SOME COUPLED-WAVE THEORY AND APPLICATION TO WAVEGUIDES

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Coupled transmission lines have been employed as transducers for selectively coupling between a single-mode waveguide and one mode of a multi-mode waveguide. Theoretical relations describing the characteristics of such devices and some results of experiments are to be presented.

(Abstract)

AUDIO MODULATION SUBSTITUTION SYSTEM FOR MICROWAVE ATTENUATION MEASUREMENTS

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Summary---This paper describes an Audio Modulation Substitution System for high accuracy microwave attenuation measurements. In order to utilize the full advantages of a high-gain, narrow-band audio amplifier, problems of noise, hum, and instability had to be overcome. The techniques used to overcome these difficulties are discussed. The system is used over the frequency range of 240-40,000 mc and can measure up to 40 db.

Introduction

One of the several methods used by the Electrical Measurements Laboratory for microwave attenuation measurements is the audio modulation substitution method which is capable of a measurement range up to 40 db from 200 - 40,000 mc. A simplified block diagram of this system is shown in Fig. 1. The audio modulated klystron oscillator is used as a stable source of r-f power and the barretter as a square-law detector. Any attenuation of the microwave carrier results in a linearly proportional change of the modulation superimposed on that carrier. Upon reaching the barretter mount, the modulated r-f power develops an audio frequency voltage across the barretter. This a-c voltage passes through the audio attenuator, is amplified, and then measured by the output level indicator. The requisite for successful operation of the system is that this level, once selected, is maintained constant by matching any changes in the unknown microwave attenuator being tested with an equal and opposite change of the standard audio substitution attenuator. The change in the microwave power level at the barretter is then equal to the change in the calibrated audio attenuator.

The basic principles involved in this method are relatively simple. However, a careful analysis has disclosed many possible sources of error. This article summarizes the improvements which have been made in the system in use at the present time.

Equipment Used

The particular use of a barretter in this system should not be confused with its use in the measurement of microwave power. Ordinarily a barretter is used in conjunction with some type of bridge circuit to measure microwave power. In this system, however, it is used as a detector to recover modulation from a microwave carrier.

Since the measurement technique is based on the use of a barretter as a detector, a few basic facts pertaining to the physical and electrical characteristics of a barretter will help in understanding the design requirements for the measurement system.

The detecting ability of a barretter is based on the physical property that the resistance of the barretter is a function of its temperature. The static characteristics of a typical Sperry barretter are such that the rate of change of resistance with applied power is linear over a major portion of the operating range. Generally, a quiescent operating point is chosen by biasing the barretter with d-c power. The sensitivity of the barretter, expressed in ohms per watt, is primarily a function of the slope of the resistance power characteristic at this quiescent point, modified by the type of biasing circuit used.

Temperature changes and corresponding resistance changes in the barretter element can be obtained by the application of the modulated r-f power. When such a variable resistance is fed from a constant-current source, the voltage developed across the resistor is then a function of the changing resistance. This voltage, Δe, is directly proportional to the change in resistance ΔR. Since ΔR is directly proportional to the applied r-f power, the output voltage is directly proportional to the applied power. Such a relationship satisfies the definition of a square-law detector.

This simple square-law relationship in the barretter is actually complicated by many physical and electrical characteristics of the barretter which will not be discussed in detail at this time. In general, most of the complications will cause a negligible error in the behavior of the barretter when the applied r-f power is much less than the d-c bias power.

To utilize this small a-c voltage developed across the barretter, certain conditions must be fulfilled. First, the signal must receive sufficient amplification so that a suitable, sensitive level indicator can be used. Second, it should be possible to measure accurately any change of this signal level in the audio section. In conjunction with these requirements, the signal input into the amplifier should be kept constant to avoid nonlinearity effects in the amplifier. Another requirement is that means must be provided to couple the audio voltage developed across the barretter to the audio attenuator, and simultaneously, provisions must be available to supply a constant d-c biasing current. Finally, proper impedance conditions between these audio components must be maintained to avoid any errors due to mismatch.

The circuit used for barretter bias and coupling is the result of a number of compromises in attempting to obtain a voltage transfer device that is linear and relatively noise-free, so as to obtain the maximum signal-to-noise ratio.

