selection of the desired sideband is accomplished by tuning the output cavity to the appropriate frequency. If the Q of the output cavity is sufficiently high and the spacing between sidebands sufficiently large, the excitation of the cavity by the undesired sidebands will be low enough to be ignored. Otherwise some additional filtering may be required in the system.

If the intermediate frequency energy is frequency modulated, the frequency of the sideband will also be modulated on a one to one basis. Thus the intelligence is converted from intermediate frequency to high level radio frequency power. The only distortion introduced into the system by the tube is the phase delay distortion common to all resonant circuits which is introduced by the cathode driving circuit and the output resonant cavity.

The primary tube characteristics to be discussed are listed in Table 1 along with the values which apply to SAC-19. These values will later be used as those of the standard tube at 6000 Mc.

Table I - SAC-19 Characteristics

| | | |
|---|---|---|
| Center Frequency | 6000 | Mc |
| Bandwidth | 25 | Mc |
| Power Output | 1-1/4 watts | |
| Beam Voltage | 500 | v |
| Beam Current | 90 | ma |
| Gain (as an amp.) | 7 | |
| Modulating Voltage | 150-180 V pp | |

## BANDWIDTH

The bandwidth of a two cavity klystron mixer is determined by the loaded Q of the output cavity and by the Q of the intermediate frequency driving circuit. The modulated r.f. power does not appear in the input cavity so no bandwidth is lost there. Bandwidth can be increased by overcoupling to the load which will, at the same time, decrease the output power and gain. However, neither the gain or output power have been sacrificed in SAC-19 to obtain the bandwidth. The wide bandwidth comes more as a result of low-voltage high-current operation.

Since the cathode-anode portion of the tube is part of the output circuit of the modulating intermediate-frequency amplifier, this circuit must be designed to give sufficient bandwidth. Additional loading of the modulating circuit may be necessary. This subject will be considered further in connection with the modulating voltage. Bandwidth variations with carrier frequency over the microwave range will also be discussed later.

## POWER OUTPUT

Power output is closely related through efficiency to the power in the beam and the perveance of the beam. Perveance is defined by Child's law in which the space charge limited current is equal to a constant which is the perveance, times the applied voltage to the three halves power. It has been found desirable to use high perveance (low voltage) for greatest overall economy of power supply and modulating equipment. Low Voltage tubes have lower efficiency but this is compensated for by the wider bandwidth resulting from the naturally greater capacitive and electronic loading of the output cavity. It becomes increasingly difficult to build tubes as the perveance increases so that a practical limit is reached for a micro-perveance of about 10. Such a tube would draw 112 ma. at 500 volts. (SAC-19 has a $\mu$-perveance of 8.)

The efficiency of SAC-19 as an amplifier is about 7%. This rather low figure is the result of low voltage operation. The output as a mixer when the first sideband is used is reduced to 1/3 of the amplifier output. The amplifier efficiency increases with lower frequencies but the reduction to 1/3 does not change with frequency.

It was mentioned before that increased bandwidth can be obtained by sacrificing output. This can be done advantageously by overcoupling the load to the cavity. The output is shown in Figure 6 as a function of the bandwidth relative to that for a matched load. Note, for instance, that to double the bandwidth requires a loss of only 1.3 db or 35% in output power whereas a 50% loss would occur if the cavity was sufficiently loaded internally and the load was kept matched to give the increased bandwidth.

middle cavities to the sideband frequency. The latter method gives the maximum output which is about 2/3 of the output of the tube as a straight amplifier compared to 1/3 for a single stage mixer. This method, however, gives the least bandwidth since two cavity resonant circuits limit the bandwidth.

## CONCLUSION

Every application, of course, has specific requirements which may differ from the general outline which has been presented and these can frequently be satisfied by compromises with less critical specifications. It is hoped that this outline of power mixer klystron specifications will be of some service in the consideration of tubes for mixer application.

## REFERENCES


1. The Klystron Mixer Applied to Television Relaying - Vincent Learned, Proceedings of the I.R.E., Vol. 38, No. 9, September, 1950.

2. "6,000 Mc Television Relay System", - W. H. Forster, Electronics, Vol. 22, p. 80, January 1949.


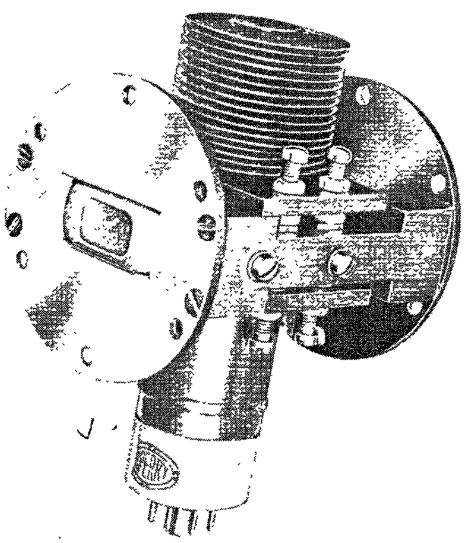

Fig. 1 - SAC-19.

