A Ferrite Serrodyne for Microwave Frequency Translation*

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Summary—**A ferrite serrodyne has been developed to produce a frequency translation of *X*-band microwave signals over ranges from zero to 50 kc. The device consists of an efficent longitudinal field ferrite phase shifter and an associated electronic driver for generating the modulating sawtooth. Transmission or reflection operation is possible. A conversion loss of 1 to 2 db is obtained. Suppression of spurious output spectral components is 33 db or more for a 10-kc translation and 21 db for a 50-kc translation.**

Introduction

THIS PAPER discusses the theory, design, development, construction, and performance of a ferrite serrodyne for translations of *X*-band microwave signals from 0 to 50 kc. It consists of an efficient longitudinal field ferrite phase shifter and associated electronic drive circuitry necessary to produce a periodic sawtooth of phase shift. These components are described in detail.

Theory

The term, serrodyne, was coined to describe a class of modulators which can cause frequency translation by sawtooth transit time modulation of a signal. When used a bit more generally, this term also includes frequency translators using a sawtooth of phase modulation. A comprehensive analysis of serrodyne operation employing transit time modulation (TTM) has already been accomplished by Cumming,[1] and various successful serrodyne devices employing klystrons, TWT and microwave crystal modulators[2] have been described. The performance of the ferrite serrodyne discussed here is in terms of the criteria established by Cumming. A brief comparison is made between the TTM and phase modulation points of view. The phase modulation approach appears to be the more appropriate formulation for the particular device discussed in this paper although TTM formulations are adequate to describe the small frequency translations encountered here.

Consider a wave disturbance propagating along a transmission line of length, l, with the usual spatial and time variation, expressible as

$$E = E_1 \sin (\omega t - \beta z). \tag{1}$$

A frequency translation may occur at the output of this line in either of two ways; first, by a phase modulation. Consider a change in βz such that

$$\frac{d}{dt} (\beta l) = \text{constant} = \omega_m. \tag{2}$$

If βl is considered here as supplying a particular phase angle relative to the ωt variation for a signal emerging from the given length l of the transmission line, and $d(\beta l) = \omega_m dt$ as postulated, then it is evident that frequency translation has taken place under this phase modulation. A constantly increasing phase angle added to a sinusoid displaces its frequency.

$$E_{\text{out}} = E_1 \sin (\omega t - \omega_m t), \tag{3}$$

$$E_{\text{out}} = E_1 \sin (\omega - \omega_m) t. \tag{4}$$

A displacement to a higher frequency may be had simply by changing the sign of $d/dt(\beta l)$. For the ferrite serrodyne discussed here, β is varied as a sawtooth function under the influence of an external applied magnetic field. Linear increase (or decrease) of β with time by 360 degrees followed by rapid flyback is used to achieve results similar to a continuously increasing β.

A second way to secure frequency translation is by the TTM of individual successive wave periods. Following the theory developed by Cumming, let a wave incident upon the input of the transmission line section be broken into periodic intervals and represented as follows.

$$E_{\text{in}} = \sum_{k=1}^{\infty} E_1 \sin \omega \left(t - \frac{2\pi k}{\omega} \right)$$

when

$$(2k - 1) \frac{\pi}{\omega} \leq t \leq (2k + 1) \frac{\pi}{\omega} \tag{5a}$$

$$E_{\text{in}} = 0$$

when

$$t < (2k - 1)\pi/\omega$$

$$t > (2k + 1)\pi/\omega. \tag{5b}$$

[See Fig. 1(a) and 1(b).]

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[1] A general theory of serrodyne operation has been developed by R. C. Cumming and presented in two reports. "Frequency Translation by Modulation of Transit Time Devices," Applied Electronics Lab., Stanford Univ., Stanford, Calif., Tech. Rep. No. 39, ONR Contract N6 onr 25132, NR 373 762; August 1, 1955. "The serrodyne frequency translator," PROC. IRE, vol. 45, pp. 175–186; February, 1957.

