Some Characteristics of Microwave Balanced Modulators*

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Summary—**Microwave modulator characteristics pertinent to two state balanced modulation are discussed. An equivalence between balanced modulation and phase modulation is shown for rectangular modulation waveforms and experimental results are described. The characteristics of a tuned hybrid tee, untuned hybrid tee and novel circulator type of balanced modulator are compared. *X*-band measurements show that a carrier rejection of 70 db and modulator loss of 3 db can be achieved with carrier levels up to several hundred milliwatts. The carrier rejection of an untuned modulator is dependent on crystal match and data showing dependence of the match on orientation and temperature are presented.**

MICROWAVE balanced modulators are used primarily to generate double sideband, suppressed carrier signals and to generate a signal of accurately known frequency offset from a given microwave carrier. The devices most feasible from the point of view of high-modulation rates employ microwave crystal diodes in combination with waveguide transmission components. This paper discusses modulator characteristics when the modulation signal is of binary form and the diode bias is switched from forward to reverse. Waveforms typical of this type of modulation are symmetrical square wave, rectangular periodic and rectangular pseudorandom. Many applications using sinusoidal modulation approach the above when the modulation amplitude and source impedance cause the diode to be operated essentially in a switching mode. This is evidenced by a modulator output spectrum which is rich in higher order sidebands even though the modulation waveform is sinusoidal. Experimental work was carried out at X band.

Balanced and Phase Modulation Equivalence

The conventional balanced modulator is a device in which the modulation signal and carrier are combined in such a way as to cancel the carrier component and reinforce the sideband components. This may be illustrated by the usual rotating phasor diagram shown in Fig. 1. Now for the particular case of a rectangular wave form representative of two states, the resultant phasor is either full up or full down depending on the modulation state [Fig. 1(b)]. For this case there is an equivalence between phase modulation and balanced modulation. The rotating phasor representation for phase modulation is shown in Fig. 2. For the particular case of a rectangular modulation waveform and a phase modulation index of $\pi/2$ the equivalence is shown in the figures. It can be shown mathematically as follows: Consider the expression for a carrier amplitude modulated by a function of time $f(t)$ of unit amplitude

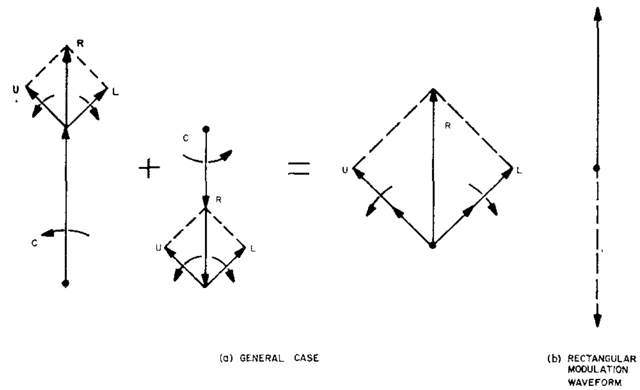

Fig. 1—Phasor diagrams for balanced modulation.

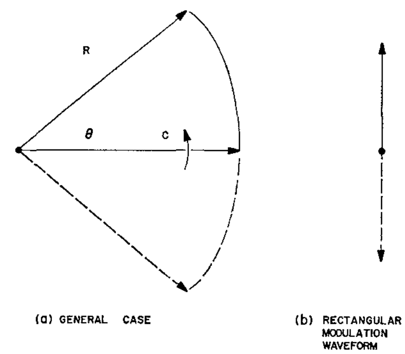

Fig. 2—Phasor diagram for phase modulation.

$$e(t) = E[1 + m_a f(t)] \cos \omega_c t,$$

where m_a is the modulation index and ω_c is the carrier frequency. For the case of a rectangular waveform of unit amplitude $f(t) = \pm 1(t)$ with the time dependence not specified; then,

$$e(t) = E[1 \pm m_a(t)] \cos \omega_c t.$$

The balanced modulator performs the operation

$$e(t) = E[1 \pm m_a(t)] \cos \omega_c t - E[1 \mp m_a(t)] \cos \omega_c t,$$

which combines to

$$e(t) = E[\pm 2m_a(t)] \cos \omega_c t. \quad (1)$$

The phase modulation case may be represented by

$$e(t) = E \sin [\omega_c t + m_p f(t)],$$

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where m_p is the phase modulation index. For $f(t)$ again equal to $\pm 1(t)$ and $m_p = \pi/2$,

$$e(t) = E \sin [\omega_c t \pm \pi/2(t)] \quad (2)$$
$$e(t) = \pm E(t) \cos \omega_c t.$$

This equivalence of (1) and (2) is the basis of operation of a number of microwave balanced modulators.

