A 6-kw Peak Power Varactor Duplexer*

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Summary—A strip transmission line varactor duplexer was developed for 6-kw operation at 1600 Mc for a missile application. The insertion losses were 0.6 db from antenna to receiver, and 0.3 db from transmitter to antenna. Transmitter to receiver isolation was greater than 40 db. The paper discusses the parameters leading to the choice of varactor and circuit configuration as to provide the power handling ability.

Also discussed are the characteristics of interest to system designers that are peculiar to the varactor duplexer.

Introduction

THIS SOLID-STATE duplexer was designed for use in an altimeter radar for the booster stage of a space rocket. The duplexer was required to operate at a peak power of 6 kw with low insertion loss and small size. A composite ferrite-semiconductor[1] approach seemed attractive at first because of the peak power requirement but was ruled out due to the large magnet weight needed at 1600 Mc.

The development of the duplexer followed an all semiconductor approach embodied in a strip transmission line structure. A novel circuit arrangement was devised where the varactors are coupled to the receiver line by means of a quarter wavelength transformer to allow easy tailoring of power handling ability.

Varactor Limiting

The varactor diode, due to its voltage dependent capacity, exhibits a nonlinearity in impedance with changes in RF power level. This change in impedance is sufficient to provide switching action. In addition to this switching action, the varactor junction has burnout level on the order of a thousand times that of a mixer diode. Because of these two properties, the varactor is very applicable in solid-state duplexers and limiters for mixer diode protection.

The performance of the solid-state duplexers depends on the degree of change in the impedance level of the varactor.[2] This impedance change can approach the square of the change in Q of the varactor junction. If the varactor is driven into conduction in the high-power state, the change in Q will be the operating Q of the varactor. This Q is the ratio of junction capacitive reactance to the diode series resistance, or equivalently, the ratio of cutoff frequency to operating frequency. At 1 Gc a feasible Q is 40. Thus the dynamic range in impedance would approach 1600.

Because of the Q^2 relationship the dynamic range would fall off at higher frequencies by a factor of the frequency squared. This limits the development of varactor duplexers using presently available varactors to frequencies up to about 2 Gc; above this frequency composite ferrite-varactor approach would be better. In spike clipping applications, where the varactor can safely dissipate the total spike energy, practical devices can be built at frequencies into X band.

Basic Limiter Circuit

The duplexer was composed of two of the limiter stages shown in Fig. 1. At high power the varactor pair is conducting and thus exhibits only the lead inductance and a resistive term as its impedance. This inductance is parallel resonated by a capacitive screw C_1 so as to provide a high impedance at the end of the stub. The quarter wavelength of the stub transforms the high impedance to a low shorting impedance at the transmission line. At low power the varactors will be capacitive and so will be transformed as an inductance at the transmission line. This inductance will be matched out by C_2 and thus provide for a low loss transmission of signal from input to output.

At the center frequency the high impedance at the end of the stub during the transmit cycle will be a pure conductance G_1. Because of the quarter wavelength stub, the conductance at the RF line is

$$G_l = \frac{1}{Z_s^2 G_1}. \tag{1}$$

It is the value of G_l that determines the amount of isolation and the power handling capability of the limiter. As an example, a value of $G_l = 2$ mho (*i.e.*, 0.5Ω) across

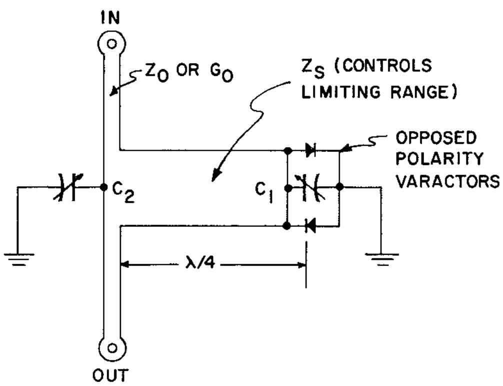

Fig. 1—Varactor solid-state limiter in strip transmission line.

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[1] J. Clark and J. Brown, "A miniaturized ferrimagnetic high power coaxial duplexer-limiter," *J. Appl. Phys.* (suppl.), vol. 33, pp. 1270–1271; March, 1962.

