Measurement of Relative Phase Shift at Microwave Frequencies*

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Summary—A method is described for measuring the relative phase shift of microwave devices, such as traveling-wave tubes, which utilizes the serrodyne technique to transfer the measurements into the audio-frequency range. The method is used to measure the phase shift incidental to the variation of the dc potentials applied to the several electrodes of a 2- to 4-kmc traveling-wave tube. This method is particularly useful in coaxial systems, where accurately calibrated phase shifters (and attenuators without phase shift) are not available.

Introduction

A PROBLEM often encountered, when making relative phase-shift measurements at microwave frequencies through active devices, is the determination of the phase shift between two signals whose relative amplitudes may vary over some dynamic range. In such cases, the common method of comparing the two signals by a measurement in the shift of the null of a standing-wave pattern created by the two signals traveling in opposite direction through a transmission line cannot be conveniently used, because in such cases the minima may not be very well defined. If the relative amplitudes of the two signals differ by 10 db or more, it becomes extremely difficult even to observe a minimum. The system to be described below avoids this difficulty by shifting the measurement to audio frequencies at which such large dynamic ranges can be readily handled with existing instruments. A similar technique has also been used for the measurement of the phase-shift characteristics of ferrites as a function of the applied magnetic field,[1] and although complex, proves to be quite workable and speedy.

In the present instance, the method was (independently) developed in an effort to measure changes in RF phase shift through traveling-wave tubes with changes in the several tube dc-supply potentials. Measurement of over-all phase shift was not necessary; only relative phase-shift measurements were needed.

Phase characteristics of traveling-wave tubes must be known in the design of many systems: keeping incidental phase modulation within specified limits is often an important requirement. For instance, the phase characteristics of a tube can be used to specify stability and hum level for its power supplies. In some cases traveling-wave tubes may be used for phase or frequency modulation, and phase shift must be accurately known.

For the series of phase measurements reported here, the requirements on the phase-measurement system (see Fig. 1) were rather severe; a wide range of phase shifts had to be measured accurately. Because of the number of measurements needed, they had to be taken quickly to make useful results available in a reasonable time. Since the gain of a traveling-wave tube varies greatly for some changes in its supply potentials, it was essential that the phase-measurement system should not be affected by large changes in signal amplitude.

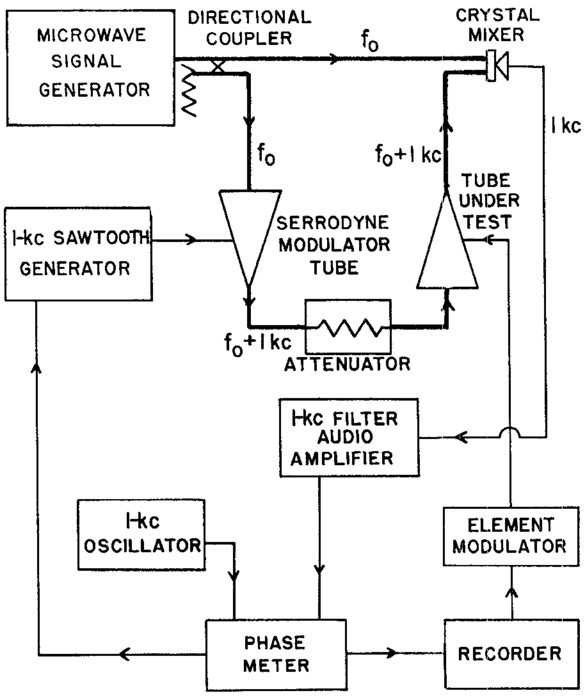

Fig. 1—Phase-measurement system.

Phase-Measurement System

The key component in the phase-measurement system is a serrodyne frequency translator.[2] This device yields two stable microwave frequencies, f_0 and f_0+1 kc, as shown in Fig. 1. The latter signal is passed through the tube under test and mixed with f_0; the difference

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[1] J. B. Linker, Jr., and H. H. Grimm, "Automatic microwave transmission measuring equipment," *Rev. Sci. Instr.*, vol. 28, pp. 559–563; July, 1957.