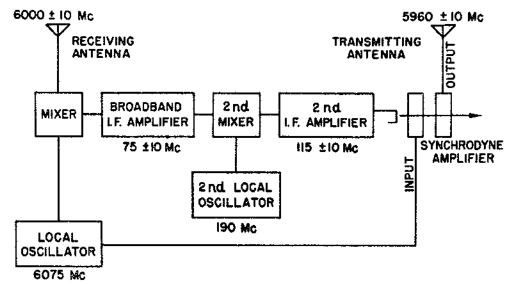


Fig. 2 - Simplified block diagram of television relay repeater.

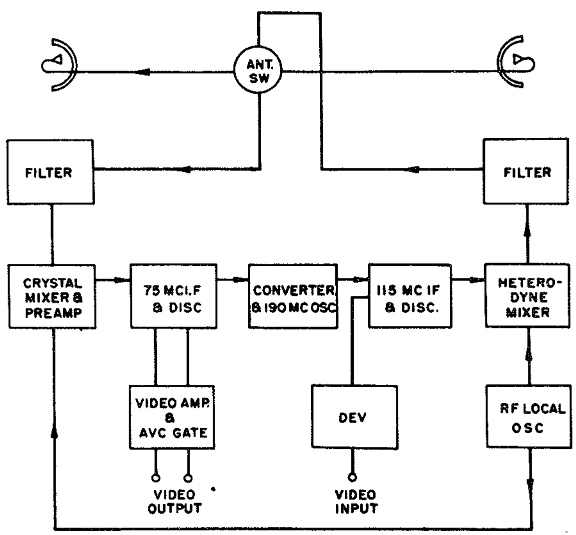


Fig. 3 - Television relay repeater.

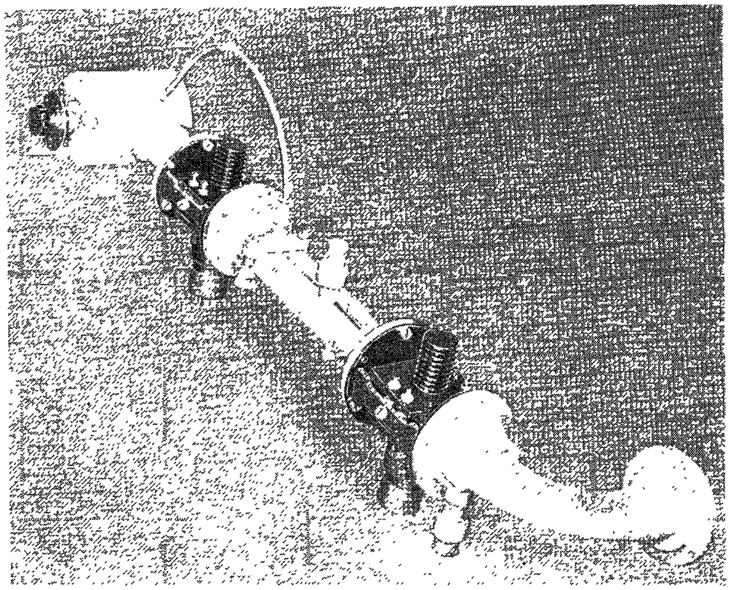

Fig. 4 - RF head of television relay repeater.

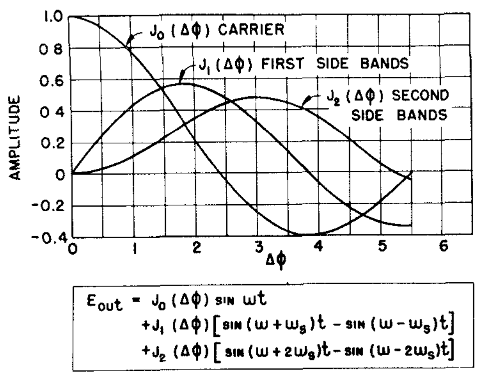


Fig. 5 - Phase modulation frequency spectrum.

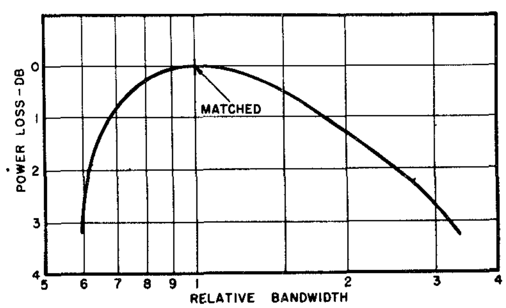


Fig. 6 - Power loss vs. bandwidth for variable coupling.

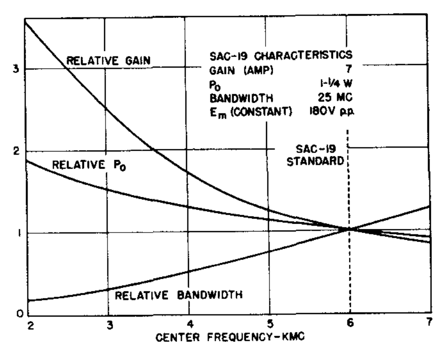


Fig. 7 - Relative gain, output power and bandwidth vs. frequency based upon SAC-19.