A Stripline Frequency Translator*

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Summary—**A frequency translator is discussed which operates at *C*-band frequencies. The modulators in the frequency translator are crystal diodes, and modulation is obtained by periodic variation of the reflection characteristic of the crystal modulators. The conversion loss of the frequency translator is 6.5 db at 8-mw input power. The unwanted sidebands are at least 25 db below the translated signal.**

I. Introduction

A FREQUENCY translator in stripline technique operating at *C*-band frequencies was developed in a program of miniaturizing microwave components. In the frequency translator, crystal modulators are connected to the symmetrical ports of a hybrid junction. The arms to which the modulators are connected differ in length by an eighth of a wavelength. The modulating voltages which drive the crystal diodes are in phase quadrature. The modulation characteristic of the crystal diodes is such that each diode effectively operates as a balanced modulator. The frequency translator is similar in principle to the continuous phase modulator which has been described before.[1]

II. Analysis

The performance of the frequency translator can be analyzed by correlating the transmission and reflection characteristics of the individual circuit elements. An RF signal entering port 1 of the hybrid junction in Fig. 1 is divided and directed into the symmetrical arms of the hybrid, which differ in length by an eighth of a wavelength. Semiconductor diodes are placed at ports 2 and 3 of the hybrid.

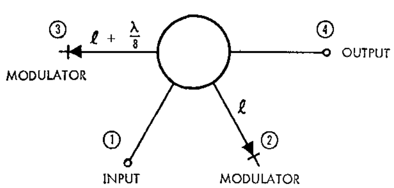

Fig. 1—Schematic of frequency translator.

The impedance of the crystal modulators is varied periodically with the phase of the modulation voltage. The reflection characteristic of the crystal diodes when operated as modulators is such that a microwave signal which is reflected by each of the crystal diodes has the characteristics of the output of a balanced modulator. The variation of the reflection coefficient of the crystal diode with the phase of the modulation voltage, $A \cos \omega_1 t$, which results in the balanced modulator characteristic, is sinusoidal; it can be represented by:

$$\Gamma = \Gamma_0 \cos \omega_1 t \tag{1}$$

where Γ_0 is a constant and $\omega_1/2\pi$ is the modulation frequency. The modulation voltages which are applied to the diodes in port 2 and port 3 are in phase quadrature.

A scattering matrix presentation describes the performance of the frequency translator. A scattering matrix of hybrid junction is given by

$$\begin{vmatrix} 0 & \frac{\sqrt{2}}{2} e^{-j\beta L} & \frac{\sqrt{2}}{2} e^{-j(\beta L+\pi/4)} & 0 \\ \frac{\sqrt{2}}{2} e^{-j\beta L} & 0 & 0 & \frac{\sqrt{2}}{2} e^{-j\beta L} \\ \frac{\sqrt{2}}{2} e^{-j(\beta L+\pi/4)} & 0 & 0 & \frac{\sqrt{2}}{2} e^{-j(\beta L+5\pi/4)} \\ 0 & \frac{\sqrt{2}}{2} e^{-j\beta L} & \frac{\sqrt{2}}{2} e^{-j(\beta L+5\pi/4)} & 0 \end{vmatrix}.$$

Input signals are given by

$$\begin{vmatrix} \mathcal{R}(e^{j\omega_0 t}) \\ \frac{\sqrt{2}}{2} \Gamma_0 \cos \omega_1 t \, \mathcal{R}(e^{j(\omega_0 t - \beta L)}) \\ \frac{\sqrt{2}}{2} \Gamma_0 \cos \left(\omega_1 t + \frac{\pi}{2} \right) \mathcal{R}(e^{j(\omega_0 t - \beta L - \pi/4)}) \\ 0 \end{vmatrix}$$

where $\mathcal{R}(e^{j\omega_0 t})$ is the real component of the complex rotating vector representing the incident wave at port 1.

Outgoing signals are given by

$$b_1 = \frac{1}{2} \Gamma_0 \cos (\omega_0 t + \omega_1 t - 2\beta L)$$

$$b_2 = \frac{\sqrt{2}}{2} \mathcal{R}(e^{j(\omega_0 t - \beta L)})$$

$$b_3 = \frac{\sqrt{2}}{2} \mathcal{R}(e^{j(\omega_0 t - \beta L - \pi/4)})$$

$$b_4 = \frac{1}{2} \Gamma_0 \cos (\omega_0 t - \omega_1 t - 2\beta L).$$

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[1] E. M. Rutz and J. E. Dye, "Frequency translation by phase modulation," 1957 IRE WESCON Convention Record, pt. II; pp. 201–207.

