Improved Microwave Noise Measurements Using Ferrites*

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Summary—**The ferrite isolator and the ferrite circulator have been applied separately to improve the accuracy of measuring small microwave noise powers or small power differences. Either the isolator or the circulator effectively isolated the input circuit of a microwave receiver from the impedance of the source. As a result, the measurement errors introduced by mismatched source impedances were reduced by as much as 98 per cent. The added input circuit losses of the ferrite components reduced the receiver sensitivity by only about 10 per cent. Since the accuracy of measuring small noise power differences was limited principally by impedance errors, the addition of ferrite isolation to the receiver input circuit increased the sensitivity of measurement to near the theoretical limit.**

The ferrite isolator was used as a passive transmission element in these experiments. The ferrite circulator, however, was used as an electrically-operated, microwave switch. This switch was used to replace the mechanical chopper in a Dicke-type radiometer. In addition to impedance isolation, the ferrite switch makes possible rapid comparison measurements of the microwave noise powers from any two sources, or of the noise powers from the same source in two different polarizations.

INTRODUCTION

THE MEASUREMENT of microwave noise powers is complicated by the similar characteristics of the signal power and the noise power generated in the measuring apparatus. When the signal power is small compared with the apparatus noise level, a measurement must be made of a small change in the total output noise power. The limiting sensitivity of a simple microwave receiver is generally determined by variations in the gain and noise factor of the receiver. The effects of receiver instabilities can be greatly reduced by adding the rapid comparison technique described by Dicke[1] to the simple receiver. The resulting apparatus is referred to as a microwave radiometer. In this system, the noise power output of the receiver is modulated by periodically substituting a second noise source for the source being measured. The modulation amplitude is a measure of the difference between the noise powers from the two sources. When the second noise source is a known standard, the noise power from the unknown source is measured relative to an absolute power level. With the microwave radiometer, the sensitivity of measurement approaches the theoretical limit set by the statistical nature of the receiver noise power. This limit can be controlled by adjusting the instrumental constants of the radiometer; in practice, noise power differences of the order of 0.1 per cent of the noise level of the apparatus should be detected with a one-second response time. For a typical microwave radiometer the minimum detectable power is about 10^{-16} watts.

With this high sensitivity, the measurement inaccuracies resulting from small changes in the radio-frequency impedance presented to the receiver input circuit become most important. The input impedance and consequently the noise power output of a microwave receiver are dependent on the radio-frequency source impedance. In the comparison radiometer, a changing impedance is presented to the receiver as the input is switched between the antenna, or other source of microwave noise power, and the comparison standard noise source. This change in impedance is synchronous with the desired modulation of the receiver noise level which corresponds to the difference between the power level of the source and the power level of the comparison standard. Since the desired and the undesired modulations pass through the receiver circuits together, the output reading of the radiometer is in error by an amount dependent on the radio-frequency impedance connected to the radiometer input, and on the coupling between the radio-frequency and intermediate-frequency circuits. When a superheterodyne receiver without image frequency rejection is used in the radiometer, the error in the radiometer output depends also on the length of the radio-frequency transmission line because of interference effects between the sum and difference frequency bands. Experimental observations indicate that when the receiver input circuit is a simple microwave converter, a source impedance mismatch corresponding to a voltage standing-wave ratio of 1.2 can cause errors in the output reading of a radiometer which are of the order of 100 times the minimum power which is detectable in the absence of reflection effects. These impedance errors place a serious limitation on the accuracy of measuring small microwave noise powers because of the difficulty of impedance matching antennas and other microwave components over the broad frequency bands used in microwave radiometry. Corrections for impedance error are uncertain and time consuming because of the complex dependence of the receiver response on frequency, input impedance, and line length. It is, therefore, desirable to isolate the receiver from the source impedance if this can be done with little sacrifice in receiver sensitivity. A balanced converter circuit can be made to minimize the interaction between the radio-frequency source impedance

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[1] R. H. Dicke, "The measurement of thermal radiation at microwave frequencies," *Rev. Sci. Instr.*, vol. 17, pp. 268–275; July, 1946.

and the intermediate-frequency circuit.[1,2] However, it has been found difficult to balance and maintain the critical factors in the converter circuit so that the impedance-induced output variations are consistently less than 10 or 20 times minimum detectable power.

