Compact Microwave Single-Sideband Modulator Using Ferrites

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Summary—**This paper describes a single-sideband modulator for shifting the frequency of an x-band signal by means of a rotating magnetic field transverse to a ferrite differential half-wave section. The device is one of the first practical applications of the double-refraction properties of ferrites.**

Improvements over an earlier model include reduction in size and continuous operation without drift. An efficient and compact magnetic structure has been designed for producing the rotating magnetic field. Excessive heating of the ferrite and voltage breakdown of the coils is eliminated by a forced-air cooling system.

The modulator shifts the microwave-carrier frequency of 9375 mc by plus or minus 20 kc. With a rotating field of approximately 200 oersteds the microwave insertion loss is 1.0 db. The undesired sideband suppression is above 40 db while the carrier suppression is 23 db. For a frequency bandwidth of 500 mc, the insertion loss remains below 5 db.

WHEN A FERRITE is magnetized in a plane transverse to the direction of a propagating wave, the ferrite becomes birefringent. The principal axes are in the transverse plane and have a fixed orientation with respect to the magnetic field. By rotating a suitable transverse field about a round waveguide containing ferrite, a half-wave plate can be made to rotate in effect without any mechanical motion. One of the authors[1] has incorporated this use of a transversely magnetized ferrite in a phase shifter described by Fox[2] to obtain a shift of microwave frequency much larger than was previously possible. It is the purpose of this paper to describe a compact practical single-sideband modulator which shifts the frequency of an incident microwave signal by 20 kc.

The single-sideband modulator (Fig. 1) has an input section consisting of a transition from rectangular to round waveguide, followed by a quarter-wave plate which converts the plane polarized wave to clockwise circular polarization, which may be represented by a vector rotating clockwise f times per second.

The second section contains the transversely magnetized ferrite which acts like a half-wave plate. As the magnetic field rotates, the principal axes of the half-wave plate rotate n times per second. With respect to these rotating axes, the rotating vector representing the incident wave rotates f plus n times per second. The half-wave plate converts the clockwise wave to a counterclockwise wave. In transforming from the rotating axes of the second section to the stationary output section, another n rotations per second are introduced, so that the output has a frequency f plus $2n$.

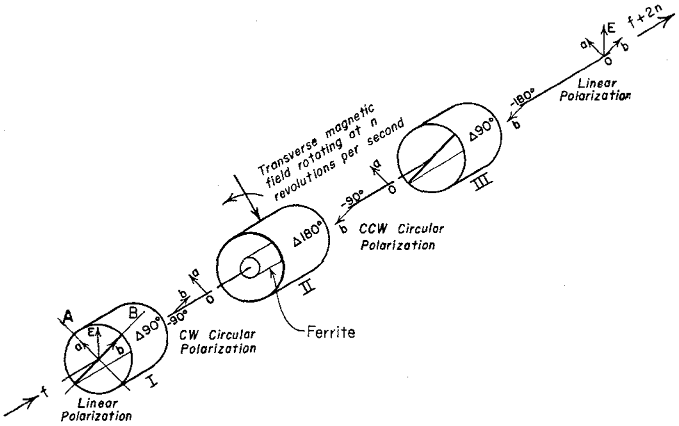

Fig. 1—Microwave single-sideband modulator.

Since the single-sideband modulator is symmetrical about a plane bisecting section II, a short circuit placed in this plane can replace the second half of the single sideband modulator. The output now appears as a reflection from the unit, with the frequency of the reflected wave shifted $2n$ cycles from the incident wave.

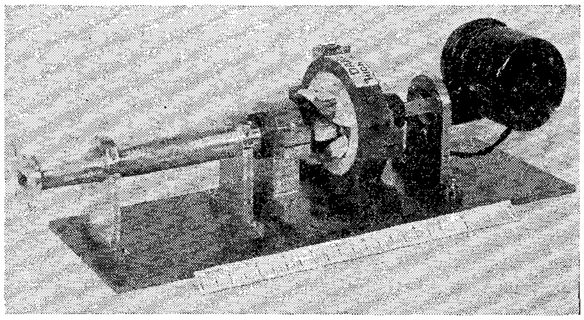

Fig. 2—Microwave single-sideband modulator (reflection type).

