Some Applications and Characteristics of Ferrite at Wavelengths of 0.87 Cm and 1.9 Cms

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***Summary*—This paper describes the use of ferrites in waveguide to produce Faraday rotations at 0.87 cm and 1.9 cms wavelengths. The Dicke radiometric receiver is briefly reviewed and its improvement by the use of ferrite waveguide components is described. Experimental equipment for securing data on the behavior of ferrites is discussed. Details are given for the construction of a unidirectional waveguide transmission line for 0.87 cm wavelength.**

Introduction

The use of ferrites for producing Faraday rotations in waveguides at microwave frequencies has recently received a considerable amount of attention from workers in this field. Ferrite loaded waveguides have been used as one way transmission lines, modulators, attenuators, and microwave switches. Many other applications are also under development. Very little information is available regarding the behavior of ferrites at wavelengths shorter than three centimeters. Recently some investigations have been conducted by the writer directed towards the use of ferrite waveguide components to improve the operation of a radiometric receiver. The results of these investigations should have many applications in other fields of microwave research.

Faraday in 1845 found that the plane of polarization of light was rotated when under the influence of a magnetic field. He also found that a ray traveling in the opposite direction had the same sense of rotation as the original ray, demonstrating a nonreciprocal relation. Later investigations showed that a suitably shaped piece of ferrite placed in cylindrical waveguide would produce large rotations of the plane of polarization in microwaves when a magnetic field was applied, as shown in Fig. 1.

Ferrite Waveguide Components

If a tapered rod of ferrite is enclosed in a circular waveguide and excited by a longitudinal magnetic field the electromagnetic wave can be visualized as consisting of two oppositely rotating circularly polarized waves, each, of half the amplitude of the original wave. Due to the presence of the magnetic field the two waves propagate through the ferrite with different velocities. When they recombine the plane of polarization is rotated by an angle which is determined by the amount one component lags the other component. If the two components merely differ in velocity without being attenuated the outgoing wave still has the same amplitude and is linearly polarized. In available ferrites there is some attenuation of the components, when one component is absorbed more than the other the outgoing wave is elliptically polarized. If the absorption of one wave is total the outgoing wave is circularly polarized. A measure of the ratio of the relative magnitudes of the two components expressed in decibels is called the ellipticity.

Two types of ferrite waveguide components appear to be attractive for use in radiometric receivers. The first is the unidirectional transmission line; the second the microwave gyrator used in a device called circulator.[2]

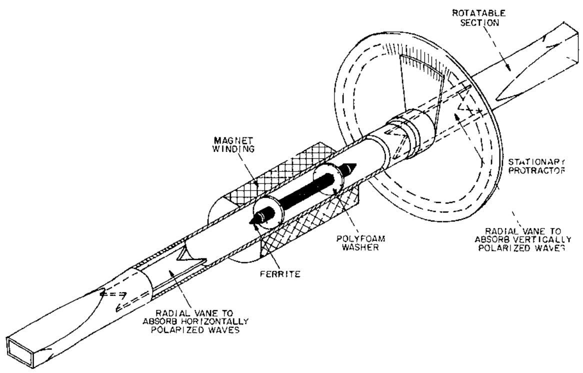

Fig. 1—Test section details.

The Dicke Radiometric Receiver

There are several types of radiometric receivers in use. The Dicke type receiver is, almost without exception, universally used in the microwave region. The Dicke receiver is shown diagrammatically in Fig. 2.

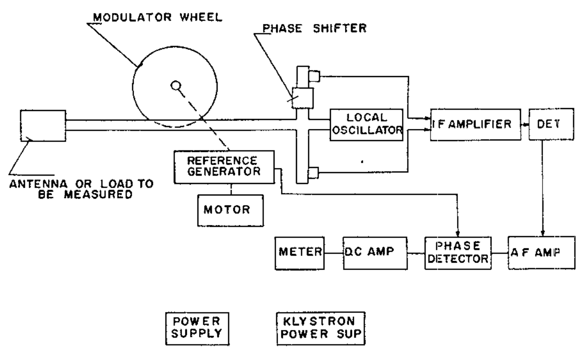

Fig. 2—Block diagram of Dicke radiometric receiver.

Functionally it is a microwave receiver very similar to a radar receiver. It contains a waveguide input to a balanced mixer, the output of which is passed through a wide-band IF amplifier and to a detector. In making

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a measurement of the thermal temperature of a load which is used to terminate the receiver input guide it is necessary to discriminate between the input circuit noise of the receiver and the energy being sent towards the receiver by the termination. Since the energy that is being received from the termination is in the form of white noise and has a small amplitude in comparison to the input noise of the receiver, it is necessary to resort to special means to detect this signal.