[2] E. M. Rutz and J. E. Dye, "Frequency translation by phase modulation," 1957 IRE WESCON CONVENTION RECORD, pt. 1, pp. 201–207.

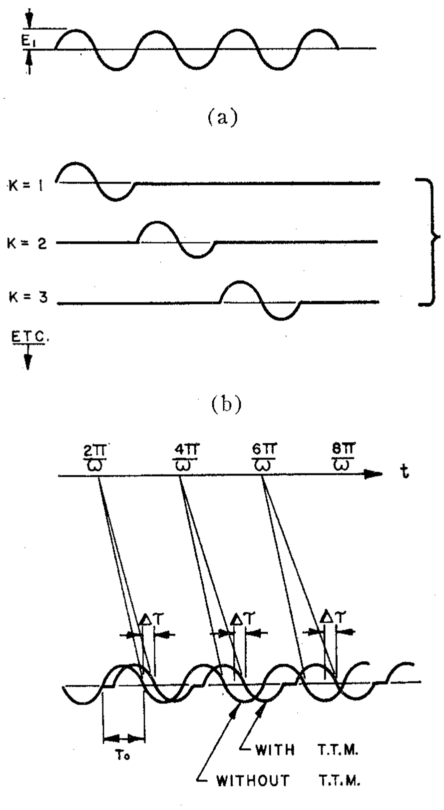

Fig. 1—Transit time modulation.

In the absence of any TTM, the wave emerging at the output of the transmission line section may be represented as

$$E_{\text{out}} = \sum_{k=1}^{\infty} E_1 \sin \omega(t - t_k)$$

when

$$t_k - T_0/2 \le t \le t_k + T_0/2 \tag{6a}$$

$$E_{\text{out}} = 0$$

when

$$t < t_k - T_0/2$$
$$t > t_k + T_0/2 \tag{6b}$$

where T_0 is the output wave period, $t_k = 2\pi k/\omega + T_k$, and T_k is the transit time of the kth wave period. Here, $T_k = T_0 = l/v = \beta l/\omega$; for t as in (5a):

$$E_{\text{out}} = \sum_{k=1}^{\infty} E_1 \sin \left[\omega \left(t - \frac{2\pi k}{\omega} \right) - \beta l \right] \tag{7}$$

has the form to be expected.

Now introduce an ideal TTM in which a constant interval ΔT_k is added to the transit time of each successive disturbance, so that

$$t_k = \frac{2\pi k}{\omega} + T_0 + \sum_{k=1}^{\infty} \Delta T_k. \tag{8}$$

In this way the period of the output signal disturbance becomes longer than the input signal periods:

$$T_{\text{out}} = T_{\text{in}} + \Delta T_k = \frac{2\pi}{\omega} + \Delta T_k, \tag{9}$$

$$\omega_{\text{out}} = \frac{2\pi}{\dfrac{2\pi}{\omega} + \Delta T_k} = \frac{\omega}{1 + \dfrac{\Delta T_k}{T_{\text{in}}}}. \tag{10}$$

[See Fig. 1(c).] This frequency translation has been accomplished by maintaining the pure sinusoidal form of the output disturbances, but there is now a short, blank interval between them. This distortion limits the validity of the TTM analysis, but a Fourier analysis of the output wave train shows that if $\Delta T_k/T_{\text{in}} \ll 1$ the TTM formulation is sufficiently accurate.[3]

Physical limitations of most modulating devices preclude infinite changes in transit time or phase shift as have been described. However, a sawtooth of transit time variation or of phase shift may be used as an approximation to infinite continuous change. A spectrum of frequencies periodically spaced about the carrier at the sawtooth modulation frequency may be generated. The amplitude of the sawtooth is carefully chosen so that the periodic signal disturbances from one interval coincide with an extension of those disturbances from the preceding modulation interval and also into the following intervals. The resulting phase coherence insures that most of the output signal energy appears in one sideband adjacent to the carrier. The flyback discontinuity produces a perturbation in the output wave train. For the ideal case of zero flyback interval and for relatively small frequency displacements, this perturbation has negligible effect on the output spectrum since signal energy associated with it is negligible. Carrier and translated frequencies are related as follows.

$$f_o = f_i + n f_m \tag{11}$$

where f_o is the output frequency; f_i, the input frequency; f_m, the modulation frequency; and n, an integer and modulation index, usually is taken equal to one.