[2] A. Uhlir, "Potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, p. 1113; June, 1958.

a 50-Ω line would result in an isolation of 34 db and the power dissipated in the varactor would be 14 db down from the incident power, *i.e.*,

$$\alpha_i = 10 \log \frac{4\left(\frac{G_o}{G_l}\right)^2}{\left(1 + 2\frac{G_o}{G_l}\right)^2} \tag{2}$$

$$\alpha_r = 10 \log \frac{4\left(\frac{G_o}{G_l}\right)}{\left(1 + 2\frac{G_o}{G_l}\right)^2}, \tag{3}$$

where α_i is the isolation obtained and α_r is the "varactor decoupling."

The important point to observe in (1) is that G_l and thus the power handling ability can be controlled by the stub impedance Z_s. In fact a 41 per cent ($1.41 \approx \sqrt{2}$) decrease in Z_s could double the power handling ability of the limiter.

Unfortunately decreasing the stub impedance also increases the low power insertion loss as the loss conductance in this case is also reduced. For low loss a high shunting conductance is desired. The stub impedance thus gives a way to distribute the losses between the high power and low power states.

Duplexer

Fig. 2 shows how the limiter circuit is used in the duplexer. The limiting junction C is placed one quarter of a wavelength from the antenna port D. At high power, point C is a very low impedance and is reflected at D as a high impedance; thus the transmitted energy goes out the antenna arm.

The presence of the antenna port to dissipate the transmitted power reduces the incident power reaching the limiter injunction and thus the varactor by a factor of four. Thus the factor of four will disappear from (2) and (3) with a resulting 6-db improvement.

To further increase isolation a second limiting stage is used. A single section low pass filter is used to prevent transmitter harmonics from reaching the varactors with a second low pass filter placed in the receiver arm to further protect the receiver from transmitter harmonics and to block harmonics generated by the varactors during transmission. The first stage limiter is optimized for power handling ability by making the stub impedance Z_1 low and uses a pair of 100-Gc cutoff frequency varactors. As the second stage has the benefits of the limiting of the first stage during the transmit cycle, it can be optimized for low insertion loss during the receive cycle and thus can use lower cutoff frequency varactors. The optimizing is done by making the stub impedance high.

The transmitter when not transmitting presents a large VSWR and is properly spaced to prevent loading during the receiving cycle, eliminating the need for any "ATR" function.

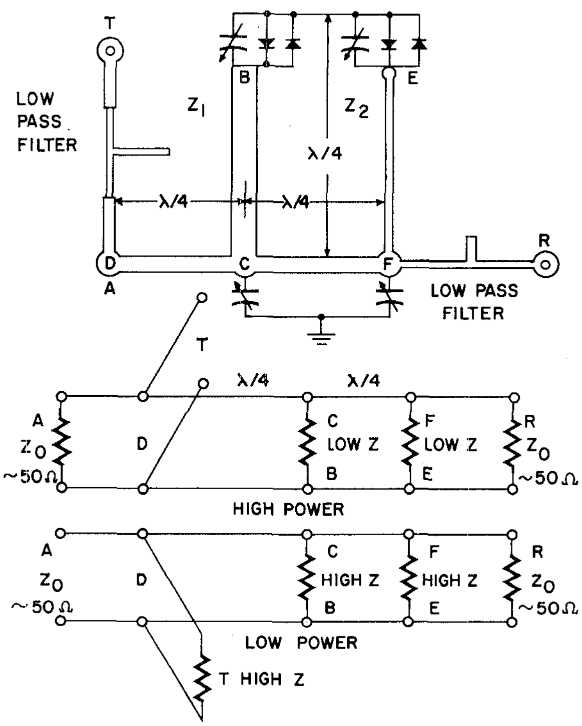

Fig. 2—Structure and equivalent circuits of diode duplexer.

Characteristics

The duplexer was tested at a peak power of 6 kw, 6 w average at 1600 Mc. The theoretical power handling capability was 24-kw peak based on the available impedance change of the 100-Gc cutoff varactors. Actual measured insertion losses were 0.3 db from transmitter to antenna and 0.6 db from antenna to receiver. The transmitter to receiver isolation was greater than 40 db in all units tested with a typical value of 50 db. Photographs of this duplexer are shown in Figs. 3 and 4.