To accomplish this result a modulator wheel is injected into the waveguide between the termination and the balanced mixer. This modulator wheel is essentially a circular resistance card which is rotated on an eccentric shaft by a motor. The modulator wheel therefore, serves to switch the input of the receiver from the termination under measurement to the modulator wheel itself since it terminates the waveguide when fully extended into the guide. The output of the receiver is amplitude-modulated at a frequency corresponding to the rotation rate of the modulator wheel. This modulation is subsequently extracted through the use of a phase demodulator which allows the system to recognize an amplitude-modulation component corresponding to the modulator wheel rate. This can be done in this type of circuitry with an extremely narrow band. The application of the modulator wheel to this type of system allows it to detect a very small amount of energy difference represented by a difference of temperature of the modulator wheel and the termination being measured.

The extreme sensitivity of the radiometric receiver requires the consideration of some factors not normally considered in receiver design. Local oscillator and crystal noise in the image and signal bands can cause an output in the receiver if coupled into the antenna line and then reflected back into the receiver input. The power levels involved may be 10^{-14} watts or less, but this can cause an output proportional to 50 degrees antenna temperature. This residual output will vary with frequency and is generally the limiting factor in the accuracy of measurement when the Dicke radiometric receiver is used to measure small temperature changes or low absolute temperatures. This effect may be eliminated if no power from the rf mixer is coupled into the antenna line and permitted to be reflected back into the input appearing as a signal. The unidirectional transmission line and the microwave gyrator may be used to effect this isolation. Placing a unidirectional transmission line between the rf mixer and modulator wheel so that power may flow only towards the mixer has been found by C. H. Mayer of the Naval Research Laboratory to reduce by 90 per cent the residual output of an X-band Dicke radiometric receiver. The addition of a unidirectional transmission line thus enables the receiver to measure absolute temperatures with an accuracy of a few degrees Centigrade.

The properties of a microwave gyrator can be utilized to replace the modulator wheel in a Dicke radiometric receiver, and in addition it prevents any power from the rf mixer antenna line from being modulated and reflected back into the mixer input.

The arrangement of components is then called a microwave circulator and is shown in Fig. 3. The gyrator is placed in a line connecting two colinear arms of the two hybrid junctions and the other two colinear arms are joined by a line of length equal to that of the line containing the gyrator for one direction of current flow through the gyrator solenoid.

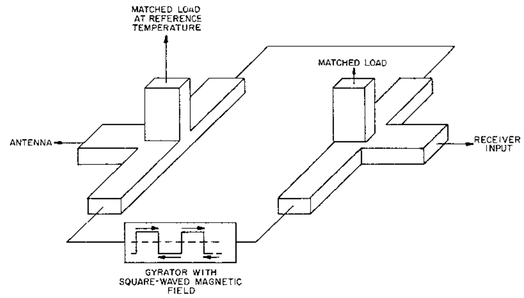

Fig. 3—Microwave circulator as used in a Dicke type radiometer.

Inspection of the circulator reveals that for one direction of current flow through the solenoid energy from the antenna is coupled into the receiver input line and for the other direction of current flow the matched reference load is connected to the input. The current through the gyrator solenoid can be controlled by an electronic circuit such that a square wave of current is produced at some convenient frequency such as 100 cycles per second. For both directions of solenoid current, power emerging from the receiver input when partially reflected by the antenna or reference load ends up being dissipated in the matched load—thus reducing greatly any residual receiver output. Mayer has found that the use of a circulator at X-band reduces the residual receiver output to 2 per cent of that measured for a Dicke radiometric receiver using a modulator wheel. This makes the receiver excellent for measuring small absolute temperatures accurately. Also the reference temperature is the temperature of a waveguide load, not an absorbing wheel, and may be more easily stabilized or varied for receiver calibration purposes.

