VII-7 PLASMA VARACTOR X-BAND PHASE SHIFTERS

J.Y. Wada and R.C. Knechtli

Hughes Research Laboratories

B.J. Forman and A. Fafarman

Hughes Aircraft Company

INTRODUCTION

A microwave phase shifter (x-band) which utilizes plasma varactors has been developed. It has demonstrated continuous phase shifting of 360 degrees with low rf loss, low noise and high average rf power handling capability heretofore unobtainable in previous microwave plasma devices or in solid state devices. The plasma varactor is a high Q variable microwave reactance produced by means of a low pressure and highly efficient electron injection mode of gas discharge.

Overall rf losses, including the reflection, circuit and plasma losses, smaller than 0.5 dB have been obtained over a bandwidth of 12% at X-band for continuously variable phase angles up to more than 360°. An average power handling capability in excess of 200 W has been obtained from this device. Excess noise temperature of the phase shifter is smaller than 100°K for phase shifts up to 360° over the same frequency range. Extrapolations from the performance of this prototype indicate that the average rf power handling capability could be increased to the multi-KW level, without deterioration of the other characteristics.

PLASMA VARACTOR

The essential feature of the plasma varactor is the selection of an efficient low noise, electron injection mode of gas discharge capable of being sustained at relatively low gas pressure typically two orders of magnitude lower than for a conventional positive column gas discharge). The advantages of low gas pressure result from the corresponding low electron-neutral collision frequency. These advantages include low rf loss, low excess noise temperature and high rf power handling capability.

The electron injection discharge used for the plasma varactors is shown in Fig. 1; the corresponding potential distribution is shown on Fig. 2. In this mode of discharge, the electrons are injected into the gas at an energy corresponding approximately to the full discharge voltage, and adjusted to be appreciably higher than the ionization potential of the gas. This electron injection takes place through a plasma sheath, such as in the plasma triode illustrated in Fig. 2. The energy of the injected electrons is approximately equal to the applied discharge voltage and therefore can be controlled externally. If the electron injection energy is adjusted to a value between 1.5 and 2 times the ionization potential, the probability of ionization approaches its maximum value. This permits operation at the desired low gas pressure. Furthermore, in this type of discharge the electron energy is used with optimum efficiency for ionization. The resulting discharge power is therefore relatively low. Finally, this mode of discharge is found to be free from unwanted oscillation or instabilities which would contribute to noise or unacceptable modulation.

The plasma produced in the discharge is confined to a well-defined cylindrical column by a modest dc magnetic field (150 to 200 G). The reactance of this plasma varactor is electronically controlled by adjusting the gas discharge parameters (current and voltage).

A set of typical characteristics measured on a xenon filled plasma varactor is summarized in Table-I. It is seen from this table that a quality factor Q>150 was achieved at X-band, with a dynamic range corresponding to susceptances up to 1.2 Y_o (Y_o = characteristic susceptance of standard X-band wave-guide). This compares favorably with any state of the art device (ferrites or semi-conductor). The total driving power requirement (including 0.6 W of heater power) is less than 1 watt or corresponds to less than 1% of the rf power handling capability of 200 W average. The insertion loss corresponding to the high Q of this varactor is extremely small.

PHASE SHIFTER DESIGN

The experimental phase shifter is of the reflection type shown schematically in Fig. 3a. It consisted of a 3 dB directional coupler and variable reactance elements (plasma varactors). A standing wave is produced by the waveguide short in each section of the waveguide containing the reactive elements. The effective phase shift is produced in essence by shifting the phases of standing waves by the plasma varactors and properly channeling these reflected waves with the use of the 3 dB directional coupler. The equivalent circuit representation of this device is shown in Fig. 3b. The plasma columns are representable as variable reactances in shunt with the equivalent transmission line.

A photograph of an X-band plasma varactor phase shifter with its light-weight magnetic circuit is shown in Fig. 3. The plasma columns are confined by the permanent magnetic field of the circuit and extend through apertures in the common broad wall of the top and bottom waveguides. The spacing between these varactors ($L_1 = L_2 = L_3 = 0.88$ cm) and the positioning of the waveguide shorts ($L_4 = 1.71$ cm) were slected so that maximum phase shift occurs at 8.8 GHz.

PHASE SHIFTER PERFORMANCES

The magnitude of the phase angle can be continuously controlled by several means, one of which is the use of a discharge voltage adjustment. With all four varactors in parallel, the phase shift as a function of the discharge voltage was measured and is shown in Fig. 5(c). The discharge characteristics (Fig. 5(a)) of each varactor were nearly the same. With the total discharge power of less than 3.8 W (including the heater power of 2.2 W), the phase angle could be varied continuously over 360° simply by adjusting the discharge voltage from 15 to 18 V. Alternatively, grid control could be used to control the phase shift by means of this discharge current.

