S-BAND, 3-BIT, 1 KW PEAK, 0.8 DB AVERAGE LOSS, DIODE PHASE SHIFTER AND DRIVER UNDER $100[1]

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Abstract and Introduction

There is a need for an S-band high power electronic phase shifter with low insertion loss and low cost for ground and ship-based phased array radars. Both diodes and ferrites are candidates for this application. Typically, the ferrite phase shifter is known to have low insertion loss; however, the recent use of wafer glassed PIN diodes removes the necessity for an expensive ceramic diode package and, furthermore, improves performance by eliminating diode package parasitic reactances. With these diodes, a complete 3-bit phase shifter having only 0.8 dB of average insertion loss has been made. This device has a rated power of 1 kW peak (the burnout level is 4 kW peak) using 120 microsecond-long pulses and 0.05 duty cycle. This paper describes the construction and testing of the phase shifter and a cost estimate for large quantities.

Device Configuration and Results

The schematic and constructional diagrams for the 3-bit phase shifter are shown in Figure 1. Each bit uses a backward wave, 3 dB hybrid coupler to maximize bandwidth. Similar couplers used between bits serve to isolate the RF from the bias. Except for diodes, the entire circuit can thus be printed entirely on opposite sides of a stripline board. This both minimizes cost and enhances insertion phase reproducibility.

A photograph of the complete phase shifter, along with a close-up of the "packageless" diode, is shown in Figure 2. The diode chip is soldered to the metal heatsink shown and soldered to the circuit with a flexible metal strap to separate forces that might otherwise be transmitted to the diode due to differential thermal expansion of the circuit board and phase shifter housing.

Measured performance of the phase shifter is shown in Figures 3 and 4. The departure of measured phase shift from an ideal characteristic (i.e., 0°, 45°, 90°, 135°, ... 270°, 315°) is the "phase shift error", shown for the three bits individually and averaged over the seven phase shift states (the first state is used as a reference) in Figure 4b. This performance was obtained for a model designed about the diode capacitance values available, and the resulting phase shift accuracy is therefore better than what would be practical in large scale production. Usually, for a 3-bit phase shifter, an rms phase error tolerance of 7-10 degrees is made, permitting use of diodes with about a 10% capacitance tolerance.

The phase shifter was high power tested to burnout which occurred at 4 kW peak using 120 microsecond-long pulses and 0.05 duty cycle. The high power limit is set by the maximum RF peak voltage sustainable by the diodes in the 180° bit in the reverse biased condition. At the 4 kW level, the diodes in this bit have a calculated peak RF voltage of about 750 volts, and they were biased with -150 volts. Use of shorter pulse lengths would probably permit somewhat higher RF peak power to be sustained since the diode breakdown voltage exceeded 1,000 volts. Use of a larger magnitude of reverse bias might also be expected to increase peak power capability; however, this is undesirable because of the unfavorable impact on the cost and availability of suitable driver transistors.

The diodes used for this phase shifter have $C_J = 0.7$ pf and series resistance of $R_R = 0.8$ ohms when reverse biased at -150 volts. Under forward bias (150 mA/diode), the resistance is about $R_F = 0.5$ ohms giving a diode cutoff frequency $f_c = \left(2\pi C_J \sqrt{R_F R_R}\right)^{-1}$ of 360 GHz. The average diode losses for a 3-bit phase shifter are found using Hines[2] theory to be:

$$\text{I.L.} \approx 38\ (f/f_c) \quad \text{(dB)}$$

or, near F = 3 GHz, about 0.3 dB. The remaining average loss measured at low power, about 0.5 dB, can be attributed to dissipative and reflection losses in the circuit. The RF losses near the burnout power with all diodes reverse biased, can increase by about 0.5 dB, but the loss increase near rated power of 1 kW peak would be only about 0.1 dB. This occurs only on transmit and only with back biased diodes; thus, the overall effective phase shifter loss increase due to high power averaged over both transmit and receive conditions is usually negligible.

Driver

A schematic diagram for the driver for one bit of the phase shifter is shown in Figure 5. Three identical circuits form the complete driver (fitted within the housing shown in Figure 2) required for the 3-bit phase shifter. Forward bias is obtained when the emitter lead of transistor T_1 is grounded (this corresponds to a TTL "zero"). When the emitter is terminated in a high impedance (corresponding to a TTL "one"), the forward bias supply is shut off and any residual charge contained in the PIN diodes is removed by the current drawn by the reverse bias supply resistor, R_3, and the enhanced counterpart of this current amplified by transistor T_2. A transition time of a few microseconds is easily obtained with this circuit, which is more than satisfactory for the phased array antennas likely to use this phase shifter. Faster switching can be obtained with moderate increase in the complexity of the driver.