Experimental Apparatus

Fig. 4 facing shows a block diagram of microwave test equipment for investigating Faraday rotations. Two complete setups have been constructed, one for a wavelength of 0.87 cm, and one for the wavelength of 1.9 cms. A calibrated attenuator is used to measure the insertion loss of the ferrite section and also to measure the ellipticity of the wave emerging from the ferrite section. The slotted section is used to measure the impedance of the ferrite section. In Fig. 1 the ferrite test section is shown in greater detail. Resistive vanes are placed on either side of the ferrite section to absorb the energy of that polarization which is in quadrature with that of the rectangular waveguide. The resistive vanes were made from 100 ohm per square carbon coated phenolic which was ground down to 0.008 inches thickness. A rotating joint is incorporated in the connection between the cylindrical guide and the second transition section. This joint permits the output rectangular waveguide to be rotated through any desired angle. The relative orientation of the input and output guides is measured by a 360-degree protractor and pointer assembly. The longitudinal magnetic field is produced by a random wound solenoid wrapped around the circular section of waveguide. For the 0.87 cm wavelength setup the solenoid has 10,000 turns of number 30 enamel covered wire. The solenoid is 2.125 inches long with an inside diameter of about 0.358 inches. The cylindrical waveguide has an inside diameter of 0.280 inches. R. G. 96/U rectangular waveguide is used for the 0.87 cms wavelength. For the 1.9 cms wavelength assembly a solenoid two inches long having 23,600 turns of number 33 enamel wire was wound on cylindrical guide of 0.643 inches outside diameter. The inside diameter of this guide is 0.563 inches. The rectangular guide used for 1.9 cms wavelength is R.G. 91/U.

The ferrite used in these tests was obtained from General Ceramics and Steatite Corporation of Keasby, N. J. The trade name of this product is MF1331. In general ferrites are difficult to fabricate to the desired size and shape, being extremely hard and brittle.

Preliminary experiments were conducted in an attempt to find suitable materials and methods of supporting the ferrite rods in the cylindrical waveguide. Most common dielectrics showed excessive loss and high standing wave ratios. Polystyrene foam washers were finally selected as a suitable material since it showed negligible loss and unity standing wave ratios.

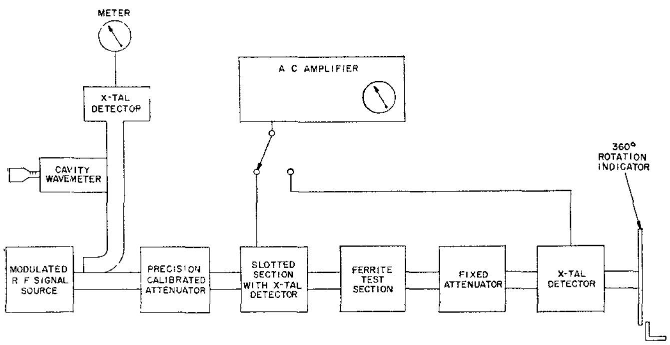

Fig. 4—Complete test equipment.

Initial tests were made at 0.87 cm wavelength with $\frac{1}{8}$- and $\frac{1}{4}$-inch ferrite rods. The ends of the rods were tapered to a sharp point. Since the supporting polystyrene foam behaved very much like air no taper was used on the supporting cylinder. Rods of this size showed very erratic rotations with a variation of solenoid current. The conclusion was reached that this action was probably due to the generation of higher transmission modes in the ferrite section besides the dominant TE_{11} mode. Another undesirable characteristic of the $\frac{1}{8}$- and $\frac{1}{4}$-inch diameter ferrite rods was poor values of ellipticity. Since the dielectric constant and permeability of ferrite is much greater than air the ferrite has the effect of making the waveguide diameter electrically larger. This can result in the propagation of higher modes. Attempts were made to compensate for this effect by placing the ferrite rods in tapered brass sleeves with an outside diameter equal to the inside diameter of the cylindrical waveguide. By grinding a taper on the ends of the ferrite rods and selecting the proper diameter and taper for the brass sleeve it is possible to keep the electrical diameter of the waveguide constant. The actual fabrication of the brass sleeve to meet this condition presents a difficult problem because of the unknown parameters involved. Several brass sleeves were tried with various ferrite rod diameters, but the results were not encouraging. Such sleeves gave high insertion losses and poor standing-wave ratios.

To eliminate the presence of higher modes it appeared to be advisable to try smaller diameter rods. A centerless grinder was used to grind a $\frac{1}{8}$-inch rod down to 0.062 inch. This was the smallest diameter that could be obtained with the centerless grinder without excessive breakage. The ends were then given a 10-degree taper. Several pieces of 0.062-inch rods of varying lengths were obtained. Voltage standing-wave ratios of less than 1.1 were obtained with this size rod. The ellipticity for most of these samples was measured to exceed 30 decibels. Insertion losses were also low varying from 0.3 to 0.6 decibels depending on the length of rod used.