Fig. 2 is a photograph of a compact modulator employing the principle above to obtain a 20-kc frequency shift. A rotating magnetic field is produced by two perpendicular magnetic fields excited 90° out of phase. The two phase magnet structure is similar to those used as deflection coils for cathode ray tubes. Pancake coils are bent to fit around the waveguide. A return path is provided for the magnetic flux by an outside ferrite yoke. The short circuit is a sliding plunger which is positioned by a plastic screw. The entire magnet assembly is mounted on a rigid base plate to prevent de-

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[1] J. C. Cacheris, "Microwave single-sideband modulator using ferrites," PROC. IRE, vol. 42, pp. 1242–1247; August, 1954.

[2] A. G. Fox, "An adjustable waveguide phase changer," PROC. IRE, vol. 35, pp. 1489–1498; December, 1947.

formation of the circular waveguide. The magnet coils are cooled with a small blower. In addition, a small hole in the short plunger, together with vents, permits cooling air to move past the ferrite inside the waveguide.

An important feature of the single-sideband modulator is that the half-wave section may deviate appreciably from a differential phase shift of 180° without introducing appreciable loss or spurious signals. Fig. 3 shows the effect on an incident clockwise circularly polarized wave of a differential section which differs from a half-wave plate by $\theta°$. The two linearly polarized components of the input circular wave, vectors E_x and E_y, after transmission through a $180°-\theta$ section, have a relative time phase $90°-\theta°$. Each of these vectors may be resolved into time quadrature components as shown. The output vector E_{x1} and E_{y1} produce the desired counterclockwise wave of amplitude cos $\theta/2$ and the remaining vectors E_{x2} and E_{y2} form an undesired clockwise wave. As a result, the desired power varies as $\cos^2 \theta/2$ which very slowly departs from unity as the center section departs from a half-wave plate. For example, for a differential phase shift of 135° (instead of 180°) a loss of only 0.7 db is produced. For the dashed curve of Fig. 4, the differential phase shift was measured as a function of frequency, and the relative power in the counterclockwise wave calculated. The solid curve showing the measured conversion loss is the ratio of shifted frequency reflected power to the input power. This shows that the bandwidth is limited primarily by the variation of differential phase shift with frequency. The undesired circularly polarized wave produced is almost completely attenuated by the input section. Fig. 5 shows that a suppression of the undesired component of 25 db is obtained over the band. The purity of the output is made primarily dependent on the input section, and permits the ferrite half-wave plate to be uncritical.

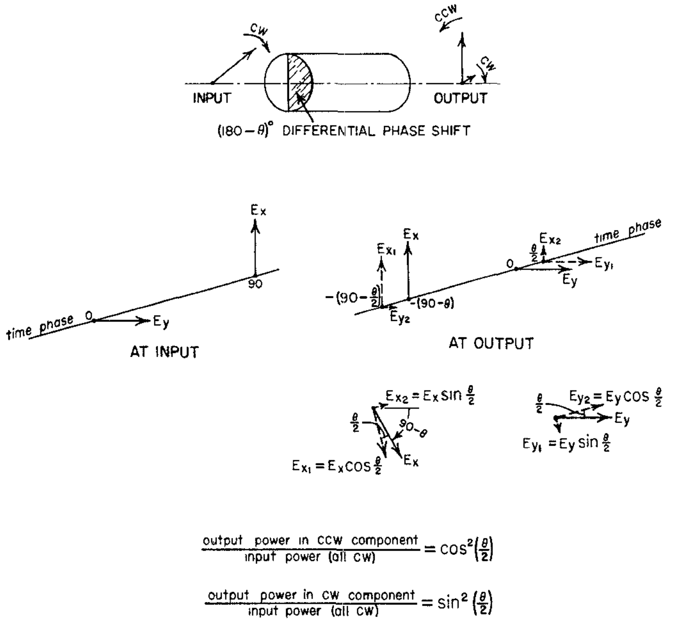

Fig. 3—Effect of imperfect half-wave plate on circularly polarized input.

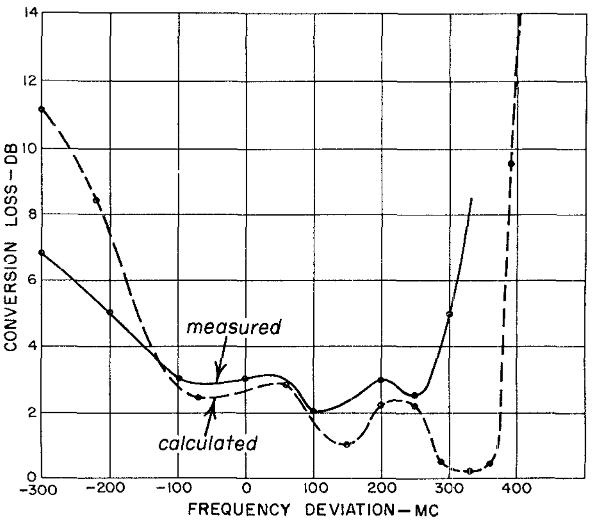

Fig. 4—Conversion loss calculated from differential phase shift compared with measured conversion loss.