Cost Estimates

Estimates of the cost of this high power phase shifter are shown in Table I based on a production quantity of 200,000 phase shifters, as might be required, for example, for 25 radar systems each having two antenna faces of 4,000 elements each.

TABLE I

3-BIT DIODE PHASE SHIFTER AND DRIVER
COST ESTIMATE
(200,000 UNIT QUANTITY)

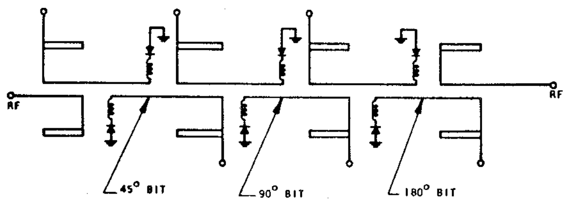
Diodes - 6 at $1.50 each	$ 9.00
Stripline Boards	2.00
Housing, Connectors and Hardware	7.00
Driver	10.00
Assembly and Test Labor	15.00
Overhead and Markups (110%)	47.00
	$90.00

Acknowledgments

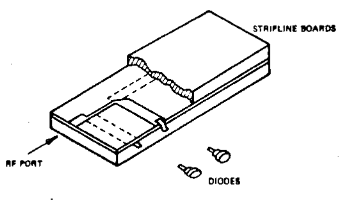
The author wishes to acknowledge the many engineering contributions made to this work by his associates, particularly, Dr. C. Buntschuh, D. Gallagher, C. Genzabella, C. Ward and the Project Engineer, Dr. Bob Smith.

[1] This device technology resulted from a continuing diode phase shifter development program at Microwave Associates, Inc. since 1960. This particular phase shifter was supported by the Advanced Ballistic Missile Defense Agency under Contract DAHC60-70-C-0062.

[2] M. E. Hines, "Fundamental Limitations in RF Switching and Phase Shifting Using Semiconductor Diodes", Proc. IEEE, Vol. 52, No. 6, pp. 697-708, June 1964.