Experimental Results

Fig. 5, on the next page, shows a plot of the measured rotation as a function of magnetic field for five different lengths of 0.062-inch diameter ferrite rods at a wavelength of 0.87 cm. The rotation is seen to vary linearly with magnetic field for field strengths exceeding 150 oersteds. Inspection of Fig. 5 reveals that the rotation varies almost linearly with the over-all length of the ferrite rod. This seems to indicate that the rotation per unit length is the same in the tapered section as in the cylindrical section.

The 1.016-inch ferrite rod yields a 90-degree rotation for a 43-oersted field. It was measured to have an insertion loss of 0.3 decibels at 43-oersteds field and a voltage standing-wave ratio of less than 1.05 for magnetic fields from 0 to 300 oersteds. As such it would be very well suited for use in a microwave gyrator.

For all samples tried the rotation has been found to vary rapidly with frequency. This is indicated in Fig. 6 (next page) in which is shown the rotation produced by 0.062 by 1.016-inch rod as a function of magnetic field for three different frequencies. From the curves a 1 per cent change in frequency is seen to produce a 10 per cent change in rotation.

Results at 1.9 cms wavelength follow the same general pattern as obtained at 0.87 cm wavelength. A tapered ferrite rod 1.5 by 0.187 inches was ground down to smaller diameters in steps of two- to five-thousandths inches using a high speed drill press. Measurements of rotation, ellipticity, standing-wave ratios, and insertion losses were made at each diameter. The ferrite rod was

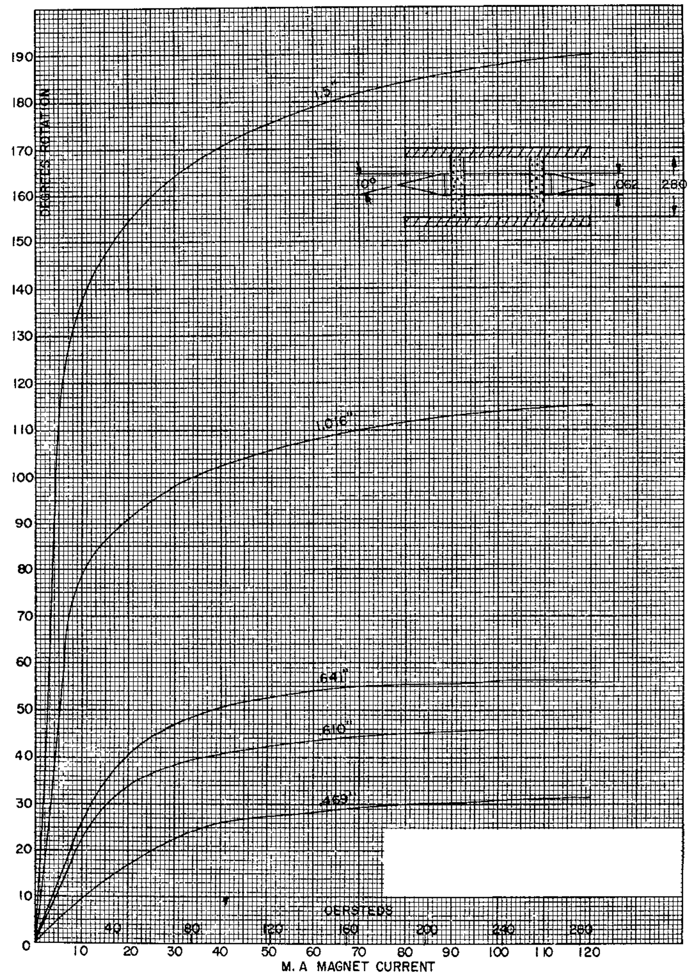

Fig. 5—Rotation vs magnetic field for various lengths ferrite rods at 0.87 cm.