Phase modulation is effectively accomplished by applying the modulation signal to a microwave crystal diode to cause a variation in reflection coefficient. The operation and equivalent circuit of a crystal mounted across a waveguide through the broad wall has been treated previously.[1] Basically, the crystal is considered as a series RLC circuit as in Fig. 3. When the crystal is biased in the forward direction, barrier resistance R_b is small and effectively shunts the capacitance. The crystal then appears as a high impedance because of the series R-L circuit shunting the waveguide. This condition results in a small mismatch and small insertion loss. When biased in the reverse direction, R_b is very large, but it is shunted by the capacitive reactance. The equivalent circuit then becomes a series RLC circuit resonant in the frequency band for which the crystal is designed. A large mismatch occurs causing most of the incident RF energy to be reflected from the plane of the crystal. By placing a shorting plunger behind the crystal diode the point of reflection may be switched from the plane of the short to the plane of the diode.

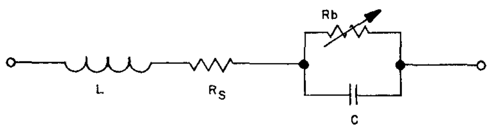

Fig. 3—Microwave diode equivalent circuit.

The Hybrid Tee Modulator

A common form of balanced modulator for a microwave carrier is the hybrid tee type. The modulator may be constructed of standard waveguide components and consists of a hybrid tee with a tuned detector mount on each of the collinear arms. The carrier signal enters the *H*-plane arm of the hybrid and the modulated signal leaves by the *E*-plane arm. The use of one reversed polarity diode, paired with one of forward polarity allows the modulation signal to be supplied in the same phase to each diode resulting in out-of-phase conduction. The use of a matched forward pair requires that the modulation signal be supplied out-of-phase to the diodes.

Under ideal conditions the output of the balanced modulator will consist of the upper and lower sidebands associated with the modulation signal and the carrier will be balanced out. These conditions can be realized very closely in practice if matched crystal diode pairs are used and the diode mounts are carefully balanced by adjustment of the shorting plungers. It has been observed that carrier rejection is somewhat dependent on modulation signal amplitude due to the dependence of crystal impedance on modulation signal level.

Laboratory measurement of the modulator performance was achieved by use of a periodic modulation waveform (500-kc symmetric square wave) and a spectrum analyzer. By careful adjustment of the crystal mount tuning and diode selection it is possible to achieve a carrier rejection of greater than 70 db. Carrier rejection is the ratio of incident carrier power to the carrier power output from the modulator expressed in db. With a 1-mw carrier input level the output carrier component was reduced below the −73-dbm noise level of the spectrum analyzer. After achieving carrier balance the carrier frequency may be shifted ±60 Mc before the carrier rejection becomes less than 40 db. This indicates that two or more signals RF separated by several megacycles may be simultaneously modulated with reasonable carrier rejection.

Modulator Efficiency

Modulator efficiency is defined as the power ratio of the double sideband output to the carrier input expressed in db. Modulation efficiencies of −10 db were observed with almost any matched pairs and a few pairs gave efficiencies as high as −4.3 db. Best results were obtained at *X* band using matched reverse pair IN23E crystals. The modulator efficiency is determined in part by the transmission characteristics of the waveguide structure; in particular the hybrid tee losses may be reduced by 0.5 db if the junction is matched. Thus, with a 10 mw incident carrier a 4 mw output signal can be achieved using ordinary receiving diodes.

Untuned Balanced Modulator

A conventional-type balanced mixer was evaluated for balanced modulator service. This unit is essentially a hybrid tee with the collinear arms folded in the *H* plane so that a common wall is formed. The same configuration serves either as a balanced mixer or balanced modulator depending on how the input and output signals are connected. Fig. 4 shows both the laboratory and commercial configurations. The unit is physically much smaller than the laboratory model made of standard waveguide components and has no tuning adjustments. Without tuning adjustments the carrier balance is particularly dependent upon the matched crystal diode characteristics. Actually the match of the diodes to the modulator is more important than the match of one diode to another when very high carrier suppression is desired. This is because it is impossible to make the two halves of the hybrid tee absolutely symmetrical and, therefore, a pair of diodes mismatched in such a way as to compensate for the modulator unbalance will give better carrier rejection than a perfectly matched pair.

[1] M. R. Millet, "Microwave switching by crystal diodes," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 284–290; July, 1958.