Fig. 2 is a circuit diagram of this unit. The a-c coupling circuit consisting of a 2000-microfarad condenser blocks d-c current from the audio attenuator and provides a very low impedance to the barretter output signal.

Constant bias current is obtained from a 45-volt source in series with a high resistance potentiometer. This source is composed of three 45-volt B-batteries, connected in parallel to minimize the current drain during operation.

The effectiveness of this circuit as a constant current source has been investigated and found to have a maximum change in current of less than 1/10 of one per cent. This maximum change applies to the range of resistance changes in the barretter.

In a Thevenin's equivalent a-c circuit the effective lossless generator voltage is the voltage developed across the barretter, and the effective series generator impedance is the internal resistance of the barretter. This equivalent circuit is shown in Fig. 3 with the 200-ohm audio attenuator coupled to the circuit.

When the barretter is properly biased at 200 ohms and only low microwave power is being detected, the voltage across the attenuator input, e_a, is almost one-half the value of the voltage developed across the barretter, e_b. However, when the microwave attenuation of the measured component is removed from the r-f portion of the system during a measurement, the power level at the barretter increases from some fraction of a microwatt to possible a milliwatt. Such a change in r-f power results in an increase of about 7 ohms in the internal impedance of the barretter. This changes the voltage transfer ratio. The change represents a maximum since the maximum power is always limited to less than 1 milliwatt to avoid non-linearity effects in the barretter. Curves showing the magnitude of this effect on the measurements are shown in Fig. 4. The actual measurement error, Δdb, as a function of range, and maximum power level is about 0.02 or 0.03 db in the region where the system operates.

Audio Substitution Attenuator

The audio attenuator used as the substitution standard in the system is a drum-type attenuator. It is electrostatically shielded and has four dials calibrated in decibels. It has a characteristic impedance of 200 ohms and a range of 0 - 110 db with increments of 10, 1.0, 0.1 and 0.01 db. The design accuracy in db is 1/10 of one per cent and includes a frequency range of d-c to 10 kc. By actual calibration in the laboratory, the accuracy at d-c was found to be much better than the design accuracy.

In a measurement, the actual microwave attenuation is one-half the calibrated increment of the audio attenuator. This factor of one-half is required because the r-f power ratio at the barretter is measured in terms of a ratio of output voltages that are directly proportional to the applied power rather than to the square root of the applied power as in a normal linear circuit.

The attenuator used in the system was designed and calibrated for operation with a 200-ohm resistive termination at both the input and output terminals of the attenuator. By actual measurements at 100 cps, the amplifier input impedance is not exactly a 200-ohm resistive load. The effects of incorrect terminal impedances on such an attenuator, however, have been described in literature on this subject.[1] It has been shown that adjustment of the attenuator will change the actual transmission loss of the attenuator by increments equal to the calibrated increments of the attenuator. This holds, regardless of the load impedance, as long as a 10 db loss is maintained in the attenuator.

Amplifier

Microwave attenuation measurements with this system require some means capable of detecting alternately a large signal and a relatively small signal.

the ratio being equal to the attenuation of the unit being measured. However, in the discussion on the characteristics of the barretter as a square-law detector, emphasis has been placed on the square-law relationship being true only at low levels of microwave power. This effectively places a limit on the maximum power level which can be used for any measurement. As a result of this limitation, in order to be able to measure as large a signal difference as possible, very small power levels must be detected and amplified.

The use of very small signal voltages implies the use of a high gain amplifier. The maximum amount of gain that can be used is limited, however, by the input noise level of the amplifier. Sources of this noise include noise developed in the associated circuits connecting the barretter to the amplifier, extraneous audio pickup due to a-c power radiation and a-c loop currents, and thermal noise induced by the tube and its circuit components in the first stage of the amplifier.

By using the present barretter bias and coupling circuit, the noise from this source is reduced considerably. Since the audio attenuator is a passive network and is well shielded, it contributes no extraneous noise. The problem of reducing the noise level from a-c power radiation and ground loops will be discussed later.