Ferrite waveguide components with nonreciprocal transmission characteristics and small absorption losses provide a means of isolating the radiometer from the source impedance which does not depend on critical mixer characteristics. The applications of the ferrite isolater and the ferrite circulator[3] to the problem of receiver isolation were investigated experimentally. The results described in the following paragraphs indicate that either of these ferrite components can be used effectively to reduce the measurement errors caused by mismatched radio-frequency source impedances. In this application, the ferrite circulator was used as an electrically-controlled microwave switch and was substituted for the mechanical modulator in the radiometer referred to earlier. When used in this way the ferrite switch gives the added advantage of electrical switching and makes possible a wider variety of measurements with the radiometer.

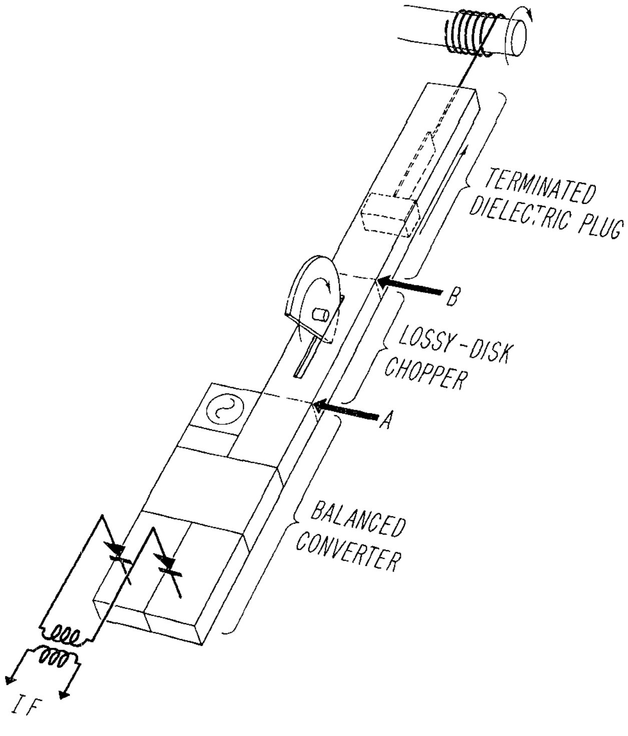
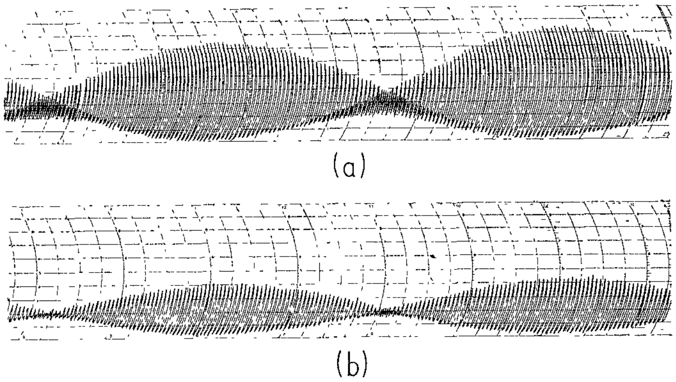


Fig. 1—The apparatus used to observe the effect of a mismatched source impedance on the noise power output of a microwave receiver at 3.15 cm wavelength. The dielectric plug was drawn through the input waveguide at a constant rate to simulate a source impedance with a variable line length.