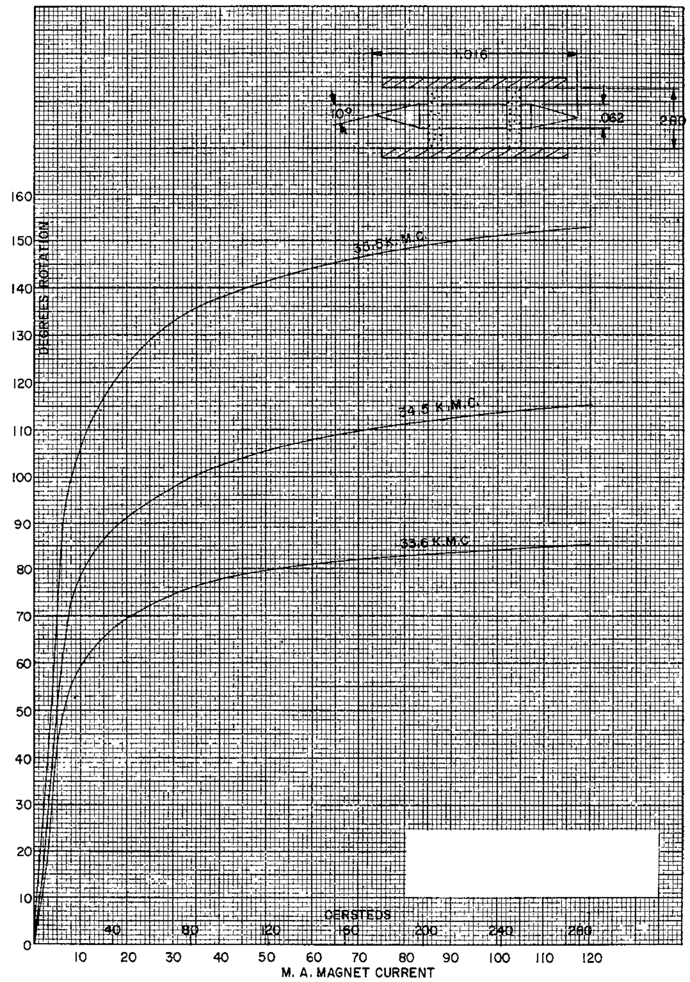

Fig. 6—Variation of rotation with frequency.

supported in a polyfoam cylinder. Erratic rotation, probably due to higher modes, was observed until the diameter was reduced to 0.154 inch. This is well shown by the crossover of the 0.154-inch and 0.1585-inch curves (Fig. 7, facing page), which is a plot of rotation versus magnetic field strength for various diameter ferrite rods of constant length. An inspection of this data shows the variation of rotation to be nearly linear with diameter over the range in which higher moding is absent.

Insertion losses varied from 0.1 to 0.6 decibel over this range. Voltage standing-wave ratios were in general about 1.2 and values of ellipticity varied from about 20 to 30 decibels over the range. Several checks were made of the variation of rotation with frequency at various diameters. One check at a diameter of 0.149 inch showed a 11 per cent change of rotation for a 1 per cent change of frequency, which agrees fairly well with the results obtained at 0.87 cm wavelength. One set of observations was taken with two ferrite rods 0.123 inch in diameter butted end to end to simulate one rod 2.656 inches in length with 10-degree tapers on the two free ends. This data showed about the same variation of ellipticity and rotation with frequency. It slightly improved standing-wave ratios, yielding a median value of 1.1.

A Unidirectional Transmission Line

A unidirectional transmission line has been constructed for a 0.87 cm wavelength. This device has a solenoid two inches in length wound with 5,000 turns of number 33 enamel wire on a 0.358-inch diameter cylindrical waveguide. A 10-degree tapered round ferrite rod 0.062 by 0.641 inch is supported by a single polystyrene foam washer in the cylindrical waveguide. A 45-degree rotation was obtained with a solenoid current of 20.6 ma at a frequency of 34.5 kilomegacycles. Fig. 8 (facing page) shows directivity and voltage standing-wave ratios as a function of frequency. The directivity is defined as the ratio between the forward and reverse transmissions of the device. Fig. 9, facing page, is a plot of directivity versus solenoid current. This unidirectional transmission line has been installed in a 0.87 cm wavelength radiometric receiver for field testing.

Conclusion

From the data obtained it seems entirely feasible to construct unidirectional transmission lines and other waveguide devices using ferrites at wavelengths of 0.87 and 1.9 cms. The use of ferrite loaded waveguide components achieves results that are unequaled in the lower