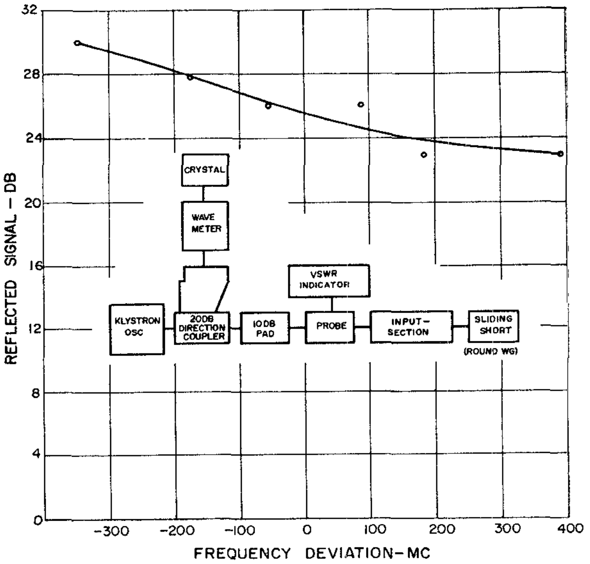

Fig. 5—Suppression of clockwise circular wave by input section.

The principal problem in the practical attainment of single-sideband modulation is to achieve the required differential phase shift with a sufficiently small applied magnetic field. A field of 230 oersteds across the $1\frac{1}{8}$-inch air gap presented by the waveguide requires 25 watts at 10 kc for each of the crossed magnetic fields. This represents the greatest power available without cumbersome power amplifiers, and also approaches the heat dissipating capacity of the coils. By using a tuned class C output stage, the two channels required for the crossed magnetic fields, together with the oscillator, phasing network, and power supply are mounted on one 7-inch high standard rack mounting chassis.

The Polder[3] equation for an infinite plane wave propagating through lossless ferrite magnetized transversely to the direction of propagation predicts that for the two polarizations the differential phase shift per unit length is given by

$$\frac{\Delta\phi}{l} = \frac{57.3(\epsilon_r)^{1/2}\gamma^2 B M_s}{2c\omega}$$

where ϵ_r is the dielectric constant, c the velocity of light, and the gyromagnetic ratio $= 2.8 \times 10^{-6}$ sec^{-1} oersted^{-1}. At a frequency $f = \omega/2\pi$ of 10,000 mc, for a ferrite having a saturation magnetization M_s of 1700 gauss, and with a field H of 200 oersteds, this equation predicts about 2° of differential phase shift per inch. Experiments show that differential phase shifts of 180° are obtained with a field of 200 oersteds. However, the actual propagation is through a cylindrical waveguide containing a large tapered ferrite cylinder inhomogenously magnetized, filling $\frac{1}{4}$ of the waveguide cross section, followed by a short circuit. Although a theoretical analysis of this geometry is impracticable these large differential phase shifts may be qualitatively ascribed to multiple reflections and higher order modes existing in the ferrite sample. Fig. 6 shows the variation of conversion loss and audio power with field excitation. Also shown are air-gap-flux density and differential phase shift. (The differential phase shift is actually somewhat greater because of temperature difference.) At approximately 200 oersteds, indicated as the operating level, a compromise between least insertion loss and least audio power is reached.

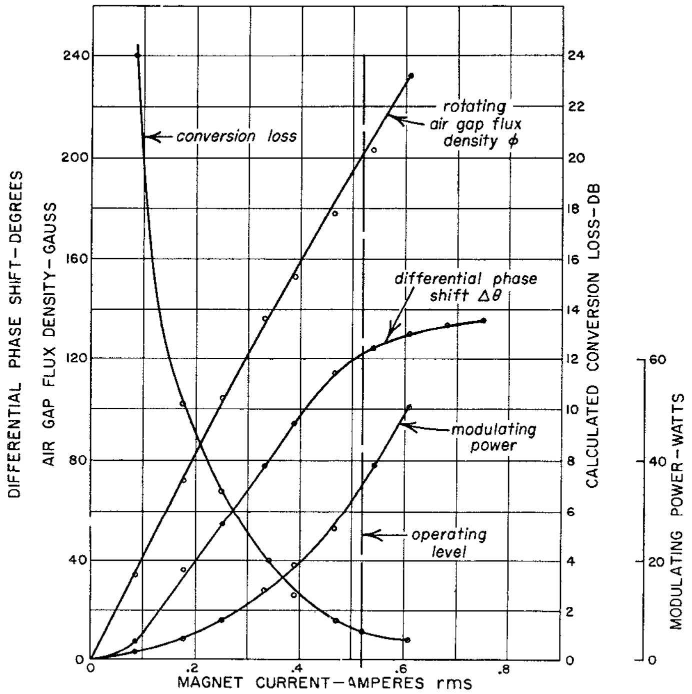

Fig. 6—Characteristic of single-sideband modulator as a function of magnet excitation.