With the use of proper design techniques and high quality components, amplifiers can be designed with a very low input noise voltage. Furthermore, one way in which there is direct control on the input noise level is through the use of narrow-band techniques. An amplifier tuned to a very low audio frequency was selected so that a very narrow bandwidth of 10 cycles could be utilized. This, of course, necessitates a low audio frequency for the modulating voltage which in turn satisfies the required relationship for the barretter response, namely, that the pulse length be much greater than the thermal time constant of the barretter.

The thermal time constant of the Sperry barretter under consideration is approximately 320 microsecs. The selection of a modulating frequency of 100 cps gives a pulse length of 5000 microsecs, which meets the requirements needed between the time constant of the barretter and the pulse length.

The amplifier that is used at the present time has four resistance coupled stages, but the input into the first stage is coupled through a specially shielded, high-gain input transformer. A 60-cycle rejection filter of the parallel-T type is inserted between the second and third stages to discriminate against hum pickup. Another parallel-T filter is used to provide degenerative feedback over the third stage at all frequencies except the tuned frequency. The amplifier is shielded electrostatically and mounted on springs to avoid microphonic disturbances. Its power supply is mounted on a separate chassis.

The electrical specifications of the amplifier are:

Gain	3,000,000
Noise Input.	1.2×10^{-8} volt
Peak Frequency	100 cps
Bandwidth.	10 cycles
Input Impedance.	200 ohms

With an amplifier input noise level of 1.2 x 10^{-8} volt, a useful minimum r-f power level of about 1/10 microwatt can be detected. This power level at the barretter will compensate for the 6 db voltage loss in the barretter coupling circuit and the 10 db padding maintained in the audio attenuator, and will still provide an input signal voltage almost 100 times the input noise level. Hence, up to 40 db can be measured and the power level at the barretter can still be kept below 1 milliwatt.

Output Level Indicator

The output level indicator used in the system is a differential type vtvm similar to a unit in use at the National Bureau of Standards. It has a maximum differential sensitivity of 0.2 db per full scale deflection. With a 100 division scale on the meter face, it is possible to detect changes in output of less than 1/100 db. Using such an indicator permits the evaluation of any noise, jitter, or instability in the system and also the elimination of any errors in reading the meter.

The heart of the differential vtvm is the differential tube, a dual triode having a common cathode resistance and equal plate load resistances. Connected between the plates of the two triodes is a microammeter requiring a current of 100 microamps to produce a full scale deflection. A difference in conduction in the two triodes as controlled by the grid potentials will result in a difference in voltage level at the plates, and the deflection of the meter will indicate the existence and magnitude of this difference.

Generally, the meter is balanced initially at the center of the dial with the level of one grid fixed by a battery. The other grid is biased by the signal input after amplification and rectification.

Square Wave Modulator

In the r-f signal source section of this system, the specifications of the audio modulator are also determined by the requirements of the barretter-amplifier combination. Since it is essential to obtain the maximum possible audio voltage across the barretter with a minimum amount of r-f power, there must be 100 per cent modulation of the r-f signal source. Square wave modulation of the klystron satisfies this requisite and also minimizes any undesirable frequency modulation.

The relatively low modulating frequency of 100 cps was chosen to meet the requirements imposed by the barretter's time constant to reach thermal equilibrium and also to permit the use of a narrow bandwidth amplifier. However, in using such a highly selective amplifier, it was found that the frequency stability of a free-running multivibrator was inadequate, because any slight change in the modulating frequency would result in a change in the output of 1/10 or 2/10 db. This problem was overcome by the use of an overdriven amplifier excited from the 100 cps multivibrator of the Primary Frequency Standard whose frequency stability is, better than one part in ten million. The amplifier itself has a regulated power supply and a low impedance cathode-follower output. The output is a square wave of 50 per cent duty cycle with a rise time of less than 3 microsecs. This rise time is desirable in modulating the klystron to avoid any frequency modulation of the signal source. The output amplitude is variable from 0 to 100 volts, which is sufficient to provide 100 per cent amplitude modulation.

Minimizing Noise

In order to maintain a low noise level at the input of the amplifier, it is necessary to give considerable attention to the problem of noise pickup and a-c circulating currents in ground loops. Operating the system in a shielded room was found to be of primary importance in reducing external noise pickup.