Structure of the Ferrite Serrodyne

The type of device presented here consists of an efficient longitudinal field ferrite phase shifter driven by a

[3] For ΔT_k negative, the output signal function as constructed would be double valued where the signal intervals overlap. However the analysis is still valid since the amplitude and relative phase of an element in the output signal spectrum is the product of two separate frequency functions; one is a function only of the TTM employed and the other, a function only of the input waveform. Cf. Cumming, *op. cit.*, p. 13.

If the signal disturbances considered do not have waveforms filling the entire signal periods, but instead have a pulse character with a short duty cycle, the TTM analysis again becomes more accurate. This is the case treated by Cumming in his extended analysis of the serrodyne, where he developed the theory for particular application to klystrons and TWT. From the foregoing considerations it can be seen that a ferrite serrodyne is more accurately considered as phase modulated in the sense described above (in contrast to the definition of phase modulation employed by Cumming) rather than transit time modulated, but that for small time displacements per signal period, *i.e.*, relatively slight frequency translations, the TTM analysis is sufficiently accurate to be useful.

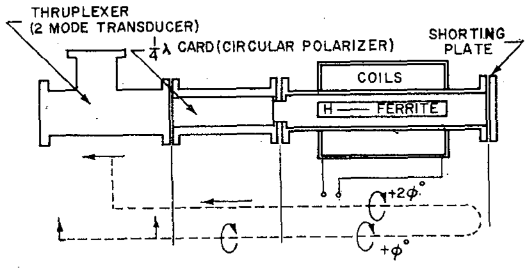

Fig. 2—Cross-polarized phase shifter (transmission-type thruplexer serrodyne).

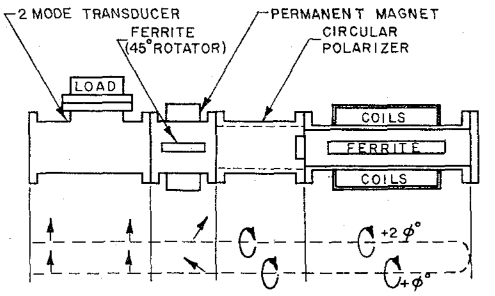

Fig. 3—Electrically controllable short circuit (reflection-type thruplexer serrodyne).

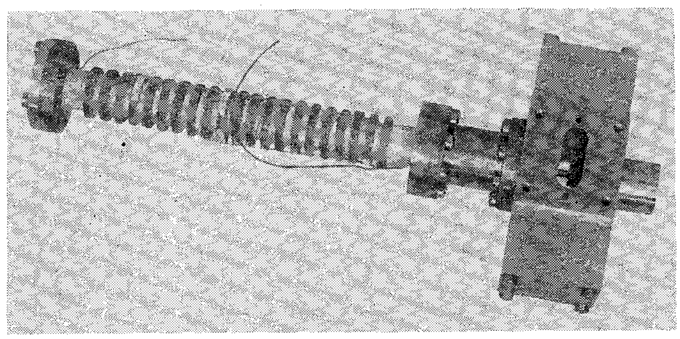

Fig. 4—Turnstile serrodyne.

