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High Speed Microwave Phase Shifters Using Varactor Diodes*

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A reflection type microwave phase shifter is described which is similar to the units developed by Hardin, Downey, and Munushian. It employs the voltage-variable capacitance of varactor diodes as the adjustable element. The "pill type" diodes tune their associated circuit through a resonance to produce phase shifts of over 90°. With proper adjustment of the tuning—a simple procedure—the output amplitude is made essentially constant. The use of two series diodes mounted back-to-back permits higher power operation, although the unit is essentially a low power device.

INTRODUCTION

MICROWAVE phase shifters that can be tuned electrically and have the advantage of high speed have been noted earlier. In at least two instances phase shifters with varactor diodes have been described,[1,2] although in one case[2] coaxial transmission lines were used in the vhf range.

Hardin *et al.*[1] used various waveguide circuits which incorporated two varactor-diode terminations. Although sizable phase shifts were reported for these transmission type units (from 41° at 9 Gc to over 180° at 1 Gc), apparently no specific means was provided to obtain an output of optimally constant amplitude.

We describe here a simple reflection type phase shifter in which "pill type" varactor diodes form a part of a resonant circuit in a waveguide in a manner similar to that of Hardin *et al.*[1] We also describe a method of matching which renders the amplitude essentially constant. With such a device, phase shifts that are variable over 144° have been obtained at 9 Gc with a constant reflection loss of 3.5 dB. Since the variable capacitance of the diodes is used to tune the associated circuit near a resonant frequency, this phase shifter is a rather narrow band device. However, this is compensated by the ease with which the circuit resonance may be tuned to any desired frequency and matched for constant amplitude of the reflected wave. The inherently fast response and constant amplitude output of this phase shifter make it particularly suitable for some types of phase measurements in circuits using a cw microwave source at a fixed frequency. Such devices have shown their utility in this Laboratory[3] in null type bridges at 24 and 9 Gc. In the latter case, phase shifts of less than 0.003° were measured.

The phase shifter consists of three basic elements, (1) the varactor diodes which are mounted across a section of waveguide that is interposed between (2) a slide-screw tuner and (3) a shorting plunger. As noted below, the slide-screw tuner may be unnecessary if the varactors are suitably positioned. For least frequency sensitivity, the distances between the components should be small—ideally the shorting plunger should be capable of moving toward the varactors until the *lowest order resonance is reached* (about one-half of a guide wavelength for the cases described).

MOUNTING THE VARACTORS

Figure 1 shows an end view of a single varactor positioned in a section ot 8 mm waveguide. The screw, which provides an electrical ground, holds the varactor tight against a copper disk. The disk and the wire feedthrough are insulated from the waveguide by a mica disk and the enamel on the wire. To prevent excessive radiation of microwave power out via the feedthrough, the insulating disk should be very thin or, better, the feedthrough system should be long enough to form a resonant choke. A more elaborate choke system may be used, of course.

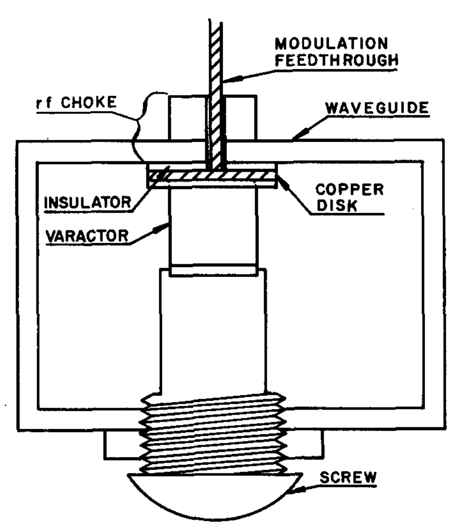

Fig. 1. Single varactor mount.

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[2] R. L. Orrick, Jr., Electron. Ind. **21**, 116 (1962).

[3] A. L. Gardner, Rev. Sci. Instr. **37**, 23 (1966), (following article).

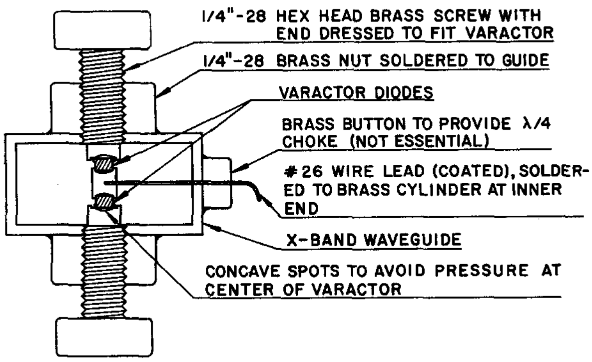

FIG. 2. Cross section of a dual varactor mount.