The outgoing microwave signal at port 4 is translated in frequency by the modulation frequency. Dependent on the relative phasing, the signal is translated either to the lower or higher sideband. In the scattering matrix presentation, the phase of the modulating voltage which drives the crystal diode in the shorter arm of the hybrid is lagging. It follows from the RF and ac phase relation that the output signal is translated to the lower sideband. The opposite result is obtained by reversing the relative phase of the modulating voltages. Because of the geometry of the hybrid junction and the length of its arms, half of the modulated energy is coupled into port 1 of the frequency translator. The signals at port 1 and port 4 are translated to opposite sidebands, since there is an inherent difference in RF phase of 180° between port 1 and port 4 of a hybrid junction.

The amplitude of the translated signal is proportional to Γ_0 in (1), and the conversion efficiency of the frequency translator is optimized when Γ_0 becomes one.

III. Modulation Characteristic of the Crystal Diodes

The crystal modulators in the frequency translator are p-type silicon diodes, and are series elements terminating the symmetrical ports of the stripline hybrid junction. The modulation characteristic represented by (1) requires that the amplitude of the microwave signal reflected by the diode vary with the cosine of the phase of the modulating voltage, while the RF phase of the signal changes suddenly by 180° whenever the amplitude becomes zero. In Fig. 2 the variation of the reflection coefficient is given, which is obtained with the crystal modulators in the frequency translator for different bias voltages. The absolute value of the voltage reflection coefficient is approximately 0.85 at -1 volt, which decreases with decreasing negative voltage and becomes very small for zero volt. With increasing positive voltage, the absolute value of the voltage reflection coefficient increases, its phase changes by 180°, and for a positive voltage of approximately 0.6 volt, $|\Gamma|$ becomes 0.85.

A close approximation of the modulation characteristic represented by (1) can be obtained with the crystal diodes by shaping the modulation voltage such that the peak voltage is 1 volt when driving the crystal in the nonconducting state and 0.6 volt when driving it in conduction. For comparison, the variation of the voltage reflection coefficient as represented in (1) for the asymmetrical modulation voltage is shown in Fig. 2.

The modulation characteristic of the crystal diode can be derived from the equivalent circuit of the diode, as given in Fig. 3.[2]

The equivalent circuit elements of the diode cartridge are the whisker inductance L and cartridge capacitance C_c. The equivalent circuit elements of the metal-to-semiconductor junction are the nonlinear resistance R, which is shunted by the nonlinear capacitance C. The two are in series with the linear spreading resistance r.

The variation of the nonlinear resistance and the nonlinear capacitance with bias voltage is given in Fig. 4, and shows the rapid decrease of the nonlinear resistance and the increase of the nonlinear capacitance with forward bias. The spreading resistance was found to be comparatively small.

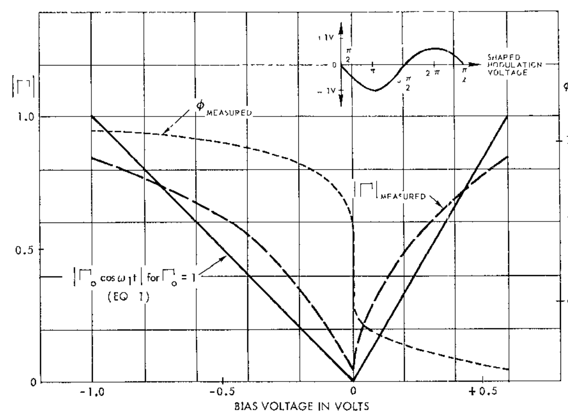

Fig. 2—Variation of voltage rection coefficient of the crystal modulator with bias voltage.

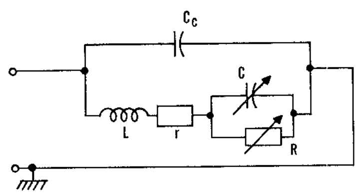

Fig. 3—Equivalent circuit of crystal diode.