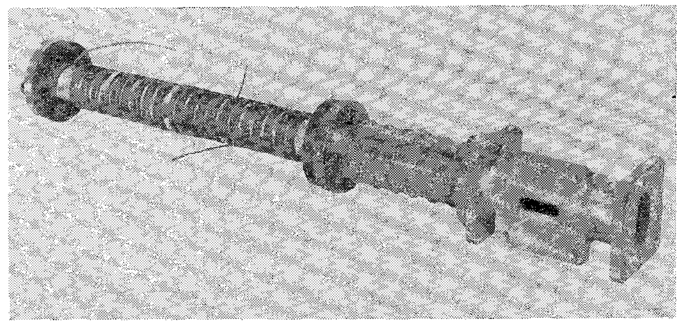

Fig. 5—Transmission-type thruplexer serrodyne.

current sawtooth generator to produce the required sawtooth of phase shift in a microwave transmission line. The phase shift is accomplished by varying the phase propagation constant of a ferrite loaded waveguide under the influence of the changing magnetic field. Several microwave configurations are possible, permitting the translated signal to be either transmitted through the device or reflected back along the line supplying the incident carrier. One such transmission device consists of a thruplexer,[4] quarter-wave plate, ferrite line section, and a shorting plate.[5] (See Fig. 2 and Fig. 5.) A linearly polarized carrier signal enters the thruplexer and in passing through the quarter-wave plate is converted to a circularly polarized wave. It then travels down and back through the ferrite phase shifter where it experiences the sawtooth phase modulation. After traversing the circular polarizer again, the emerging microwave signal is converted back to linear polarization in a plane perpendicular to the incident carrier and, therefore, leaves the thruplexer by its side port. This constitutes a transmission serrodyne. The magnetic modulating field is applied to the ferrite so that the sense of the circularly polarized wave in the ferrite and that of the current producing it is always the same, *i.e.*, the wave propagates with the same β ($\beta+$ as defined by Hogan[6]) during the round trip through the phase shifter. This insures maximum phase sensitivity for a given applied magnetic field permitting a minimum amplitude for the driving current sawtooth.

A reflection serrodyne is easily obtained from this transmission unit by inserting a 45-degree ferrite rotator between the thruplexer and the quarter-wave plate. (See Fig. 3.) The carrier is rotated 45 degrees before reaching the quarter-wave plate. After emerging from the quarter-wave plate in the return direction polarized perpendicular to the incident carrier, the translated signal is again rotated 45 degrees in the same direction as before and leaves coplanar with the carrier, thus producing a reflection serrodyne.

A different microwave configuration also is suitable for service as a serrodyne. It consists of a turnstile junction that has the ferrite line section attached to the round arm and two short circuits set in the side arms.[7] (See Fig. 4.) If the differential path length of the two shorted arms is $\lambda g/4$, and the length of one arm is an odd number of eighth wavelengths, then a signal entering at the input of the turnstile is transmitted up the round arm circularly polarized. After traversing the ferrite line section and experiencing the sawtooth modulation, the translated signal is converted back to linear polarization and passes to the output of the turnstile. Here again, we have a transmission-type serrodyne. This unit may be more compact than the thruplexer quarter-wave plate design, but it is inherently a more narrow band circular polarizer than an inductive-capacitive iris-type quarter-wave plate. (See Fig. 5.)

[4] Orthogonal mode transducer.

[5] H. Scharfman, "Three new ferrite phase shifters," Proc. IRE, vol. 44, pp. 1456–1459; October, 1956.

[6] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications," *Bell Sys. Tech. J.*, vol. 31, pp. 1–31; January, 1952.

[7] M. A. Meyer and H. B. Goldberg, "Application of turnstile junctions," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 40–44; December, 1955.

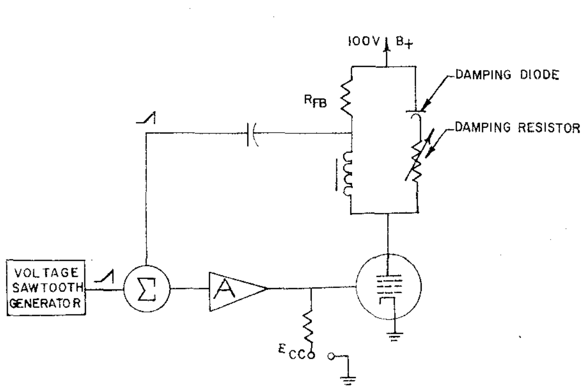

Fig. 6—Schematic diagram of modulator.