Special consideration must also be given to grounding the equipment. In those circuits where one side of the circuit is intended to operate at ground potential, it is necessary that only one point in that side of the circuit be connected to an external or earth ground. This principle must be adhered to, particularly in the case of coaxial cables where the outer sheath has the dual function of being an r-f shield and also part of the active circuit. In that case, the entire system of equipment interconnected by the coaxial cable or cables should be considered as one unit and should be connected to an external ground at only one point. The other pieces of equipment connected together using the coaxial cables must be isolated from ground to avoid noise and hum pickup caused by ground loops.

The hum pickup from the stray magnetic fields of the various power supplies, oscilloscopes, and amplifiers used in the system are best eliminated by a trial and error procedure. With all the equipment necessary for system operation turned on and with no signal input, the position of each unit is adjusted so that the observed output of the amplifier approaches that of the amplifier output caused by its own internal noise level. Failure to eliminate these effects will result in jitter and poor stability of the system output, and will introduce an error in the measurement if allowed to become excessive.

Another source of noise and jitter which can be induced in the system when using waveguide plumbing is the effect of waveguide slots in tuners and open secondary arms of directional couplers. Such openings in the waveguide plumbing are subject to erratic changes of air pressure due to klystron blowers or air conditioning ducts in the proximity of the system. When the air in the waveguide at these openings is subjected to such conditions, this turbulence is transmitted through the air inside the line to disturb the air surrounding the barretter cartridge. This upsets the rate of heat dissipation of the barretter at an audio rate, and an a-c noise voltage can be developed across the barretter by such disturbances. If such waveguide components must be used in a system, these openings are sealed with tape to prevent any pickup from this source.

Conclusion

The system as described is capable of making attenuation measurements up to 40 db through a frequency range of 200 - 40,000 mc. The range of course is limited by the availability of a properly modulated signal source, barretters, and barretter mounts to operate over the desired frequency range.

The accuracy that can be obtained in any particular measurement is not entirely a function of the system itself. Individual consideration must be given to each measurement with regard to signal source amplitude and frequency stability, r-f matching, range, and many times to the physical configuration of the measured component.

Crosschecks on this system have been made and have checked to better than 1/10 db. These crosschecks were made with reference standards which have been calibrated at the National Bureau of Standards and also by another method that is used for attenuator measurement, the 30-MC Sweep-Frequency Heterodyne Substitution System.

While this audio system has considerable usefulness in performing attenuation measurements required in the laboratory, further improvements can be made. Efforts are continuing to devise means of increasing the measurement range and improving the accuracy of the system so that more extensive use can be made of the system's inherent simplicity in making microwave attenuation measurements.