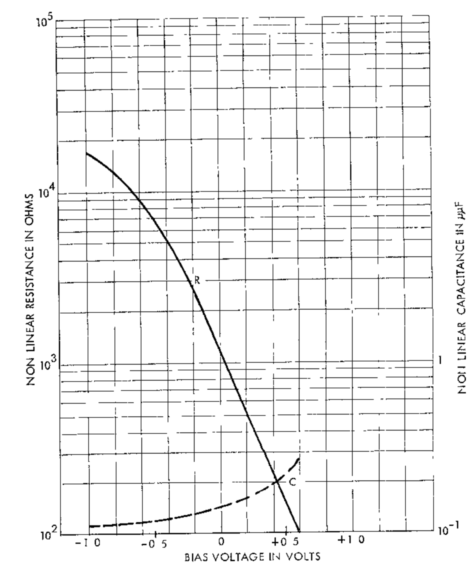

Fig. 4—Equivalent circuit elements of the metal-to-semiconductor junction of a C-band silicon diode as a function of bias voltage.

[2] R. V. Garver and J. A. Rosado, "Microwave diode cartridge impedance," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 104–107; January, 1960.

For large negative bias, the barrier reactance $1/\omega C$ approximates at C-band frequencies the conjugate of the whisker inductance ωL. The equivalent circuit of the diode for large negative bias can be simplified, and effectively becomes a series resonant circuit formed by the whisker inductance and barrier capacitance operating closely below resonance, in series with the inversed value of the nonlinear resistance. The cartridge reactance $1/\omega C_c$ is large compared to these values and can be neglected. The normalized RF impedance which the diode represents for large reverse bias is very small.

At positive bias the nonlinear resistance R and the nonlinear capacitive reactance $1/\omega C$ are small. The RF impedance of the diode is determined primarily by the cartridge capacitance and the whisker inductance which form a shunt resonance circuit. At C-band frequencies this resonant circuit operates below resonance. The real and imaginary parts of the normalized RF impedance for positive bias are comparatively large. The real part is the nonlinear resistance of the junction, which is stepped up by the ratio of operating frequency to resonant frequency of the resonant circuit, and is in series with an inductive reactance resulting from operation of the shunt resonant circuit below resonance.

At zero bias no resonance phenomena occur; the equivalent circuit elements in Fig. 3 are all of about the same magnitude. The normalized RF impedance of the diode is close to one.

The modulation characteristic of the crystal diodes follows from the behavior of series and shunt circuits when operated close to resonance. The absolute value of the impedance of a series resonant circuit is small. The absolute value of the impedance of a shunt resonant circuit is large. When operated below resonance, the phase angle of the impedance of the series resonant circuit is negative, and the phase angle of the shunt resonant circuit is positive. The absolute value of the voltage reflection coefficient for series and shunt resonant circuits is close to one. The phase angle of the respective voltage reflection coefficients differs by approximately 180°. The absolute value of the voltage reflection coefficient and the phase relation between series and shunt resonant circuits is preserved over a comparatively wide range of frequencies if both circuits operate on the same side of the resonance curve.

With decreasing bias voltages, the nonlinear resistance and the nonlinear capacitance change in magnitude, and the resonance phenomena no longer are preserved. The absolute value of the voltage reflection coefficient decreases, and the difference in the phase angle of the voltage reflection coefficient between positive and negative bias voltages becomes smaller.

In the frequency translator, modulation is obtained by variation of the reflection characteristics of the crystal modulators which reflect primarily the RF power and absorb only a comparatively small amount of the power. In conventional modulators, the entire RF power is absorbed by the nonlinear elements in order to convert it into power at different frequencies. Because of the difference in operation, the crystal diodes in the frequency translator can be operated at a higher power level than when used in conventional modulator circuits.

It seems to be of interest to mention that variable capacitance diodes were considered as modulators in the frequency translator; however, they do not perform satisfactorily at the present time in this application. The reasons for this are: 1) variation of the phase of the voltage reflection coefficient of 180° with bias voltage as required by the balanced modulator characteristic cannot be obtained with the varactors; 2) the range of phase variation is less than 150° at C-band frequencies at the present time; 3) the range is limited for large reverse bias by voltage breakdown and for forward bias by a resistance in series with the variable capacitance. However, development of varactors is directed towards increasing the breakdown voltage and decreasing the series resistance, thus widening the range of phase variation.

IV. Stripline Frequency Translator

The stripline frequency translator is shown in Fig. 5. At the comparatively high operating frequencies an air-dielectric transmission line is used, which combines the advantage of a strip transmission line and a coaxial line.