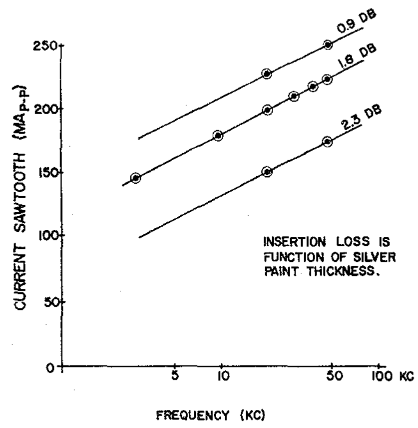

Fig. 7—Driving current vs frequency for various silver paint thicknesses (measured by insertion loss of serrodyne).

Construction Details

The ferrite phase shift section used here consists of six inches of *R*-1 ferrite 0.240 inch in diameter inserted concentrically in a 0.625-inch-diameter rexolite rod with brass flanges attached to its ends. The rexolite is lightly silver painted to form a thin walled waveguide with negligible shorted turn effect to the modulating coil outside.

This modulating coil, multiple-pie wound for low distributed capacity, has 1050 turns over 5 inches and is so connected as to have an inductance of 2.5 mh. Low inductance and stray capacity for a given number of ampere turns are important in securing rapid flyback, a crucial parameter for good serrodyne performance, since the flyback interval is one half the self-resonant period of the coil. A dc coil to compensate a direct current component in the modulating signal is used to set the magnetic operating level in a region of linear phase shift; it is wound on a $1\frac{3}{4}$-inch phenolic tube and slipped over the rest of the phase shifter. A rexolite button matches the ferrite line to 0.875-inch round waveguide with a VSWR under 1.2 across a $2\frac{1}{2}$ per cent band at *X* band.

The sawtooth current generator used here is variable in both frequency and amplitude from 500 cps to 50 kc and from zero to 400 milliamperes peak to peak. It consists of a high perveance driver driving the diode damped modulator coil. The current sawtooth is generated through a current feedback loop controlled by a variable voltage sawtooth generator. (See Fig. 6.) Sawtooth drive current required increases linearly from 145 ma pp at 3000 cps to 225 ma pp at 50 kc. (See Fig. 7.) Total modulator power consumption is 60 watts plus tube heater power.

A useful drive power index is the driver tube plate dissipation, here about 25 watts. However, acceptance of some performance degradation permits circuit simplification requiring less than 5 watts of drive power. A current sawtooth may be generated by merely impressing a large voltage spike across the coil and allowing it to integrate its own current sawtooth.

Performance

For measuring the serrodyne performance, two quantities have been examined. The first is a video waveform obtained from a crystal detector by mixing some of the translated output signal with some of the incoming carrier. (See Fig. 8.) The second is the output spectrum of the translated signal. The video waveform provides an indication of the fractional flyback time and of any distortions that may be present in the sawtooth of phase shift. Correlation of this waveform with the driving current sawtooth indicates that the phase shifter is a very linear device, and that whatever distortion may be present is due primarily to a nonlinear current sawtooth. [See Fig. 9(a) for a sketch of a typical trace.] An adjustable phase shifter is included in the detector circuit so that the flyback perturbation may be moved along the video waveform and the entire wave shape examined for distortion.

The output spectrum contains the following components. First, the translated output signal that is displaced by the modulation frequency either above or below the carrier depending on the sign of the phase shift sawtooth. This signal, designated as the desired sideband (or merely as the sideband), is used as the reference power level for measuring the relative power levels of the other spectral components. Some carrier is present also. The first spectral element on the other side of the carrier has been designated the image sideband, and additional sidebands on this same side of the carrier are called higher order sidebands. The amplitude of these depends primarily on the fractional flyback time. The maximum amplitude of this group of sidebands is displaced considerably from the carrier. [See Fig. 9(b).] Higher sidebands on the same side of the carrier as the desired sideband are called higher harmonic sidebands, *e.g.*, second harmonic and third harmonic sidebands. These are influenced principally by sawtooth waveform distortion, by incorrect sawtooth amplitude, *i.e.*, phase shift per sweep $\neq 360$ degrees, and by an amplitude modulation of the residual carrier or of the sideband it-

