III-1. A Novel Solid-State Modulator for Millimeter Waves

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This paper concerns a solid-state modulator that uses both a crystal diode and a ferrite, which is particularly useful as a high-speed pulse modulator for millimeter waves.

The primary requirements of a pulse modulator are large switching ratio, very fast switching operation and easy adjustment. However, it is difficult to achieve this performance in the millimeter wave region. A reflection type of diode modulator has nearly that performance, but requires a pair of diodes with a hybrid junction. It is difficult to secure an excellent switching ratio with a transmission type of diode modulator. Both types of modulator require variable reactance in order to achieve optimum modulation characteristics at the frequency band concerned. Therefore, in practice, an adjustable short-circuit section has been attached to them. However, a variable short-circuit is not suitable in millimeter wave bands, because of loss and critical adjustment at the movable section.

On the other hand, in the case of a ferrite modulator, it is difficult to control the magnetic field for very high-speed pulse modulation because of the inductance of the exciting coil.

A new modulator has been constructed by combining a crystal diode modulator with a ferrite gyrator in such a way that the impedance variation of the crystal diode, which is caused by the modulating signal, can control the operation of the gyrator. This modulator is adapted to better high-speed operation than may be attained by a ferrite modulator and has a higher switching ratio than may be achieved by a crystal diode modulator of the conventional transmission type.

Configuration and Operation. As shown in Fig. 1, the modulator consists of a crystal diode placed in a waveguide, and a ferrite cylinder placed in a coaxial-shaped end portion of the mount which is attached to the main waveguide. The magnetic field is applied in the axial direction. The exciting coil has 500 turns and its magnetic field intensity is about 200 gauss at exciting current of 1.0A.

With this arrangement, when no electric current flows in the exciting coil, the ferrite acts as a dielectric body, and the modulation characteristic is adjusted by moving the variable short-circuit section. On the other hand, when a magnetic field is applied to the ferrite cylinder, it becomes a nonreciprocal device, generally called a gyrator, which is controlled by the magnetic field, the variable short-circuit section, and the crystal diode impedance.

The modulating signal is applied to the crystal diode. Then the modulating operation occurs as follows: The impedance of the crystal diode varies, which emphasizes the gyration effect of the ferrite cylinder. By these effects the modulation becomes deeper. Then the modulation characteristic is smoothly adjusted by controlling the exciting current, and an optimum modulation characteristic is easily obtained at the frequency band concerned.

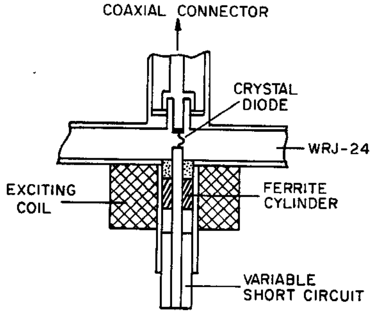


Fig. 1 Sectional view of the modulator.

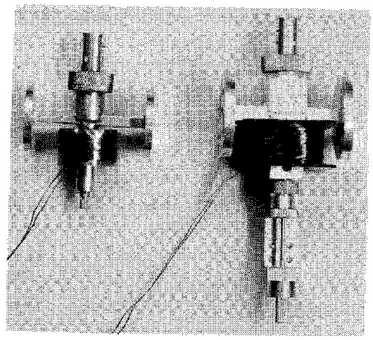


Fig. 2 External view of the modulator. Left, 50 Gc band model. Right, 24 Gc band model.

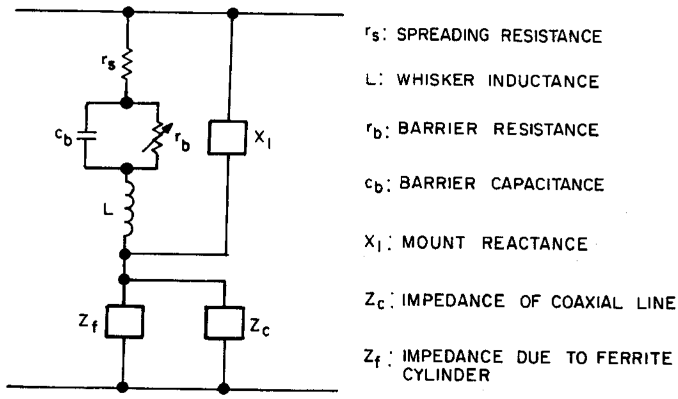


Fig. 3 Equivalent circuit of the modulator.