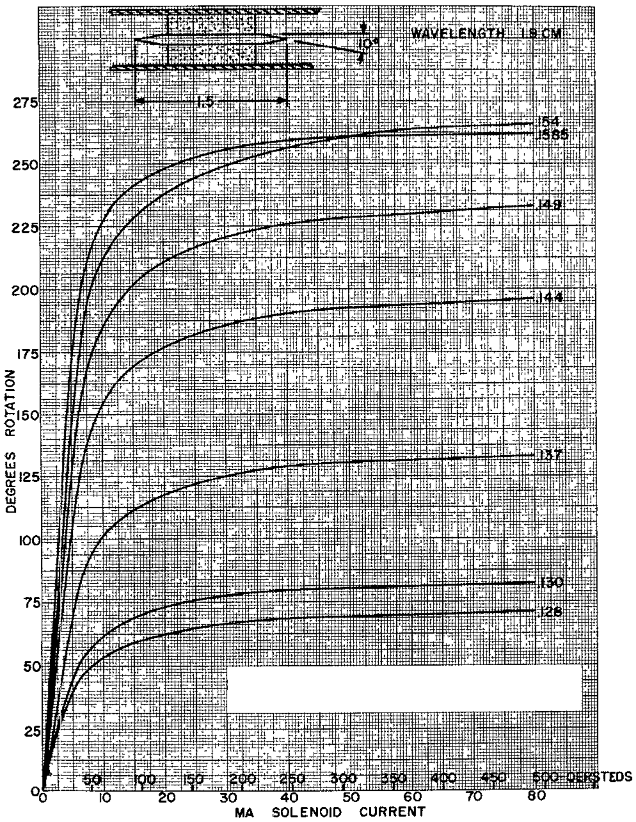

Fig. 7—Rotation vs magnetic field as a function of diameter in inches.

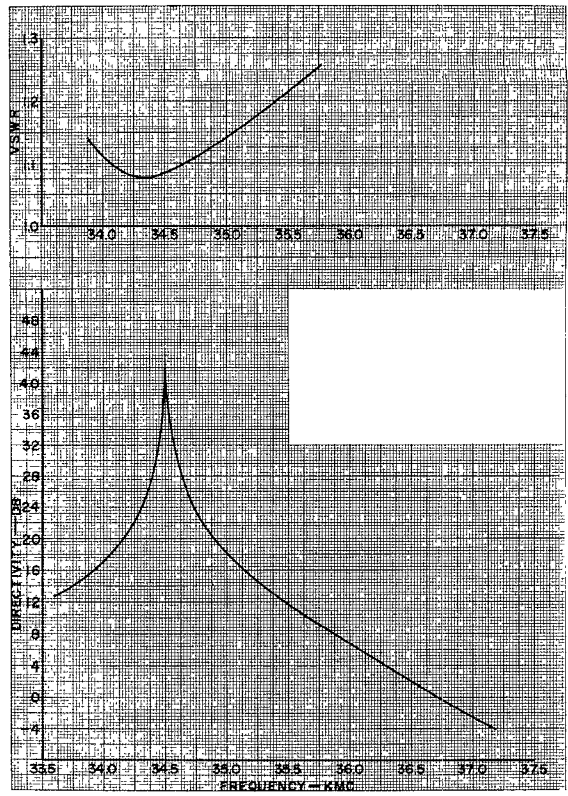

Fig. 8—Directivity and vswr as a function of frequency for a 0.87 cm wavelength unidirectional transmission line.

frequency domains. In a radiometric receiver it is possible, by the use of ferrite components, to relax the constructional tolerances on waveguide components without compromising the over-all performance of the receiver. These devices are reliable and introduce very small losses in microwave systems. Further investigations are in order to broadband these devices, still maintaining low losses and favorable standing-wave ratios.

Acknowledgment

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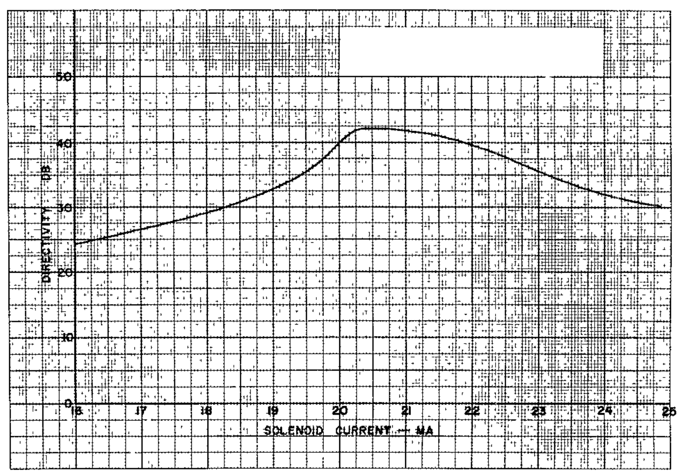

Fig. 9—Directivity vs solenoid current for 0.87 cm wavelength unidirectional transmission line.

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