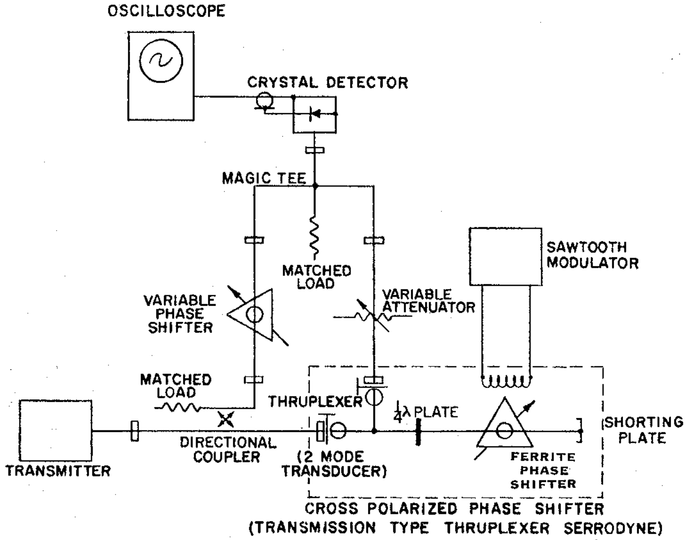

Fig. 8—Ferrite serrodyne measurement diagram.

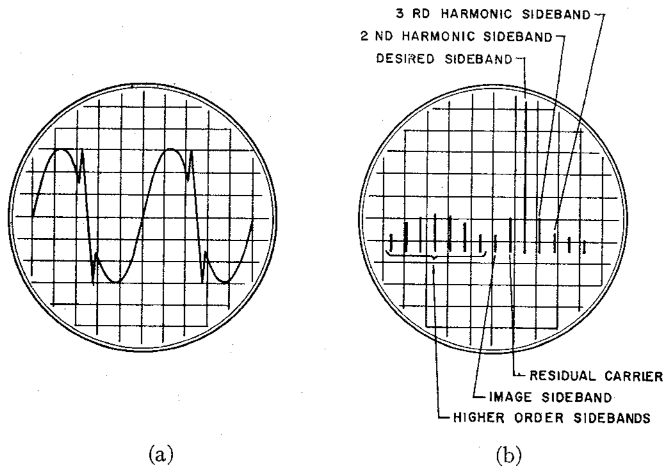

Fig. 9—(a) Oscillogram of typical detected video waveform. (b) Oscillogram of typical microwave spectrum.

self present due to imperfection in the circular polarizer. The sawtooth amplitude is a critical operating parameter. It may be set by optimizing the output spectrum, or in the case where the available spectrum analyzer has insufficient resolution, by adjusting the video wave form to have equally spaced maxima and minima. The preceding designations for the various spectral components are quite arbitrary, but necessary since the spectrum is reversible about the carrier depending upon the sense of the sawtooth drive.

Performance criteria are conversion loss and suppression of undesired spectral elements relative to the desired translated frequency component. Conversion loss is due primarily to the phase shifter insertion loss—between 1 and 2 db for different units (see Fig. 7). Translation loss, due to the energy content of the rest of the spectrum consequent upon the serrodyne modulation, never exceeded 0.5 db; this agrees with theoretical prediction. Conversion loss $= 20 \log (1-F)$ where F is the fractional flyback time. Suppression of spurious sidebands depends strongly on the optimum amplitude of the modulation sawtooth for given modulation and microwave frequencies, and also on the sawtooth retrace interval. For typical results obtained with a transmission-type serrodyne using a thruplexer and quarter-wave plate see Table I. In spite of low carrier rejection resulting from a circular polarizer with 1 db of ellipticity, the unwanted sideband suppression achieved agrees very well with the comparable theoretical values given by Cumming.