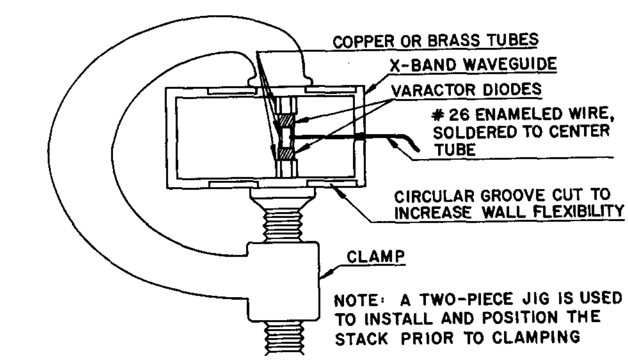

FIG. 3. Cross section of a dual mount that permits off center positioning of varactor diodes.

The dual varactor mount sketched in Fig. 2 has a feedthrough wire that is perpendicular to the microwave **E** field. The radiation losses with this arrangement are negligible. In this type of mount the two series diodes present a back-to-back (i.e., "cathode-to-cathode" or "anode-to-anode") configuration to the microwave **E** field so that the variations in the **E** field reduce one capacitance and at the same time increase the other. This reduces harmonic generation. Also, the input admittance and consequently the phase shift is less sensitive to the rf field strength. Furthermore, because the rf voltage across each diode is only half of the total rf voltage, a higher power can be accommodated before the voltage becomes comparable to the bias voltage. Another advantage of this style of mount is that it has a lower input capacitance of the bias-voltage lead, which makes faster modulation possible.

The dual varactor mount shown in Fig. 3 permits the varactor stack to be positioned at the center of the guide or to be offset toward a side wall. In some cases a suitable lateral displacement of the varactors can obviate the need for the slide-screw tuner and result in a device with less frequency sensitivity. In this mount the small diameters of the supporting tubes fairly well minimize the stray shunt capacitance across the diodes.

METHOD OF TUNING

Precise measurements of the normalized impedance of the varactor stack as a function of the bias voltage would permit calculations of the desired positions of the shorting plunger and the slide screw. However, such measurements and calculations are laborious and provide at best only approximations to the optimum positions of the components. On the other hand, these adjustments may be made quickly and accurately on the test bench without performing any calculations. A simple procedure for doing this is now given, along with some explanation of the circuit.

An oscilloscope is employed to view the amplitude of the reflected signal, while a fraction of the sawtooth sweep voltage from the oscilloscope is used to back bias the varactor diodes. It is convenient, but not necessary, to use a chopped cw microwave source, which then provides a continuous indication of the "no signal" baseline.

The shunt capacity of the diodes and the inductance of the stub which ends at the shorting plunger form a resonant circuit. The resonant frequency is continuously swept within narrow limits by the sawtooth bias voltage, but it can be manually tuned over a wide range by changing the plunger position. With the slide screw entirely withdrawn, the shorting plunger position is varied until the resonance occurs near the center of the sweep range of the varactor bias voltage, i.e., until a dip in the observed signal is located and moved to the center of the trace. If possible, the plunger should be further inserted $\lambda_g/2$ to achieve a resonance at a lower order mode. The points on the small solid circle in Fig. 4 show the normalized admittance of a circuit in this condition for bias voltages ranging from 0 to 8 V as indicated[4]. Next, the slide screw is inserted to successive depths, and positioned longitudinally with each increase in depth, until the position is found at which the signal amplitude barely dips to zero at the center of the trace. The screw should be inserted no farther than is necessary to obtain the dip to zero. In this condition, a plot of impedance or admittance as a function of varactor voltage passes through the center of a Smith chart, i.e., at resonance the tuned circuit is critically coupled. The objective, of course, is that such a plot encircle the center of the chart at a constant, preferably large, radius. The final tuning follows one of the two procedures described below. This preliminary adjustment to critical coupling makes it simple to determine whether the circuit was initially undercoupled or overcoupled and what the approximate longitudinal position of the slide screw should be.

[4] The small circle plot is closely related to the similar plot of the locus of input impedance used to determine the "canonical network" equivalent circuit representation of a four terminal microwave circuit. In that method the locus results as the shorting plunger of the output line is moved through one-half of a guided wavelength. In the present application the shorting plunger is held in a fixed position and the locus results as the reactance of the "microwave circuit" itself is altered due to the changing bias on the varactor diodes. Since the series resistance component of the normalized impedance of the diode stack is much less than unity, the admittance plot of resonant circuit almost follows a constant conductance circle.