Observation of Impedance Dependence

The apparatus shown in Fig. 1 was used to observe the effect of a mismatched source impedance on the noise power output of a microwave radiometer operating at a wavelength of 3.15 cm. The comparison radiometer system was preferred over a simple microwave receiver because of better stability in observations of receiver output variations corresponding to small power levels. The frequency response of the receiver was limited mainly by the bandpass of the intermediate-frequency amplifier; therefore, both the sum and difference bands of radio frequencies were converted to the intermediate frequency. The relative path lengths to the two crystals in the balanced mixer were adjusted for maximum coupling between the input impedance and the output noise power[1,2] so that the effect of a small impedance mismatch could be observed. A single crystal mixer was not used because of the added complexity of interpreting the data with greater leakage of local oscillator power into the antenna line. The receiver noise factor was about 13 db, the bandpass of the intermediate-frequency amplifier was 5.5 mc centered at 30 mc, and the output time constant was one-half second. A microwave noise source with constant power output and fixed radio-frequency reflection was approximated by fitting a resistively terminated dielectric plug into waveguide. The plug was drawn at a uniform rate through a long waveguide transmission line connected to the receiver input in order to change the impedance presented to the mixer in a systematic manner. The output of the radiometer was recorded with an Esterline-Angus graphic meter. The recorded output is not strictly proportional to power, however, the deviation from proportionality is small over the range of the measurements and has been neglected for simplicity of discussion.


(a)

(b)

Fig. 2—Records of the variation in the noise power output of the receiver as a mismatched impedance was moved through a length of input waveguide of about 12 feet. The right-hand side of the records corresponds to the position of the impedance nearest to the receiver input circuit. (a) vswr of impedance 2.33; (b) vswr of impedance 1.50.

Fig. 2 shows recordings of the variation in the output of the radiometer when plugs with voltage-standing-wave-ratios of 2.33 [Fig. 2(a)] and 1.5 [Fig. 2(b)] were drawn through the waveguide. The short period of the variation corresponds to a change in the length of the input transmission line approximately equal to one-half of a local oscillator wavelength in waveguide. The long period envelope of the variation results from the re-

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[2] R. V. Pound, "Microwave Mixers," McGraw-Hill Book Co., Inc., New York, N. Y., pp. 276-279; 1948.

[3] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications—the microwave gyrator," *Bell Sys. Tech. Jour.*, vol. 31 pp. 1-31: January, 1952.

sponse of the superheterodyne receiver to both the sum and the difference bands of radio frequencies which are separated by twice the intermediate frequency. This period corresponds to a length of input transmission line which is one-half wavelength longer for the signal than for the image, in this case about six feet. The recordings shown in Fig. 2 demonstrate qualitatively the dependence of the noise power output of the radiometer on the magnitude and phase of the source impedance, and on the length of transmission line separating the source impedance from the receiver input. A change in input noise power of 6×10^{-14} watts would be required to change the radiometer output by the amount of the peak variation shown in Fig. 2(a). The amplitude of the output variations shown in Fig. 2 would have been reduced by approximately 75 per cent by proper adjustment of the path lengths to the two crystals in the balanced mixer. The general reduction in the magnitude of the variation from right to left is due to waveguide attenuation.

APPLICATION OF THE FERRITE ISOLATOR

The ferrite isolator[3] is a waveguide transmission-line component with greater attenuation for one direction of propagation than for the reverse direction. At centimeter wavelengths it is practical to make isolators with less than 0.5 db attenuation for one direction of propagation, and more than 30 db for the reverse direction. When the isolator is included in the input transmission line of a receiver, the reduction in the dependence of the receiver output noise power on a mismatched source impedance is comparable to one-half the difference between the reverse and the forward attenuations of the isolator, where all of factors are expressed in decibels.

A commercially built isolator (Uniline) of the ferrite rotator type was used for the experimental tests. At the wavelength of 3.15 cm the forward attenuation of the isolator was 0.5 db and the reverse attenuation was 20 db. Fig. 3(a) shows the recorded variation in the output of the radiometer as the plug with a voltage-standing-wave-ratio of 2.33 was drawn through the input waveguide. Fig. 3(b) shows the result of inserting the isolator in the transmission line at point A in Fig. 1 and repeating the test procedure. The variations in the noise power output of the radiometer caused by the mismatched impedance are reduced about 90 per cent. The reduction in the signal response by the forward attenuation of the isolator is indicated by the change in the measured level of the heated thermal-noise source when the isolator was inserted in the transmission line. The indication is not exact because of the impedance error when the isolator was out of the circuit. The isolator used was designed to operate over a band centered at 3.26 cm. Because of greater reverse attenuation at the band center, the reduction in the receiver output variations would have been about 96 per cent if the test had been made at this wavelength.