Somewhat better performance was obtained using a turnstile junction to replace the thruplexer and circular polarizer as shown in Table II. Although the ellipticity was 0.3 db, the carrier suppression was limited by the input to output isolation of the turnstile which was only 24 db.

Performance Limitations

The ferrite serrodyne limitations arise from the minimum attainable flyback time consistent with allowable driver plate dissipation from the modulation standpoint. On the microwave side, maximum thruplexer isolation, minimum circular polarizer ellipticity, and maximum phase shift sensitivity must be kept consistent with allowable size. A 2-microsecond flyback was attainable with 25 watts of driver plate dissipation with the structure described. A flyback time of the order of 0.5 μsec with 100 watts of driver plate dissipation appears possible. This would make operation up to 100-kc frequency translation feasible with a 5 per cent flyback and, correspondingly, about 25 db suppression of unwanted sidebands. Thruplexers are readily made with isolation greater than 50 db but ellipticity of the circular polarizer and the match looking from the polarizer into the ferrite phase shift section limits the carrier rejection. Taking 30 db as an acceptable carrier rejection, the polarizer must have less than 0.4-db ellipticity and the VSWR from polarizer into ferrite section must be less than 1.05. At X band the resulting thruplexer, polarizer, and ferrite phase shifter would be about 15 inches long.

The microwave bandwidth of such a device is largely limited by match and ellipticity considerations of the circular polarizer. The 15-inch structure indicated above could probably give greater than 20-db carrier rejection over about a 10 per cent band at X band. Adjustments of dc bias and ac drive would be required to get greater than 20-db carrier and sideband rejections at 100-watt drive at 100-kc translation frequency across the 10 per cent band. Conversion efficiency including microwave losses should be about 2 db.

Comparison with Other Methods of Single-Sideband Generation

Other types of single-sideband generators use transit

TABLE I
PERFORMANCE FOR THRUPLEXER SERRODYNE

Modulation Frequency kc	Current Sawtooth ma pp	Second Harmonic Suppression db	Carrier Suppression db	Image Sideband Suppression db	High-Order Sideband Suppression db	Flyback Time μsec	Fractional Flyback Time F	Cummings' Theoretical Suppression
3	140							
10	180	33	33	>35	33	2.0	0.02	34
20	195	28	28	33	26	2.2	0.044	27
30	216	24	20	>30	23	2.0	0.06	24.5
40	220	—	25	25	22	2.0	0.08	22
50	225	21.5	21.5	28	20.6	2.0	0.1	20

TABLE II
PERFORMANCE FOR TURNSTILE SERRODYNE

Modulation Frequency kc	Current Sawtooth ma pp	Second Harmonic Suppression db	Carrier Suppression db	Image Sideband Suppression db	High-Order Sideband Suppression db	Flyback Time μsec	Fractional Flyback Time F	Cummings' Theoretical Suppression
20	200	21	20	31	31	2.2	0.044	27
30	216	27	21	33	27	2.0	0.06	24.5

time modulation of TWT and klystron characteristics as well as pairs of balanced modulators (ferrite and/or crystal) in complex microwave bridge circuits. In general, their operation and performance characteristics are not readily comparable with the ferrite serrodyne. The ferrite serrodyne is most directly comparable with the continuously rotating half-wave plate using ferrite first described by Cacheris.[8] Performance characteristics in terms of conversion loss, carrier rejections, and sideband rejection are similar. The ferrite serrodyne does appear to be somewhat smaller, lighter, less complex, and requires less driving power.

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

CONCLUSIONS

A ferrite single-sideband generator or frequency translator has been discussed. Its theory of operation, construction details, design parameters, and performance characteristics have been reviewed. Satisfactory operation up to 50 kc of frequency translation has been reported with good correlation to theoretical treatment. Operation up to 100 kc of translation over 10 per cent of X band with 20 db of carrier and sideband rejection and conversion loss under 2 db seems feasible.

ACKNOWLEDGMENT

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