In the absence of an adequate theory, the optimum ferrite geometry must be determined experimentally. Rather than make static differential phase measurements, the modulator itself was used to test the ferrite. In addition to increasing the speed and accuracy of measurement, this arrangement has the advantage of testing the ferrite in the environment of temperature and magnetic field distribution in which it is to be used. Fig. 7 is a block diagram of the setup. With the klystron frequency and power monitored, the principal signal proceeds through a precision coupler and is reflected and shifted in frequency by the modulator. The shifted frequency signal is detected in the signal crystal arm. A calibration, effected by substitution of a short circuit at *, permits the conversion loss to be read directly from settings of the calibrated variable attenuator.

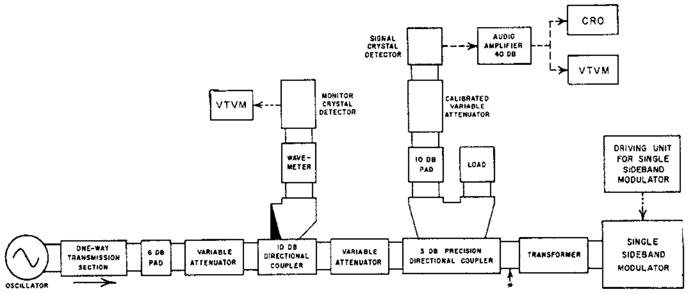

Fig. 7—Experimental arrangement for measurement of conversion loss and spurious signal suppression.

Fig. 8 shows the reduction of the bandwidth when the magnet excitation is reduced. It can be seen that the flux may be reduced 25 per cent, and consequently the power 50 per cent, if a reduced bandwidth of 350 mc is acceptable. Also, it is clear that the operation of the single-sideband modulator is in no sense critically dependent on driving current.

Variations of 1/10 inch in dimensions of the ferrite sample are sufficient to alter completely the differential phase obtainable. A number of cylinders and tapered cylinders held promise of having broadband phase shift. For several of these geometries, small dimensional variations were made to maximize the bandwidth. Essentially similar results are obtained for these various geometries. Fig. 9 shows that changes of a few thousandths of an inch in the cylinder length (t) are significant in changing the shape and the location of the conversion loss curve along the frequency axis. Despite this strong dimensional dependence, the phase properties are stable and repeatable.

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[3] D. Polder, "On the theory of ferromagnetic resonance," *Phil. Mag.*, vol. 40, pp. 99–115; January, 1949.

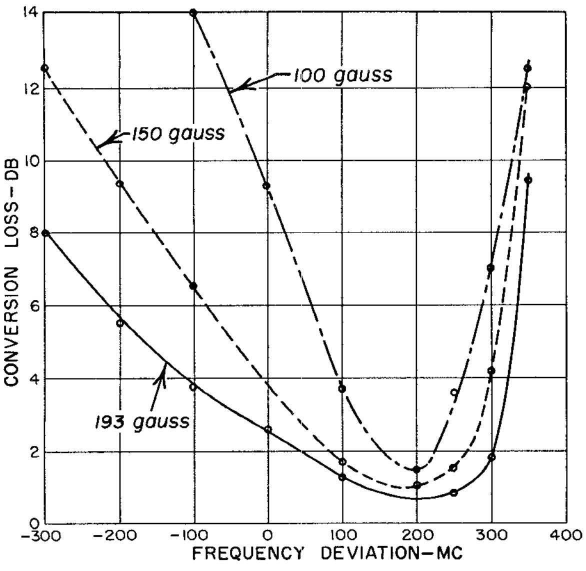

Fig. 8—Variation of conversion loss characteristic with magnetic field strength.