References

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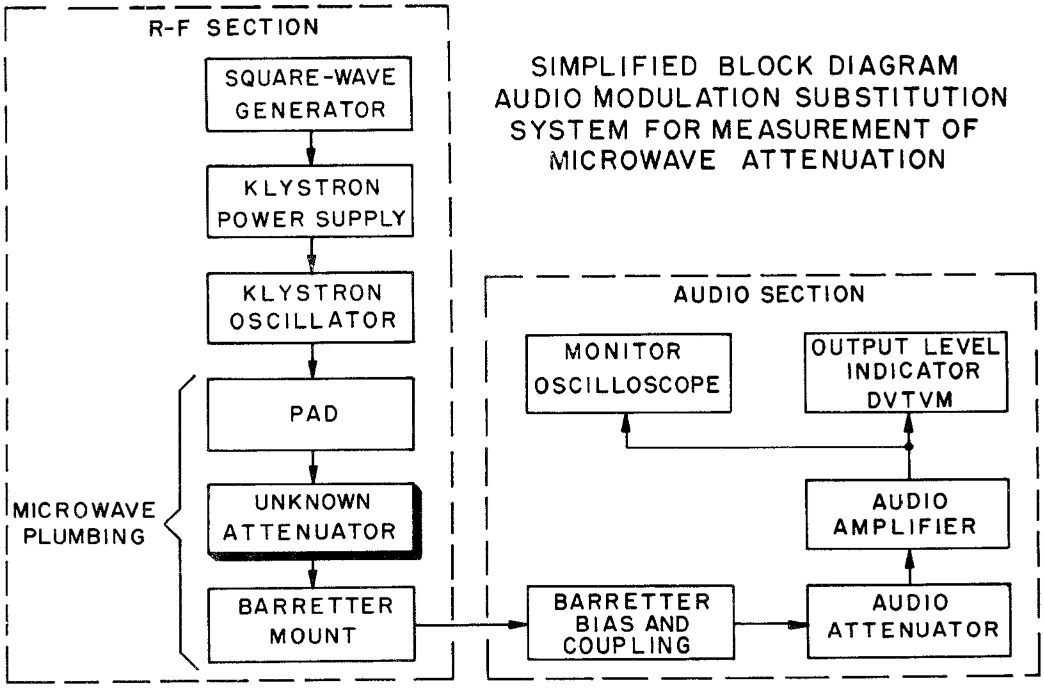
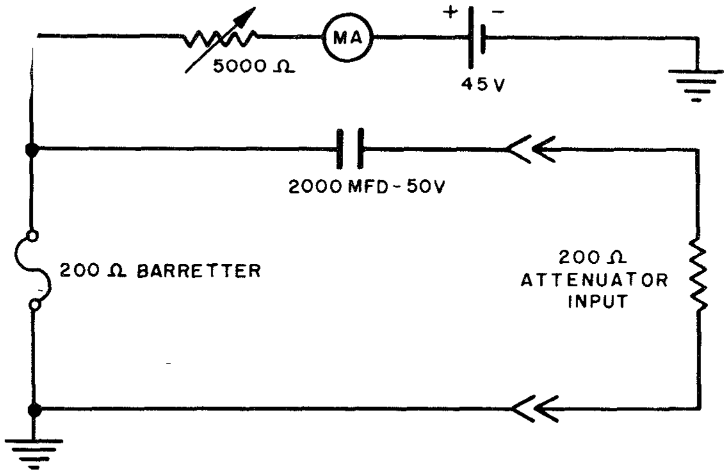
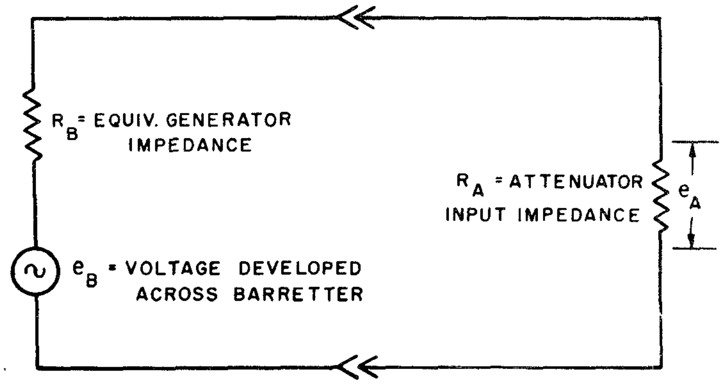


Fig. 1 — Grouping of system into r-f and audio stages.



BARRETTER BIAS AND COUPLING UNIT

Fig. 2



$$e_A = e_B \frac{R_A}{R_A + R_B}$$

THÉVENIN'S EQUIVALENT A-C CIRCUIT OF THE BARRETTER BIAS AND COUPLING CIRCUIT

Fig. 3

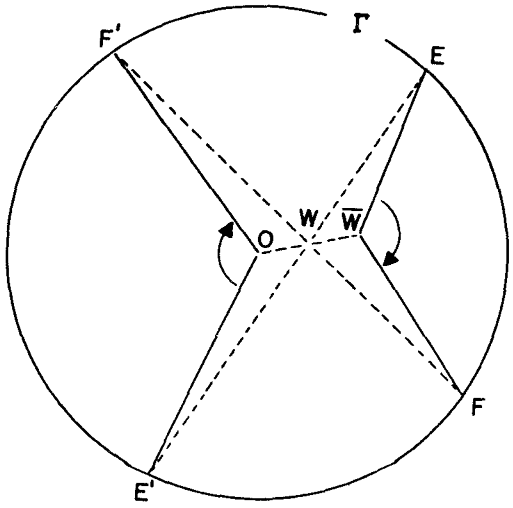


Fig. 4 — Voltage transfer error in barretter coupling unit as a function of range and power level.