Case 1: Initially undercoupled resonant circuit. In this case, further insertion of the slide screw (beyond the setting for critical coupling) moves the position of the signal minimum toward the *left* on the viewing oscilloscope, i.e., toward the lower reverse voltages on the varactor and therefore to higher varactor capacitance. This indicates that before the slide screw was inserted at all, an impedance plot would not have encircled the center of the Smith chart and that optimum tuning to achieve a more nearly constant amplitude over the range of bias voltage is achieved with still deeper penetration of the screw. To produce this minimum amplitude variation of the reflected signal, the depth of the screw should be increased accordingly and the longitudinal position should be slightly adjusted, if necessary, until the signal amplitude is as constant as the adjustments permit. A test shows that small longitudinal movements of the screw about its proper position "pivots" the observed pattern about the original resonance position.

Case 2: Initially overcoupled resonant circuit. In this case, further insertion of the slide screw (beyond the setting for critical coupling) moves the position of the signal minimum toward the *right*, i.e., to lower varactor capacitance. This shows that before the screw was initially inserted, an impedance plot would have partially encircled (would have been concave toward) the center of the Smith chart. For final tuning in this case, the screw may be completely withdrawn and then reinserted at a position roughly $\lambda_g/4$ away to a depth that produces a minimum amplitude change in the reflected signal.

For the few varactors tested, Case 1 was found to be the normal situation for diodes mounted in the center of the guide.

To some extent at least, the device may be matched without the slide screw by offsetting the varactor stack (Fig. 3) an appropriate distance toward the narrow wall of the guide. This results in a greater useful bandwidth for a given tuning and also in a higher reflection coefficient. With the diodes initially offset to achieve essentially a constant amplitude of the reflected wave, the broadened resonance naturally is more difficult to recognize. To adjust the shorting plunger to the proper position for resonance in such a case, it may be necessary to "observe" the rate of phase change of the reflected wave, as the back bias voltage is changed.

PERFORMANCE

The measurements shown here were made with approximately one milliwatt of rf power at X band and with RCA type VD-110 gallium arsenide varactor diodes. The data shown in Figs. 4 and 6 were taken with the same two varactors in a mount of the type sketched in Fig. 3.

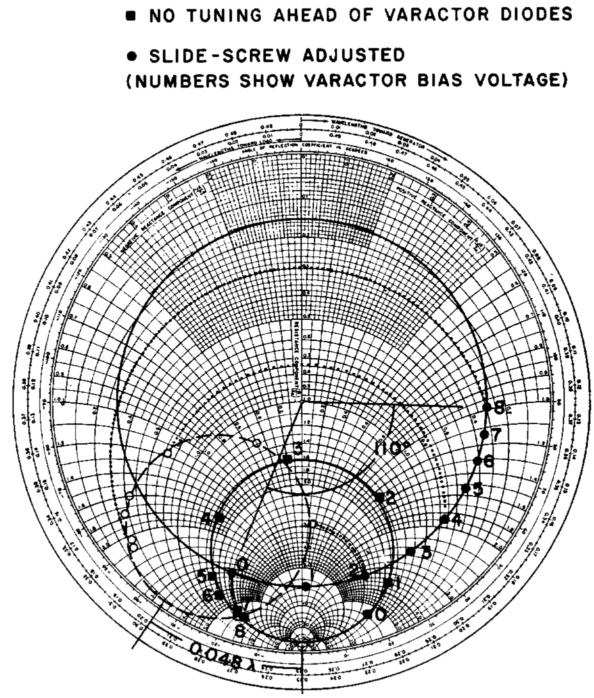

FIG. 4. Admittance plots with varactor diodes mounted at the center of the waveguide.

These particular diodes had junction capacitances of 0.38 pF and 0.34 pF at −6 V bias and breakdown voltages of about −9 V. Figure 4 shows two Smith chart plots of the measured system admittance[5] as a function of the applied bias voltage with the varactor stack positioned in the center of the guide. In this instance, the shorting plunger was originally set to give equal amplitude reflection at 0 and 8 V bias before the side screw was inserted. This requires the plotted points for 0 and 8 V on the small circle to represent equal vswr's, and thus to be at the same radial distance from the center of the Smith chart. This placed the dip of the resonance at nearly 3 V rather than at the midrange value of 4 V. The adjustment of the slide screw added a normalized shunt admittance of $j3.0$ at a position 2.048 λ_g ahead of the diodes. This capacitive susceptance transforms the small circle into the large centered circle. The final range of 110° of phase shift was obtained with measured vswr values ranging from 7.03 to 7.12, representing a loss of about 2.5 dB upon reflection and an output power variation of less than 1%. The amount of phase shift per volt of bias decreases as the bias is increased. This nonlinearity may be substantially reduced (at a sacrifice of some of the phase shift range) by initially offsetting the resonance toward the higher bias voltages. Figure 5 gives an example of this.