The difference between the two curves of Fig. 5(c) for 8.2 and 8.8 GHz, respectively, can be greatly reduced by making the plasma density distribution more uniform along the waveguide.

The phase shift, rf losses, and VSWR were measured with all four varactors connected in parallel and operating as a unit. The results are summarized in Table 2.

The measured VSWR's are smaller than 1.5 over a 10% bandwidth; the transmission losses over the same frequency range and the phase shifting of 0 to 360° are below 0.5 dB. The losses were slightly larger when the plasma varactors were completely turned off. This cold loss is believed to be produced by the combination of losses caused by the rf windows and leakage through the varactor openings and apertures on the common wall of the stacked waveguides. It appears that the rf field is sufficiently altered in the presence of low loss plasma columns so that the leakage losses are reduced. With improvements of the choke design of these plasma varactors, a further reduction in these losses can be expected.

The noise temperatures were smaller than 100°K for phase shifting up to 360° over the same frequency range. While the average power handling capability of this unit was 200 W, a straightforward improvement of the discharge (i.e., a reduction of gas pressure) should permit kilowatt rf power operation.

ACKNOWLEDGMENT

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TABLE I

Summary of Plasma Varactor Performance Characteristics

Rf Performances:	
• Frequency	X-band
• Dynamic range of the plasma admittance	≤ 1.2 Y_o
• Plasma quality factor	> 150
• Excess noise temperature	< 100°K
• Insertion loss of plasma	< 0.1 dB
• Rf power handling capability (average)	> 200 W
Dc Driving Power:	
DC discharge power	≤ 0.3 W
Cathode heater power	≤ 0.6 W

TABLE 2

Summary of Performances of Plasma Varactor Phase Shifter (Four Varactor Unit)

Rf Performances:	
• Frequency	X-band
• Bandwidth	12%
• Phase shift (continuous)	> 360°
• Rf losses (cold losses included)	< 0.5 dB
• VSWR	< 1.5
• Excess noise temperature	< 100° K
• Rf power handling capability (average)	> 200 W
Dc Driving Power:	
Voltage	< 20 V
Current per varactor	< 20 mA
Power per varactor (including heater power)	≤ 0.9 W

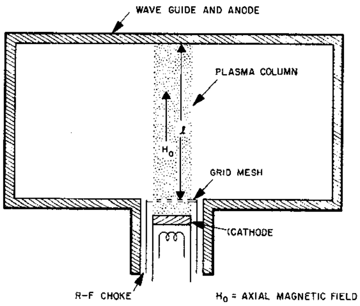

FIG. 1 - Electron Injection (triode) Plasma Varactor Integrated in a Waveguide

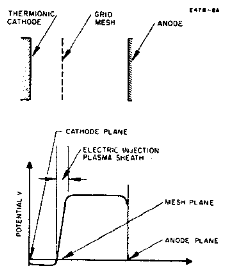

FIG. 2 - Potential Distribution in Plasma Triode Discharge

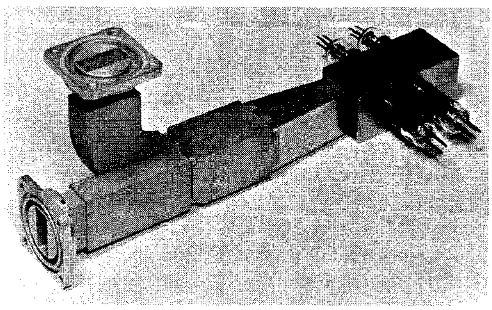

FIG. 4 - Experimental Multivaractor Phase Shifter Assembly

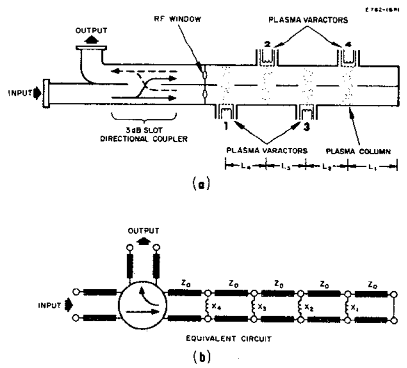

FIG. 3 - Schematic Drawing and Equivalent Circuit Diagram of a Reflection Type Plasma Varactor Phase Shifter

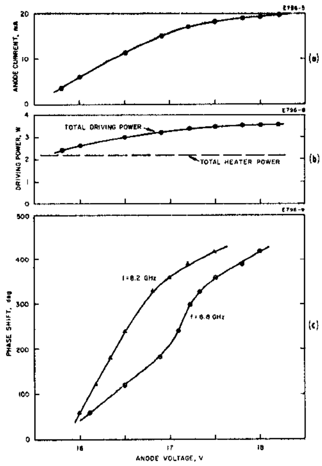

FIG. 5 - Typical performance characteristics of plasma varactor phase shifter