[2] R. C. Cumming, "The Serrodyne frequency translator," Proc. IRE, vol. 45, pp. 175–186; February, 1957.

frequency of 1 kc exhibits the same phase shift as the microwave signal f_0+1 kc. In this way, the measurement of phase shift can be carried out at the audio frequency by a simple comparison with a standard 1-kc oscillator. The principal advantage of the serrodyne technique is that it allows the generation of a phase-stable 1-kc intermediate frequency. A traveling-wave tube of the same frequency capabilities as the one under test can be used for the serrodyne. Serrodyne operation can be best visualized as an approximation to continually increasing phase modulation. If the phase of a signal is increased or decreased at a constant rate, a constant shift in frequency is produced. No known electronic device can continue to increase its amount of phase shift indefinitely, but if phase shift is increased steadily until 2π radians of phase shift has been produced, the instantaneous-signal values will be the same as at 0° phase shift.[3] A quick return to zero at this point produces only a minor disturbance, and phase shift may be continued. Phase shift through many traveling-wave tubes is approximately proportional to helix voltage for phase shifts of well over 2π radians. Moreover, the necessary change in helix voltage does not appreciably change the tube's gain, especially if the tube has more than the customary amount of attenuation between input and output. The serrodyne used here produces a shift of 1 kc in the signal passing through it when its helix is modulated by a 1-kc sawtooth wave of sufficient amplitude to produce 2π radians of phase modulation. All spurious-modulation components are lower by at least 20 db than the shifted signal.

The path of microwave signals is shown by the thick line in Fig. 1. A conventional signal generator covering the frequency range of the tube under test is used. It is adjusted to give a proper signal input to the crystal mixer to produce linear mixing (1 mw for the crystal used). A directional coupler taps a small part of this signal and sends it through the serrodyne modulator tube. After being shifted in frequency in the serrodyne tube, the signal goes to an attenuator. Enough attenuation is used to insure that the signal at the mixer from this branch of the circuit does not reach a level sufficient to cause nonlinear mixing at any time during a test. For the crystal used, this signal has to be lower by at least 20 db than that from the signal generator. Too much attenuation must also be avoided, since it results in the 1-kc IF signal being too close to noise.

After the attenuator, the signal passes through the tube under test, and then through a directional coupler to the crystal mixer, where a 1-kc sine wave is produced. The 1-kc signal passes through a narrow-band 1-kc filter (to remove spurious harmonic components) and is then amplified and applied to the phase meter. Since the signal often varies in amplitude owing to changes in the gain of the tube during a test, an amplifier with high output capability and low noise level is used. Since the phase meter can operate with signal-input amplitudes changing by ratios as high as 100:1, it is generally not necessary to change gain during a measurement series. The amplifier also has an adjustable phase-shift network which is convenient for setting initial readings.

The phase meter measures difference in phase between the signals at its two inputs. Within the meter, several limiters are used to convert each input signal to a square wave. The metering circuit measures the ratio of the time during which one square wave is positive and the other negative to the total time of the cycle. The meter is calibrated directly in degrees of phase angle between the two inputs. It can be read to within $\pm 0.5°$ for any amount of total phase shift. With this phase-metering method the input signals can have any waveforms, provided the waveforms are such that they produce square waves with equal positive and negative portions after passage through the limiters. One way to insure that this condition is met is to make the input signals low-distortion sinusoids.

In order to measure relative phase shift, it is necessary to supply a phase reference to the phase meter. This reference is provided by a stabilized 1-kc oscillator. The oscillator has to be quite stable, because any change in its frequency would be converted to a change in phase by the 1-kc filter used in the system. The oscillator output goes directly to the phase meter. As a by-product, the phase meter converts the 1-kc oscillator signal to a square wave. Part of this square wave is used to synchronize the sawtooth generator of the serrodyne frequency-conversion system. By this method, phase reference information is put into the microwave part of the system.