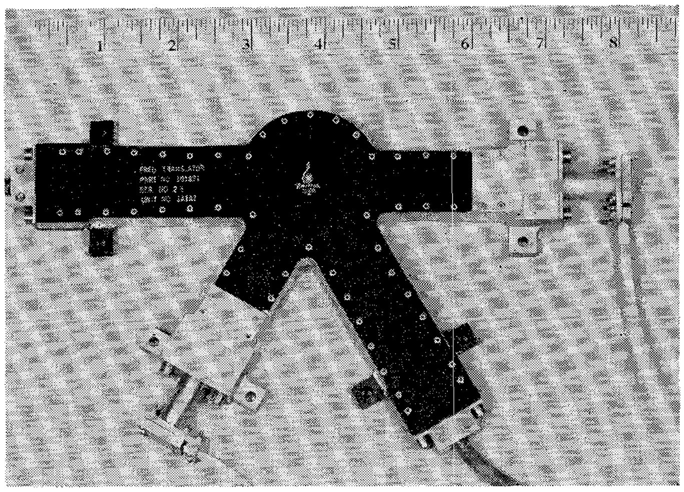

Fig. 5—Stripline frequency translator.

The transmission line is similar to the conventional strip transmission line with one exception: the spacers which support the inner conductor board are of metal, where top and bottom spacers are kept at the same electrical potential. The spacers are moved comparatively close to the inner conductor, and are placed in a region in which the electrical field strength is approximately 10 db below the field strength in the center of the transmission line. The transmission line rejects all propagation modes except the TEM mode.

The hybrid junction is of the conventional type. To obtain isolation between input port and output port, the length of one transmission path of the ring differs by a half wavelength from the symmetrical path. At *C*-band frequencies the dimensions of the transmission lines which form the ports of the hybrid ring are no longer very small compared to the wavelength. To decrease their dimension, the characteristic impedance of these lines was increased. Mechanical considerations set a limit to the highest characteristic impedance of the stripline, which is approximately 100 ohms.

To dimension the hybrid ring correctly, the phase velocity in the stripline has to be known. The phase velocity in stripline deviates slightly from its value in air because part of the fringing electrical field penetrates the dielectric which supports the inner conductor. The percentage of fringing field increases with decreasing strip width. Consequently, the phase velocity decreases with increasing characteristic impedance.

The crystal modulators are placed in series with the symmetrical port lines of the hybrid junction. The design of the crystal mount is shown in Fig. 6. A stripline-to-coaxial-line transition is the receptacle for one terminal of the crystal. In order to match the crystal impedance to the 70-ohm port line, the crystal diode is placed in a small cavity which is obtained by shaping the ground planes of the port line. The height and width of the crystal mount hardly exceed the height and width of the stripline.

The spectrum of the frequency translator output, given in Fig. 7, was measured at 8-mw input power where the measured conversion loss was 6.5 db. The undesired sidebands are at least 25 db below the translated signal.

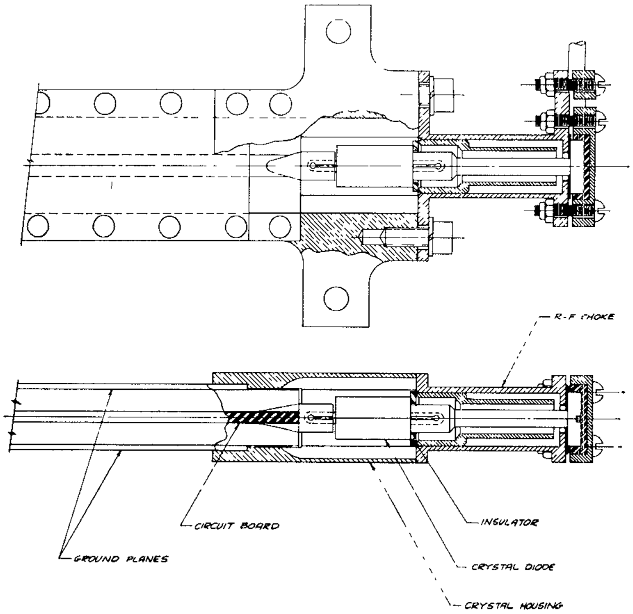

Fig. 6—Crystal holder.

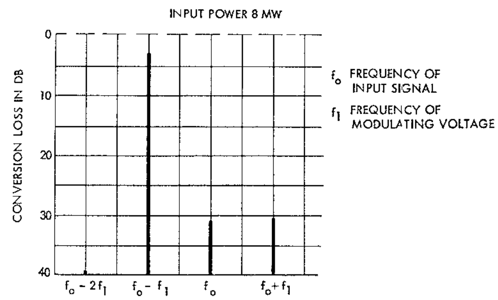

Fig. 7—Spectrum of frequency translator output.