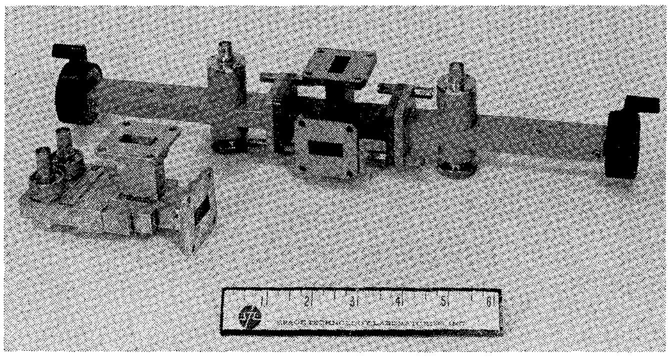

Fig. 4—Compact and laboratory-type hybrid tee balanced modulators.

Table I shows the values of carrier rejection obtained with six matched-reversed pairs of Sylvania IN23E diodes. The lined diagonal values are the result of the manufacturer's pairing and the off diagonal values represent all other combinations. The figures in the table represent random orientations of the diodes with respect to the direction of energy propagation.

TABLE 1

Carrier Rejection for Six Matched-Reverse Diode Pairs

Reverse Diodes	Forward Diodes A	B	C	D	E	F
A	42	28	26	32	34.7	31.5
B	37.7	28	24	28	33.2	28.2
C	31.7	22.4	21.5	25	28.5	25
D	24.6	20.4	19.9	22	24	22.5
E	33	25.5	23.8	27	32	29
F	60	26	23	28	33	30

FIGURES IN db

The following figures result from statistical analysis of the data:

	Carrier Rejection	
	Mean Value	Deviation rms
On Diagonal (manufacturers pairing)	29.3 db	6.9 db
Off Diagonal (other possible pairs)	28.5 db	7.2 db

These results indicate that on the average there is not a significant difference in carrier rejection between the manufacturer's pairing and other combinations. The spread of the off-diagonal combinations is slightly greater than the spread of the on diagonal pairs, and both the best and poorest combinations occurred off diagonal. The lack of a significant difference in diode pairing is probably due to the fact that the diode pairs are matched for low-level detector service without any consideration to higher-level modulator service. Considering the RF impedance tolerance for matched pairs, it is not reasonable to expect over 25 db carrier rejection without individual tuning.

During the course of the carrier rejection measurements a lack of reproducibility of high rejection figures led to measurements on the effect of crystal orientation. It was observed that the degree of carrier rejection is influenced by the orientation of the crystal diode with respect to the modulator body and consequently to the direction of energy propagation. The more complete the carrier suppression, the greater the orientation effect. Fig. 5 shows the variations of carrier rejection with crystal orientation for matched pair *EE*. An arbitrary index point was established on the crystal body and denotes zero rotation. The forward crystal was then rotated counterclockwise in fractions of a revolution and carrier rejection noted with the reverse crystal held at zero rotation. Carrier rejection was found to vary 5.0 db in an almost sinusoidal manner. A repeat of the operation for the reverse crystal with the forward crystal held fixed, showed a variation of 6.5 db. The crystals were then both oriented for greatest and poorest carrier rejection to obtain the range of values to be expected with random orientation.

Joint orientation for greatest rejection	40.6 db
Joint orientation for poorest rejection	31.3 db
Range=	9.3 db

Tests at elevated temperatures (80–160°F) showed that carrier rejection may improve or deteriorate with equal probability for any particular diode pair. For example, the rejection of pair *EE* improved 8 db while the rejection of pair *CC* decreased 5 db. The more complete the carrier rejection the greater the range of variation due to temperature or orientation.

The Circulator Modulator

A ferrite circulator and tunable detector mount may be combined into a novel form of modulator. Fig. 6 is a sketch of this device. It is a property of the circulator that a signal entering at port *A* is circulated in the direction of the arrow and leaves by port *B*. A signal entering port *B* is circulated to *C* and so on around the circle. To form a balanced modulator a matched load terminates port *D* and a tunable detector mount terminates port *B*. The carrier enters port *A* and the modulated signal leaves by port *C*. The principle of operation is as follows, the signal from port *A* enters the crystal mount by port *B* and is reflected from the crystal or the shorting plunger behind it depending on the modulation voltage applied to the crystal. When the crystal is forward