The remainder of the required system is the unit labeled Element Modulator. This is a special dc power supply that can be placed in series with any of the elements of the tube under test. It is used to vary element voltages to the tube under test by known amounts while relative phase shift is recorded.

Tube Measurement

As an example of the operation of this phase-measurement system, consider the results of measurements made on Huggins Laboratories Type HA-1 traveling-wave tubes. These are 10-mw, magnetically focused, general-purpose traveling-wave tubes capable of operation between 2 and 4 kmc. Five of these tubes were tested to obtain average results.

Relative phase shift as a function of 1) helix voltage, 2) "grid" (actually a gridless beam-forming electrode) voltage, 3) anode voltage, and 4) collector voltage was measured. In addition, changes in phase shift caused by

[3] To be sure, a mechanical phase shifter *can* be used to increase phase shift indefinitely, but owing to mechanical limitations can only do so at a rate of a few radians per second, which is not a convenient intermediate frequency.

changes in solenoid voltage (causing changes in the magnetic focusing field) were measured. Measurements were made at 2, 3, and 4 kmc. The measurements, which covered a large over-all phase shift, were generally taken twice. The phase-shift control was shifted 90° between the two tests. The average of these two curves tended to cancel out some error from the phase meter as well as errors arising from short-range drift.

Some of the details of the measurement procedure can be illustrated by a brief outline of a typical test. After a sufficient warm-up time, the signal generator is set at the proper frequency and its output to the correct value (1 mw). The proper attenuator is attached. The element modulator is next set for the range of voltages to be used and put in series with the tube element to be tested.

Adjustments of the phase-measurement system are then made, partly with an oscilloscope that is also used to monitor system operation. First, the sawtooth generator is set to 1 kc and synchronized with the 1-kc oscillator. Second, the sawtooth amplitude to the serrodyne tube is set. The oscilloscope is connected to the crystal output before the 1-kc filter. Starting from zero, the amplitude control is slowly increased and the development of the 1-kc sine wave is observed. The amplitude is set for minimum discontinuity in the detected waveform. Next, the 1-kc amplifier gain is set to produce maximum output without distortion when the traveling-wave tube under test is also at maximum gain. (Gain often changes when the voltage to one of the tube elements is changed.) Phase readings are then recorded for different values of voltage on the tube element under consideration.

Experimental Results

The average curves summarize the data best. For the range of grid voltages covered, the change in gain was considerable and signal-to-noise ratios were poor for high values of negative grid voltage. Fig. 2 shows the fair agreement between several tubes as *helix* voltage is varied. Fig. 3 shows the same result, averaged over five tubes, but showing curves at three frequencies.

The data for changes in *collector* and *solenoid* voltages resulted in phase shifts that were small, and showed relatively large variations between tubes, although the general trends were the same.

Phase shifts resulting from changes in *anode* voltage and in *grid* voltage are shown in Figs. 4 and 5, respectively, again for the average of five tubes and at three frequencies. These curves are of considerable practical interest, as variations in either anode or grid voltage are, of course, the common methods of amplitude-modulating the tube. (Phase changes have also been observed as a result of changes in RF drive level, when the dc electrode voltages were fixed. These phase changes were observed not only near the saturation level of the traveling-wave tube, where the effect is well known and is commonly ascribed to nonlinear beam behavior, but also 20 to 30 db below saturation. This observation is an extremely interesting by-product of the present measurement technique.)

Effectiveness and Potentialities of the Measurement System

The relative complexity of the phase-measurement system leads to some problems. The system is very sensitive. One-half degree of phase shift is noticeable. Poor operation of any component of the system leads to noticeable error, especially in the power supplies of both the traveling-wave tube under test and the serrodyne tube. These were electronically regulated power supplies supplied from a regulated ac power source. Despite this precaution, short-term system drift often amounted to 3°. The drift seemed to be related to the power supplies.