The isolation of the receiver from the source impedance can be increased by building an isolator with a higher ratio of reverse attenuation to forward attenuation, or by connecting several isolators in cascade. The deterioration of receiver sensitivity can be lessened by building an isolator with a forward attenuation which is smaller than 0.5 db loss of isolator used here. According to reported loss values for recently developed ferrite materials, it should be possible to construct isolators with transmission losses of less than 0.25 db.

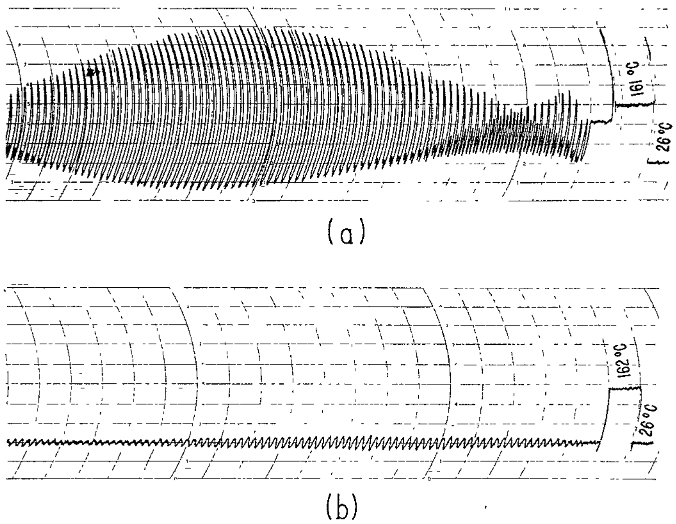

Fig. 3—The effect of inserting a ferrite isolator with attenuations of 0.5 db (forward) and 20 db (reverse) in the receiver input transmission line. The records show the variation in the noise power output of the receiver as the mismatched impedance with a vswr of 2.33 was moved through a length of input waveguide of about 6 feet. (a) Input circuit without ferrite isolator; (b) input circuit with ferrite isolator.

APPLICATION OF THE FERRITE CIRCULATOR

The ferrite circulator[3] is a four-terminal microwave network with nonreciprocal transmission characteristics. A circulator was assembled from laboratory components and a 90 degree ferrite rotator as shown in Fig. 4. The transmission properties are such that, for one direction of axial magnetization of the ferrite, power is transmitted from terminals 1 to 2, 2 to 3, 3 to 4, and 4 to 1 with small attenuation, while power transmitted in the opposite directions is highly attenuated. When the direction of the magnetic field applied to the ferrite rotator is reversed, the paths with low attenuation and the paths with high attenuation are interchanged. In this way, a microwave receiver connected to terminal 2 can be switched between a source of power connected to terminal 1 and a second source of power connected to terminal 3 by alternating the direction of the magnetic field applied to the ferrite rotator. To switch the circulator, an alternating magnetic field was applied to the ferrite by exciting a solenoid wound around the waveguide with an audio-frequency, square-wave current. This ferrite switch was used to replace the rotating lossy-disk chopper which dips into the input waveguide 30 times a second to act as both the comparison switch and the standard comparison noise source in the radiometer diagrammed in Fig. 1.

The nonreciprocal transmission properties of the ferrite switch provide good isolation of the receiver from the source impedance. In this application, the apparent isolation of the receiver is greater than would be indicated by the forward-to-reverse attenuation ratio of the switch. Because the circuit is symmetrical, the impedances presented to the receiver over the two halves of the switching cycle are nearly the same, even though the impedances of the two sources differ. The ferrite switch used for the experimental tests had attenuations of 0.4 db and 25 db for the two directions of propagation over the radio-frequency band of the receiver. In order to make a direct comparison between the characteristics of the radiometer when either the ferrite switch or the lossy-disk chopper were used, the solenoid around the ferrite was excited at 30 cycles per second to correspond to the modulation frequency of the mechanical chopper. The receiver was connected to terminal 2 of the ferrite switch, the input transmission line to terminal 1, and a resistive termination at room temperature, corresponding to the lossy chopper disk, was connected to terminal 3. A matched termination was connected to terminal 4, the unused terminal.