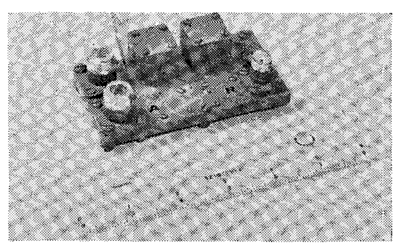

Fig. 3—6 KW, *L*-band varactor duplexer (top view).

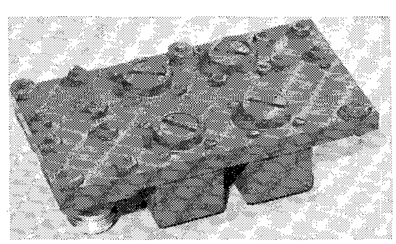

Fig. 4—Under-side of duplexer showing tuning screws.

Design Procedure

The design procedure used for both development of the duplexer and also in the design of limiters is simple and reliable. The desired value of line conductance G_l is calculated at low and high power to provide the desired insertion loss and isolation (and/or power handling ability) respectively. Eqs. (2) and (3) can be used and Smith chart techniques are also applicable. The quality of the varactors needed is then computed from the approximation

$$\frac{G_l\,(\text{low power})}{G_l\,(\text{high power})} = Q^2 = \left(\frac{fc}{f}\right)^2 \qquad (4)$$

where f_c is the cutoff frequency at 0 volts and f is the operating frequency.

The varactors are placed in the structure and the impedance adjusted such that the low-power insertion loss is in agreement with the calculated value. At this point the unit can be safely committed to high-power testing for further impedance adjustments.

Balanced Duplexer

A duplexer can be designed using a balanced type structure[3,4] with two short slot hybrids or two 3-db couplers as shown in Fig. 5. In this structure the varactors are at points marked V and serve to short out the lines under the transmit cycle but pass the signal under receiving conditions. The structure has the advantage of increasing the receiver protection by the amount of the isolation provided by the hybrids and isolating the transmitter during reception. A treatment of the structure using transmission line theory reveals that for varactors of the same Q, the balanced duplexer will have four times the loss per varactor and thus will require four times the number of varactors to handle the same power. The four-to-one difference in power handling ability is illustrated in Figs. 6 and 7. Fig. 6 is representative of the standing waves existing at high power on one line of the balanced duplexer. Fig. 7 is representative of the standing waves of the branched type structure. It can be noted that the terminated branch line of the branch type duplexer reduces the RF current through the varactor by a factor of two, thus reducing the I^2R loss by a factor of four. One good way to visualize the reason for the factor of four is that the varactors in the balanced structure must reflect all the transmitted power while in the branch line type only the power that enters the branch line must be reflected.

The advantages in terms of the required number of

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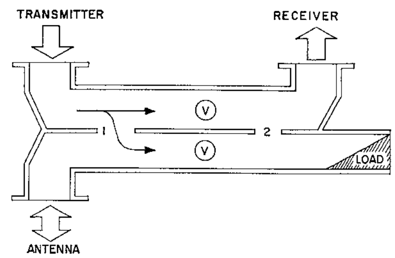

Fig. 5—Structure of balanced line semiconductor duplexer.

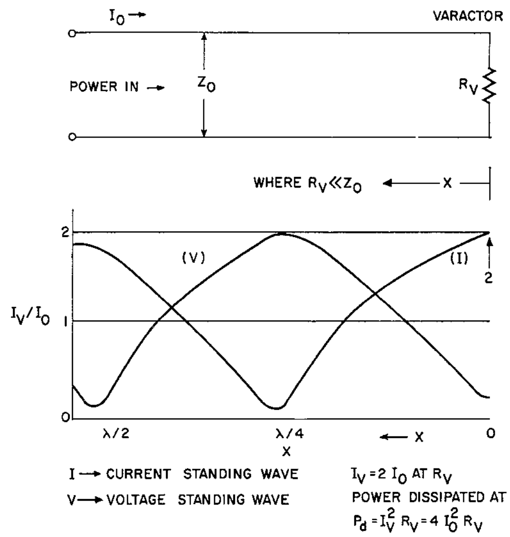

Fig. 6—Current distribution on a short-circuited stub.