The phase meter itself contributed to error. It was rated for ±2 per cent accuracy, which often amounted to ±3°. The sign of the error often changed rapidly when crossing 0° or 180° meter readings. This type of error could not be reduced except by extensive alterations of the phase-meter circuits. The error did, however, tend to average out when data were averaged for two phase-measurement tests with 90° of fixed phase shift inserted between them.

Unfortunately, this system could not be checked for accuracy by comparison with a standard, since no standard of sufficient accuracy was readily available. Many of the individual components of the system were checked and corrected. They were thought unlikely to cause noticeable error. On the basis of constancy of results, it is estimated that most of the phase measurements were within ±3°. While this accuracy is sufficient for many purposes, greater accuracy would be needed for some uses, particularly in attempts to use phase data for a better understanding of the operation of the tube itself. If higher accuracy of phase measurements were necessary, a phase measurement system of this type could probably be constructed to give data accurate to within ±0.5°. This accuracy would require a different type of audio phase meter and better power supplies.

The primary advantage of this system is its speed of measurement. With manual meter readings, a tube can be completely tested in one day. In addition, the system can be readily adapted to mechanized data collecting. The phase meter could drive a data recorder, with its paper feed driving a potentiometer wired to the element modulator. Thus a phase curve could be recorded directly. The only reason why mechanized data recording was not used in the measurements described above was that the equipment had not yet been completed.

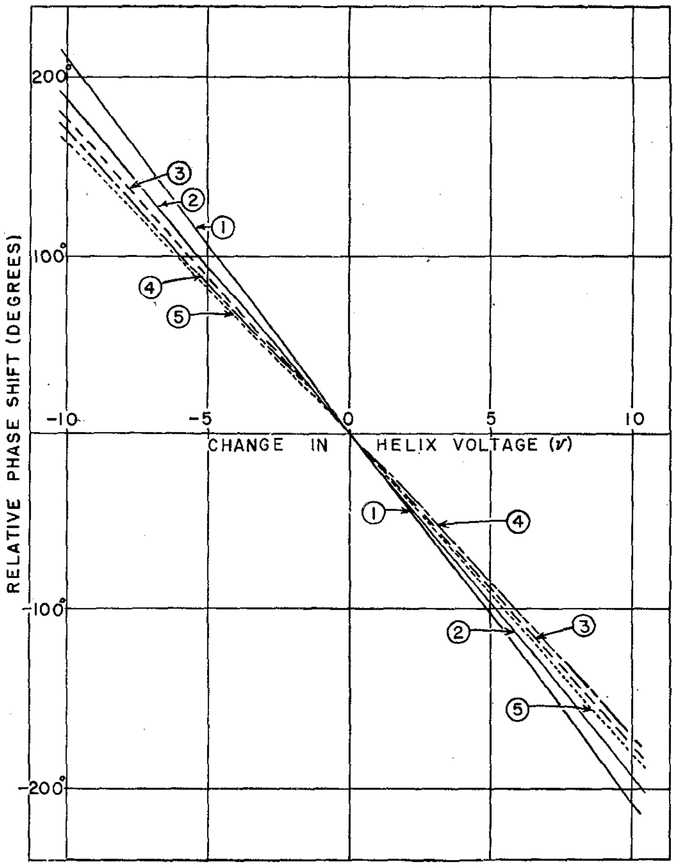

Fig. 2—Phase change for five tubes as a function of helix voltage, at a single frequency (3 kmc).