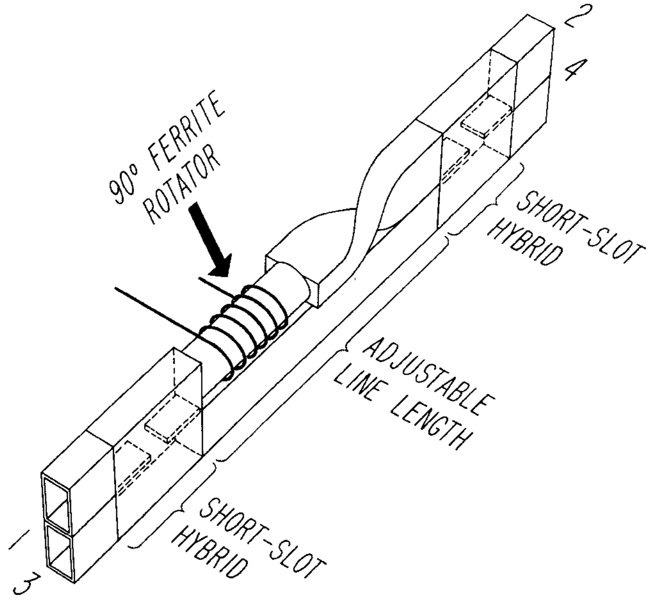

Fig. 4—The ferrite circulator used as a microwave switch in the radiometer. The polarization of the wave in the circular waveguide section was rotated from 90 degrees clockwise to 90 degrees counterclockwise 30 times a second by alternating the magnetic field applied to the ferrite. The periodic 180 degree phase shift introduced in one branch of the hybrid circuit made it possible to realize the advantages of rapid electrical switching along with the advantage of nonreciprocal transmission.

Fig. 5(a) shows the variation in the output of the radiometer with the lossy-disk chopper as the plug with a voltage-standing-wave-ratio of 2.33 was drawn through the input transmission line. Fig. 5(b) shows the variation in the output of the same radiometer when the ferrite switch was substituted for the lossy-disk chopper and the plug was again drawn through the input waveguide. When the ferrite switch was used, the magnitude of the variation in the output noise power of the receiver was about two per cent of the magnitude of the variations when the lossy-disk chopper was used. The reduction of signal response caused by the 0.4 db transmission loss of the ferrite switch is indicated by the response of the radiometer to the power from the heated thermal noise source. It is probable that a ferrite switch could be constructed to give performance which is superior to that of the experimental model used for these tests.

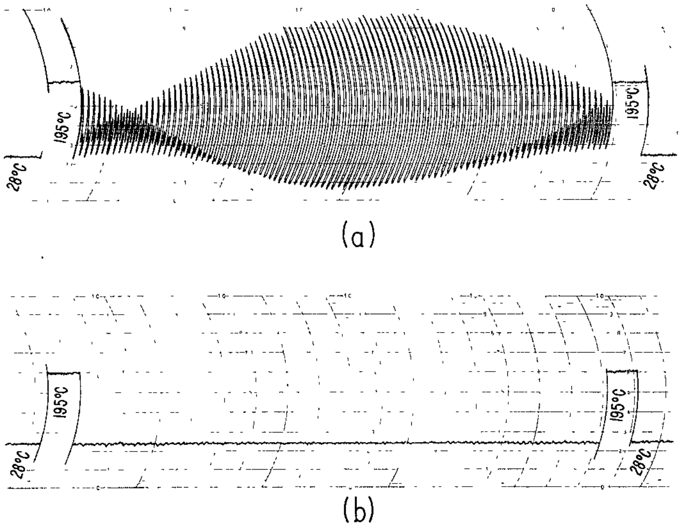

Fig. 5—The effect of substituting the ferrite switch for the mechanical chopper between the points marked *A* and *B* in Fig. 1. The records show the variation in the noise power output of the receiver as the mismatched impedance with a vswr of 2.33 was moved through a length of input waveguide of about 6 feet. (a) With the mechanical chopper in the input circuit; (b) with the ferrite switch substituted for the mechanical chopper.