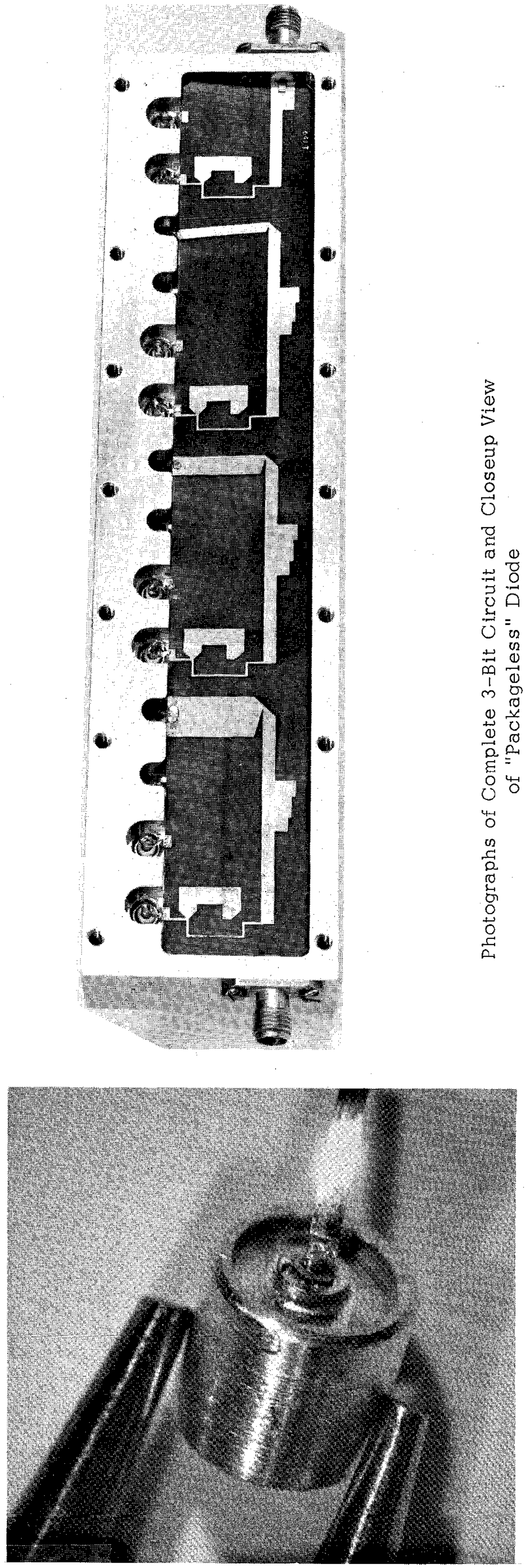


(a) SCHEMATIC DIAGRAM FOR THREE-BIT DIODE PHASE SHIFTER

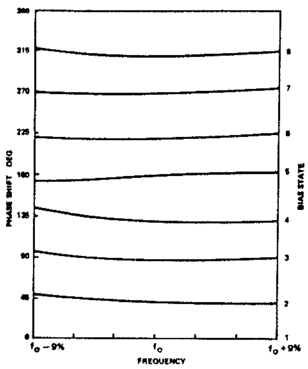


(b) S-BAND STRIPLINE PHASE SHIFTER CONSTRUCTION

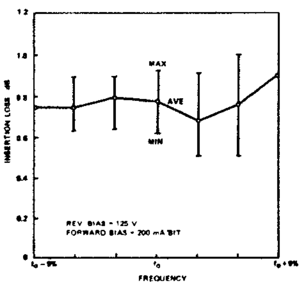
Fig. 1



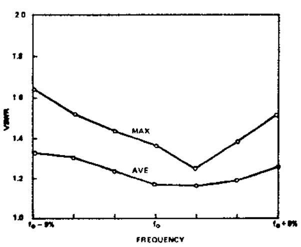
Photographs of Complete 3-Bit Circuit and Closeup View of "Packageless" Diode



(a) PHASE SHIFT VS FREQUENCY OF 3-BIT S-BAND PHASE SHIFTER

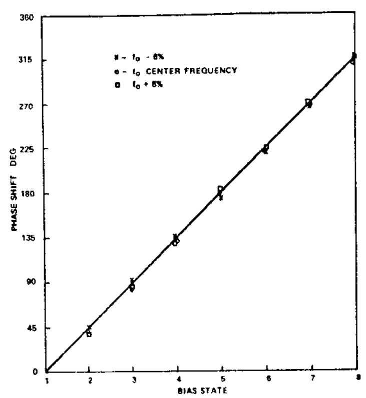


(b) INSERTION LOSS VS. FREQUENCY OF 3-BIT S-BAND PHASE SHIFTER

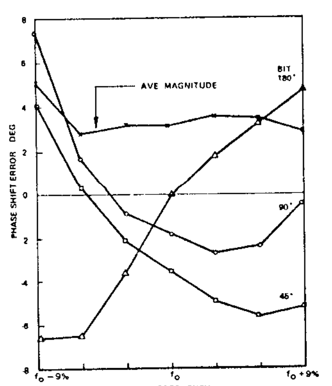


(c) VSWR VS. FREQUENCY OF 3-BIT S-BAND PHASE SHIFTER WITH 0.7 pF DIODES, .140" GPS

Fig. 3



(a) PHASE SHIFT VS. BIAS STATE OF 3-BIT S BAND PHASE SHIFTER



(b.) PHASE SHIFT ERROR VS FREQUENCY OF 3-BIT S-BAND PHASE SHIFTER

Fig. 4

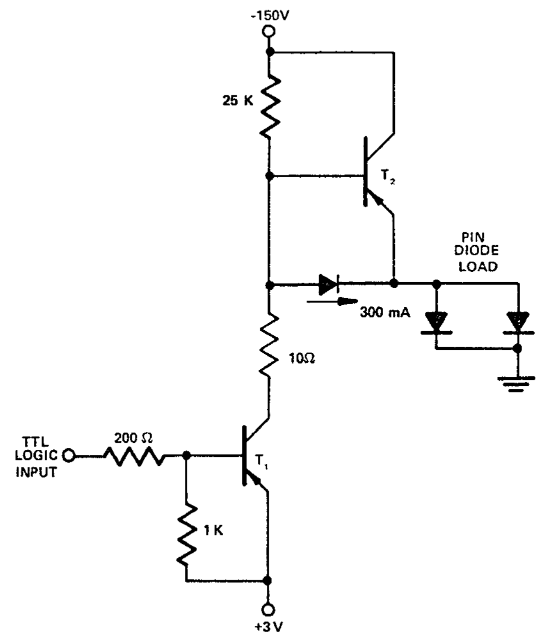


FIGURE 5 TWO-TRANSISTOR DRIVER SCHEMATIC