An indication of the useful frequency range that can be obtained with a fixed adjustment of the shorting plunger

[5] The lower plot has its plane of reference at the position of the diodes, while the large circle plot and the dashed circle use the plane of the slide screw as a reference.

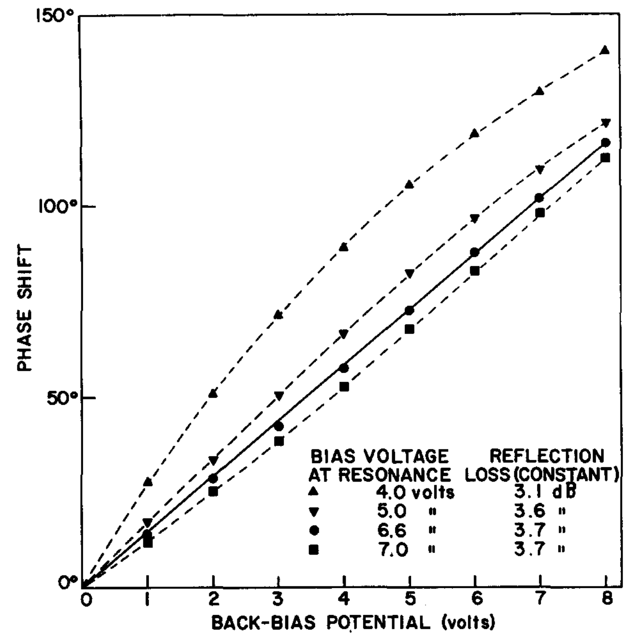

FIG. 5. An example of obtaining approximately linear phase shift vs bias voltage by offsetting the resonance toward higher bias voltages.

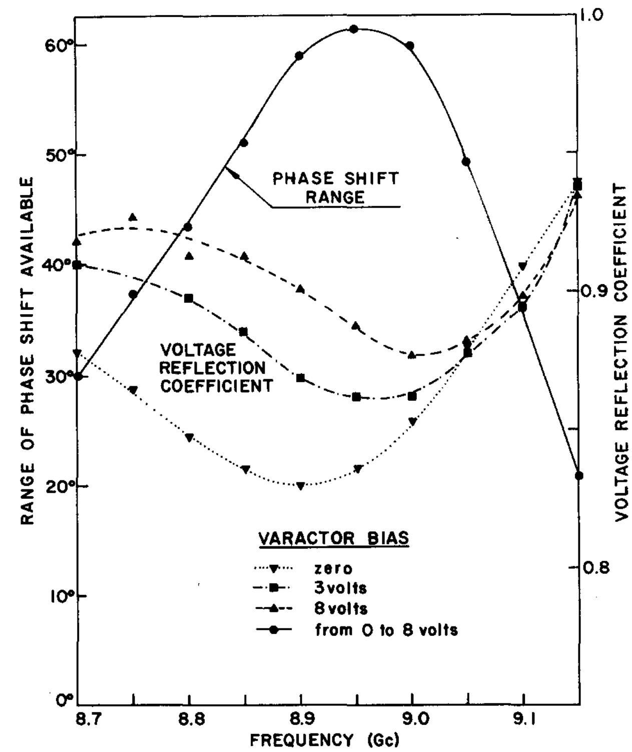

FIG. 6. Phase shift range and reflection coefficient vs frequency for a mount with off center matching.

is given in Fig. 6. For these measurements the varactor stack was offset toward the narrow wall of the guide enough to allow the slide screw to remain completely withdrawn, i.e., the dip at resonance was very slight but extended over a wide range of bias voltage. Over a range of 400 Mc (about 4.5% of the center frequency), the available phase shift is at least half of its peak value. The peak of 61° is appreciably lower than the 110° obtained with the varactors centered, but the loss upon reflection is reduced.

The rf power limitations of the dual varactor arrangement have not been measured, although in cursory checks with the varactors mounted off center (as for the data in Fig. 6), 45 mW at 9 Gc and 125 mW at 10 Gc caused no increase in losses with the back bias voltage set at the extreme values of 0 and 8 V. However, at these extremes of the bias range, a few milliwatts was enough to alter by 1 μA the average current drawn from (or delivered to) a bias supply with a dc impedance of 10 kΩ.