The ferrite switch has several desirable characteristics in addition to impedance isolation when used as the comparison switch in a microwave radiometer. Since the switching is accomplished electrically rather than mechanically, the problems associated with mechanical vibrations of the crystal mixers, the local oscillator, and the amplifiers are reduced. The rate of switching can be increased to high audio frequencies to allow more rapid comparisons and a reduction of the lower limit on radiometer response time. Another desirable feature is that any two sources of microwave noise power can be connected to the ferrite switch and compared directly. For example, the receiver input can be switched between the outputs of two antennas at an audio-frequency rate to compare the radiations received from two directions in space or the radiations received in two different polarizations. If desired, a second receiver can be connected to the unused terminal of the switch for parallel operation with the first receiver.

CONCLUSIONS

The limitation to the accurate measurement of small microwave noise powers is imposed by the dependence of the receiver output noise power on the radio-frequency source impedance. This limit was effectively reduced by the use of ferrite waveguide components in the radiometer input circuit. A reduction of 98 per cent in the effect of a mismatched radio-frequency source impedance was easily obtained and greater reductions are possible. The input circuit losses introduced by the ferrite components caused a degradation in receiver noise factor of about 10 per cent with a corresponding increase in the minimum detectable power of the system. The use of either a ferrite isolator or a ferrite circulator in the radiometer input circuit will allow accurate measurements of small powers even when some of the critical requirements on the design of the input circuit and antenna are relaxed. In addition, the use of the ferrite circulator as the radiometer comparison switch makes possible a wider variety of direct comparison measurements of microwave noise powers.

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The Characteristic Impedance of the Shielded Slab Line

R. H. T. BATES†

Summary—**The characteristic impedance of the shielded slab line is worked out exactly in terms of elliptic functions. A design graph is given to cover most practical applications.**

LIST OF SYMBOLS

THE NOTATION used for the elliptic functions follows E. T. Copson [1].

z, p, q, s, u, v	Independent complex variables.
a, b, d, t, w	Variable parameters.
$\wp(z)$	Weierstrasse's second order elliptic function.
sn z, cn, z, dn z	Jacobian elliptic functions.
k	Modulus of the elliptic functions.
K	Real quarter period of sn z.
jK'	Imaginary half period of sn z.
$\Theta(z)$	Jacobian theta function.
$Z(z)$	Jacobian zeta function.
ϵ_r	Relative permittivity of medium between shielding plates.

INTRODUCTION

The shielded slab transmission line has several advantages over the coaxial line, especially when it is used as a slotted-line standing wave indicator for wavelengths greater than one foot. The mechanical tolerances are less stringent for a given reading accuracy. A good account of the advantages and disadvantages of this type of standing wave indicator is given by Wholey and Eldred [2], who give design curves for a circular inner conductor.

In a recent paper Cohn [3] has given values of the characteristic impedance of the slab line, calculated from approximate formulas, for t/b less than 0.25, see Fig. 1. However, it is possible to solve the problem exactly, using elliptic functions. As these functions have been comprehensively tabulated, the labor involved in producing the design graphs is probably less than that necessary for evaluating the approximate expressions. Also, the exact formulas allow one to design lines having values of t/b up to unity.

This paper describes the conformal transformations whereby the characteristic impedance of the slab line is determined. The results are shown on a chart, with $\sqrt{\epsilon_r} Zo$ as parameter.

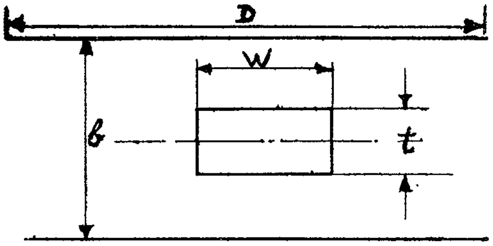

Fig. 1—Geometry of shielded slab line.

EFFECT OF FINITE WIDTH OF SHIELDING PLATES

The characteristic impedance of the slab line from now on will be referred to as Zo.

In the calculation of Zo, the width, D, of the shielding plates is assumed infinite; see Fig. 1. In practice D does not have to be excessively large for this assumption to be valid. There is a convenient method of judging the effect of the finite value of D. The infinite plates are transformed into a cylinder. Then the angular width, θ radians, of the slot in the cylinder due to the finite width of the shielding plates is given by,

$$\theta = 4 \operatorname{cosech} \frac{\pi D}{b}$$

In Fig. 2, θ in degrees is plotted against D/b. It is that the effect of a finite D can easily be made negligible.

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