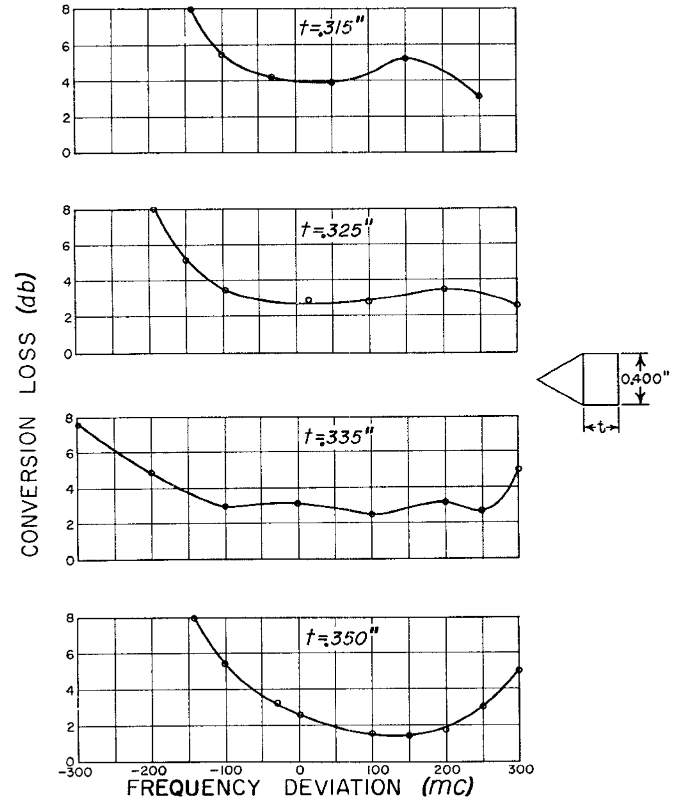

Fig. 9—Variation of conversion loss characteristic with cylinder length.

The frequency response of the reflection-type single-sideband modulator is shown in Fig. 10. The conversion loss has a minimum of about 2 db and over a 500 mc band, remains below 5 db. By adjustment of the short circuit, the minimum insertion loss can be reduced to less than 1 db, with some narrowing of the frequency response. The frequency at which the minimum loss is obtained can be shifted anywhere within the 500 mc range by the single adjustment of the short circuit plunger.

So far, the principal interest has been directed toward the conversion loss. A second important property is the suppression of undesired frequency components. The largest undesired frequency component is the unshifted signal, which is recognizable as a 20 kc envelope on the signal reflected from the modulator. The power level of the signal is determined from the relative beat amplitude, and is plotted in Fig. 10. This signal may be matched out with a transformer. Other spurious frequency components will be produced by any imperfection in the clockwise filtering action of the input section when the central section does not provide 180° phase shift. Also, it is likely that any departure from axial symmetry and any nonuniformity in the rotation of the magnetic field will produce higher order sidebands. These remain after the unshifted signal has been matched out. The power level represented by the assumption of an equivalent single frequency for these residual signals is also shown in Fig. 10.

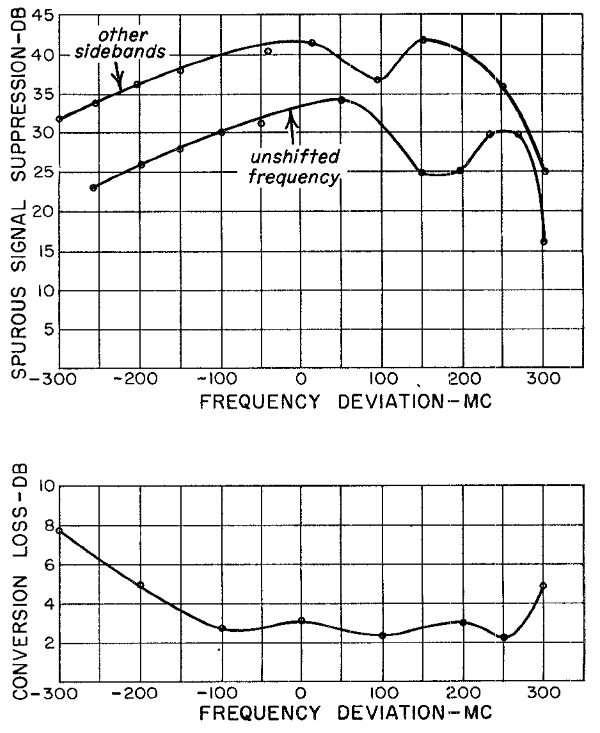

Fig. 10—Operating characteristics of compact reflection type single-sideband modulator.

The reflection-type single-sideband modulator described in this report is a compact, conservatively rated, trouble-free device. Over a 500-mc bandwidth, it has given reliable operation as an x-band 20-kc frequency shifter.