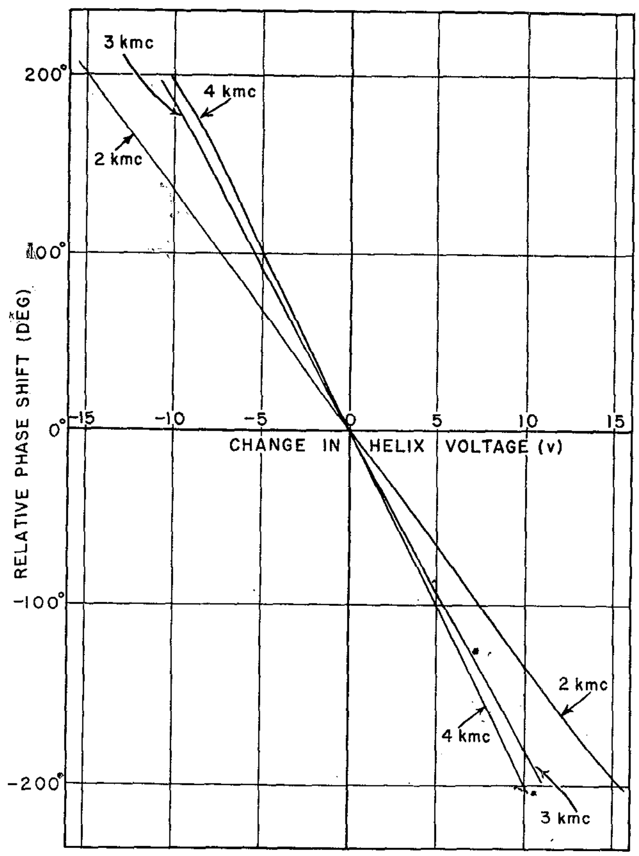

Fig. 3—Phase change for five tubes (average values) as a function of helix voltage, at three frequencies.

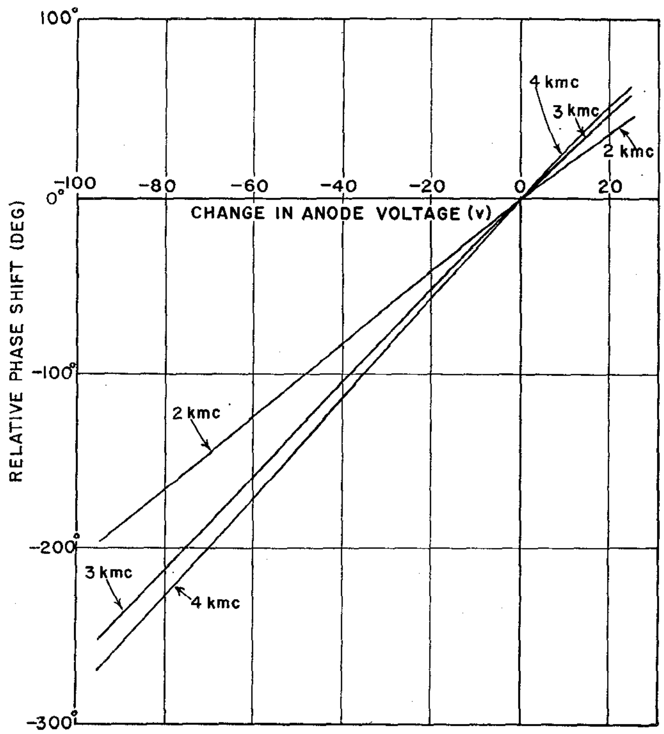

Fig. 4—Phase change for five tubes (average values) as a function of anode voltage, at three frequencies.