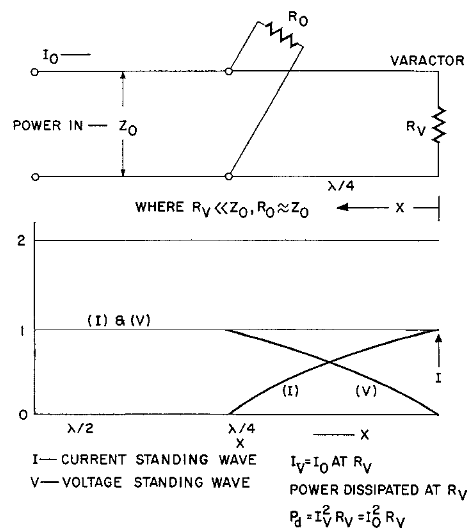

Fig. 7—Current distribution on a ported short-circuited stub.

varactors needed for the branch type duplexer is not as great as the above would indicate. Because of the greater inherent isolation of the balanced duplexer, only one stage of isolation would be needed where the branched duplexer requires two stages. Thus the advantage in the number of varactors is two-to-one not four-to-one between the two configurations.

Conclusions

Varactor semiconductor duplexers and limiters can be designed in a consistent manner to handle a specified amount of power. With use of varactors with a given Q and erg rating, the limitation in peak power that a duplexer or limiter can be designed to handle is limited only by the resulting low-power insertion loss. The two way insertion loss of the duplexer is dependent on the Q^2 of the varactor used. This insertion loss can be distributed within the wide limits between the transmit and receive cycles. From the standpoint of the design of the varactor duplexer, it is best to place most of the insertion loss in the receive state. The insertion loss on the transmit cycle determines the power handling capability of the duplexer.

Varactor solid-state duplexers differ from TR or ferrite duplexers in that there is essentially no spike leakage. The flat leakage energy that reaches the mixer diodes during transmitting is much less severe than the same ergs of spike leakage; therefore, the energy per pulse reaching the mixer diode may be safely higher than if a TR device is used.

Interdigital Band-Pass Filters*

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Summary—**The design of band-pass filters using interdigital arrays of resonator line elements between parallel ground planes is discussed. Two approximate design procedures are described, both of which permit design directly from lumped element, low-pass, prototype filters. Both design procedures will work for either narrow- or wide-band filters, but one procedure gives more practical dimensions for filters having wide bandwidths (such as an octave), while the other gives more practical dimensions for filters having narrow or moderate bandwidth. The resulting filters are very compact, have relatively noncritical manufacturing tolerances, and strong stop bands with the second pass band centered at three times the center frequency of the first pass band. The dimensions and measured performance curves are presented for a 10 per cent bandwidth design and an octave bandwidth design.**

I. Introduction

INTERDIGITAL line structures have in the past been regarded as of interest mainly for use as slow-wave structures. (See, for example, the work of Butcher,[1] Fletcher,[2] and Leblond and Mourier.[3]) However, a recent study[4] has shown that interdigital line structures also have very interesting band-pass filter properties. In that study, various image-impedance and image-propagation phase properties of interdigital line structures were determined, and the results were verified by experimental tests on an interdigital line structure. In this present discussion a different point of view is utilized to obtain approximate design equations for interdigital filters with specified pass-band and cutoff characteristics.

Fig. 1 shows one type of interdigital filter to be discussed. The structure, as shown, consists of TEM-mode strip-line resonators between parallel ground planes. Each resonator element is a quarter-wavelength long at the midband frequency and is short-circuited at one end and open-circuited at the other end. Coupling is achieved by way of the fields fringing between adjacent resonator elements. The design equations to be presented for this case (for which the terminating lines are short-circuited) give filter structural dimensions that will be most practical when the filter is of narrow or moderate bandwidth (say, 30 per cent bandwidth or less). In this structure each line element serves as a resonator, except for the input and output line elements which have an impedance-matching function.

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[2] R. C. Fletcher, "A broad-band interdigital circuit for use in traveling-wave-type amplifiers," PROC. IRE, vol. 40, pp. 951–958; August, 1952.

[3] A. Leblond and G. Mourier, "Etudes lignes a barreaux a structure periodique pour tubes électroniques UHF," *Annales de Radioélectricité*, pt. 1, April, 1954; pt. 2, October, 1955.

[4] J. T. Bolljahn and G. L. Matthaei, "A study of the phase and filter properties of arrays of parallel conductors between ground planes," PROC. IRE, vol. 50, pp. 299–311; March, 1962.