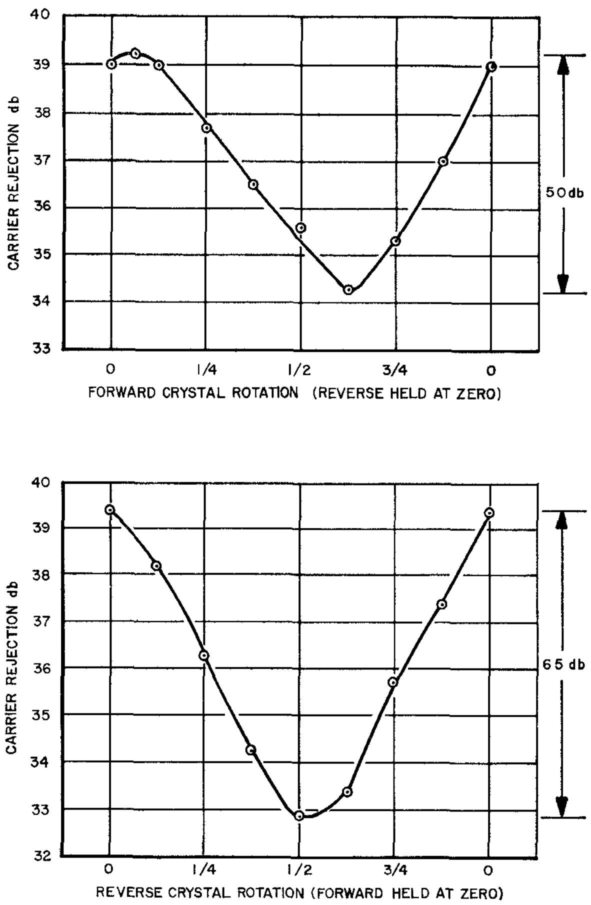

Fig. 5—Carrier rejection with crystal rotation (pair *EE*).

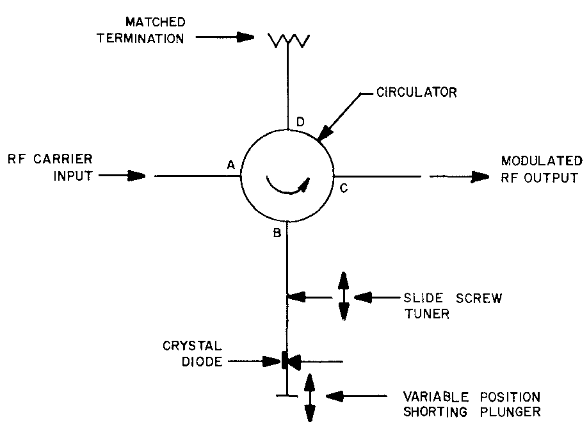

Fig. 6—A novel balanced modulator.

biased, energy is reflected from the shorting plunger behind the crystal; when biased in the reverse direction, energy is reflected from the plane of the crystal. The reflected energy enters port *B* and is circulated to port *C*.

For operation as a balanced modulator, the phase of the signal at port *C* must change by 180° in accordance with the modulation signal. This condition will be fulfilled when the shorting plunger is adjusted to be one quarter of a guided wavelength behind the plane of the crystal causing the path length from port *A* to port *C* to be changed by one-half a guided wavelength. Carrier suppression varies between 20 and 30 db depending upon the crystal used, but can be increased to greater than 50 db by the addition of a slide screw tuner between the detector mount and port *B*. The tuning of this modulator is very straightforward compared to the hybrid tee type discussed earlier. The modulator efficiency was measured at −2.0 db at 1 mw RF level and −3 db at a 10 mw RF level.

High Level Modulation

The amount of carrier power that can be properly modulated is limited by the characteristics of the diodes. Silicon point contact diodes designed for detector use are limited by a peak inverse voltage rating of approximately 4 volts. The inverse voltage rating sets a limit on the amplitude of the modulation voltage and consequently on the RF carrier level. The power handling capability increases as the square of the inverse voltage rating.

Recently point contact germanium diodes have been developed for switching applications at microwave frequencies. At the time of the experimental work reported here the Philco IN3093 diode had an inverse voltage rating of 11 volts and was rated at 100-mw RF carrier level; the switching time of the diode is less than 10^{-9} seconds. This diode has since been uprated to 500 mw.

The IN3093 diodes performed very well when tested in the circulator modulator. Rf power inputs up to 125 mw were modulated with an efficiency of −2.8 db and carrier suppression of 50 db. The circulator, diode mount and waveguide contributed 0.3 db to the loss figure. Philco now has a series of three point contact germanium diodes designed for switching service at *X* band. These diodes operate up to the following power levels: IN3481—10 mw, IN3093—500 mw, and IN3482—1.25 watts. Because the power is divided in the hybrid tee type of modulator, it should be feasible to modulate input powers up to 2.5 watts.

Conclusion

Microwave modulator characteristics pertinent to two-state balanced modulation have been presented. A comparison of a tuned hybrid tee, untuned hybrid tee and circulator type of modulator shows that carrier rejection and modulator efficiency are dependent on crystal match and modulator type. A circulator type of balanced modulator achieved 50-db carrier rejection and 3-db modulator loss for an incident carrier level of 125 mw at *X* band. Recent diode ratings indicate that modulation of a 2.5-watt carrier is feasible.