Theoretical and Experimental Analysis. The modulator may be explained by reference to the equivalent circuit, Fig. 3. The normalized impedance of the diode, Z/Z_d, and its real and imaginary components, R_d/Z_d, X_d/Z_d, are given by the following equations.

$$R_d/Z_d = r_s/Z_d + \frac{(r_b/Z_d)}{1+(r_b/Z_d)^2 A^2}; \qquad (1)$$

$$X_d/Z_d = A\left[1 - \frac{(r_b/Z_d)^2}{1+(r_b/Z_d)^2 A^2}\right]; \qquad (2)$$

$$Z/Z_d = \sqrt{(R_d/Z_d)^2 + (X_d/Z_d)^2}; \qquad (3)$$

where $Z_d = \sqrt{L/C_b}$, $\omega_o = \dfrac{1}{\sqrt{LC_b}}$, $\omega/\omega_o = A$, $r_s/Z_d = K$.

In the Eqs. (1), (2) and (3), r_b/Z_d is variable, and A, K are parameters.

The calculation shows that normalized impedance Z/Z_d is considerably affected by A, and when $A \approx 1$ (nearly equal to the diode resonance frequency), then Z/Z_d decreases, while r_b/Z_d increases. The magnitude of r_b/Z_d increases with back bias voltage and decreases with forward bias voltage. The impedance of the modulator is the sum of the crystal diode impedance and the impedance of the coaxial end section comprising a ferrite, and the latter is obtained by experimental equations. Z_f is due to the ferrite cylinder, and has different values according to the direction (forward or backward) of the electromagnetic wave in the main waveguide. A non-reciprocal effect is caused by Z_f, and it is believed that this phenomenon may be attributed to the fact that the physical dimension of coaxial line comprising the ferrite cylinder allows not only the *TEM* mode but also the higher-order modes to exist.

The analysis of the equivalent circuit shows that the ideal "on" state of the modulator is that of anti-resonance between the crystal diode reactance, X_d, and mount reactance, X_l, and the ideal "off" state is that of resonance between (X_d, X_l) and (Z_f, Z_c). Therefore, the variation of Z_f or Z_c has little effect upon the "on" state of the modulator, but considerable effect upon the "off" state. These facts have been confirmed by the experiments.

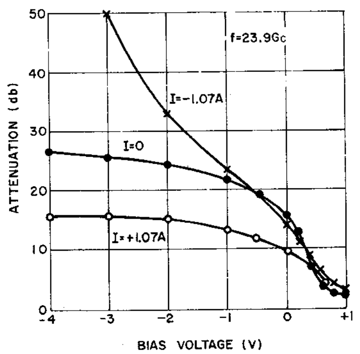


Fig. 4 24 Gc band modulation characteristics. (I = exciting current.)

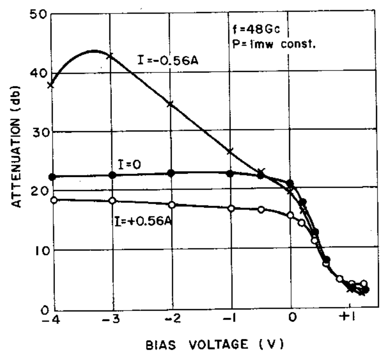
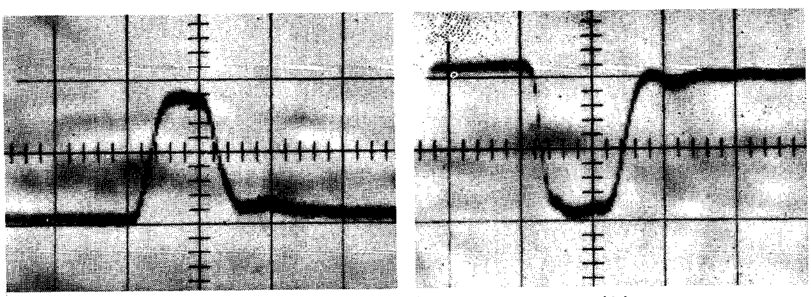


Fig. 5 Modulation characteristics. (I = exciting current.)



(a) (b)

Fig. 6 (a) Pulsed input bias to a modulator (5 ns/div–5 v pulse). (b) Detected pulse from modulated 24 Gc carrier (5 ns/div).

The modulation characteristics between bias voltage and attenuation are shown in Figs. 4 and 5. According to the results, "on" losses ranging from 2 to 3 db and "off" losses of 40 to 50 db are readily obtainable. "Off" losses are affected by the exciting current, and the difference of losses due to current polarity shows the nonreciprocity, or so-called isolation, of the modulator.

The rise and decay times of the modulator are apparently less than 2 *n*s, as shown in Fig. 6. The switching time is mainly limited by pulse response of the diode. *N*-type Ge is used as a crystal in the experiment. $M_n - M_g$ ferrite is used, which has a saturation magnetization of 2000 gauss, a line width of 300 oersted, a dielectric constant of 14, and tan δ of 2×10^{-3} at 9 Gc.

Applications. A modulator of this type will find considerable utility in applications, especially in the millimeter wave region, where high switching ratio, short switching time, and easy adjustment are of primary importance. The most obvious applications are for pulse modulators in millimeter wave communication systems, and for TR switches in millimeter radar systems.