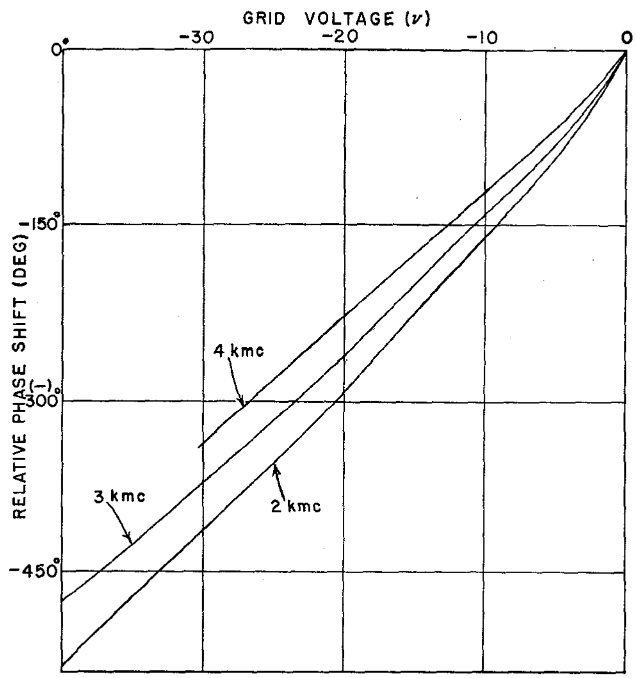

Fig. 5—Phase change for five tubes (average values) as a function of grid voltage, at three frequencies.

Conclusions

A system of making relative phase measurements at microwave frequencies has been described. It is capable of making these measurements even if the signals to be compared differ widely in amplitude. Although the system is complicated, it can yield data quickly. Many of the components of the system are in rather general use in a microwave laboratory. The audio-frequency phase meter is probably the largest piece of special equipment needed. This system would thus seem to warrant consideration whenever a large number of phase measurements are needed. The system is especially worthy of consideration where traveling-wave or klystron tubes are available for the frequencies of interest.

Examples of phase characteristics of Huggins Laboratories HA-1 traveling-wave tubes have also been given. This tube is typical of many traveling-wave tubes now in use. The curves show that fairly good filtering of traveling-wave-tube power supplies is needed to prevent spurious phase modulation.

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Resonant Modes in Waveguide Windows*

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Summary—**Analysis and experimental verification of a class of resonant fields, called ghost-modes, occurring in waveguide dielectric windows are presented. Numerical solutions for a simple geometry are given through universal curves. Knowledge about ghost-modes has importance to designers of high-power windows. It also leads to a measuring technique for dielectric constants through a frequency measurement.**

Introduction

THE general phenomenon of ghost-modes in imperfect waveguides, special cases of which have been noted before, was predicted by one of the authors.[1] The present paper presents a quantitative analysis and confirming experiments of a class of ghost-mode resonances occurring in a particularly simple waveguide window, where exact analysis, using transmission-line theory, is applicable. A ghost-mode is a resonant electromagnetic field configuration, existing in the vicinity of certain waveguide obstacles, such as dielectric windows. Its transverse field configuration is that of an ordinary waveguide mode and its resonant frequency lies below the cutoff frequency of the particular mode in the unperturbed guide. Thus, the ghost-mode fields decay exponentially on either side of the waveguide obstacle and no energy travels away. Within the region of the obstacle the z-variation of the fields must have oscillatory character.

Analysis

A window configuration simple enough to allow exact analysis is shown in Fig. 1. The dielectric slab shall be homogeneous and isotropic; the surrounding waveguide shall be straight and lossless, but its cross-sectional shape may be arbitrary. Under these assumptions the window does not introduce modal conversions, and analysis may proceed using conventional transmission-line theory.

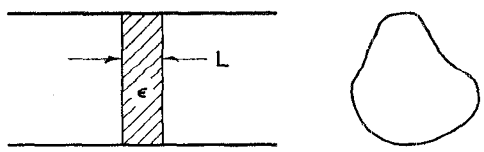

Fig. 1—Transverse dielectric slab window.

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‡ Microwave Lab., W. W. Hansen Labs. of Physics, Stanford University, Stanford, Calif.

[1] E. T. Jaynes, "Ghost modes in imperfect waveguides," Proc. IRE, vol. 46, pp. 415–418; February, 1958. (Note that Fig. 2 in this reference was incorrectly drawn; the curves should be rotated 180° in the plane of the paper, about an axis passing through the center of the diagram.)