to 14 GHz and had a peak value of 17 percent at 8 GHz. No spurious oscillations were present during the operation of the oscillator.

VII. Conclusions

Design techniques that have been successfully used on the development of an X-band YIG-tuned FET oscillator have been presented. The design involves an investigation of the interface between the microwave resonator and device and feedback circuit. Small-signal device characterization is utilized and is found to result in excellent agreement between the computer bandwidth predictions and experimental results. The design technique results in maximization of the oscillator bandwidth. Potential resonance and spurious oscillation problems have been discussed and methods for their elimination presented.

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A Fast Low-Loss Microstrip p-i-n Phase Shifter

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***Abstract*—A 4-bit p-i-n phase shifter with low RF attentuation, fast switching time, and low switching power requirements is described. The circuit, made in microstripline, consists of four cells giving phase shifts of 180, 90, 45, and 22.5°, respectively. Each cell consists of a 3-dB coupler loaded by two p-i-n diodes. The transmission loss is 1.6 dB ±0.2 dB over the operating bandwidth of 11.7–12.2 GHz for a biasing current of only 5 mA/cell. Switching time between phase states is 1 ns.**

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I. Introduction

A PHASE SHIFTER has been developed at 12 GHz which has faster switching time, lower switching current requirement, and lower RF transmission loss than phase shifters previously reported at this frequency [1]–[3]. This phase shifter looks attractive for use in phased arrays for airborne and space applications [4]. These utilizations impose severe constraints on the phase shifter in terms of switching power dissipation and switching time duration. To fulfill these requirements, circuit design and diode

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selection were aimed at minimizing the power drain and achieving a switching time in the nanosecond range. The RF circuit is fabricated in microstripline using copper evaporated on a silica substrate in order to obtain a compact circuit with low transmission loss. RF circuit and driver circuit are both enclosed in a single package in order to minimize the switching time.

II. Circuit Description

The circuit consists of four microstrip cells in cascade as shown in Fig. 1. The four cells are designed to provide phase shifts of 90, 180, 45, and 22.5° in the order shown in the figure starting from the bottom of the circuit. Each cell is made of a 3-dB branch-line coupler whose coupling arms are connected to open sections of transmission line with a p-i-n diode in each line to change its electrical length. The four cells are identical except for the position of the diodes and the tuning stubs. In designing the cells, the diodes were positioned to give approximately the required phase shift. Fine phase shift tuning was achieved by means of stubs as shown in Fig. 1. Each cell has an independent biasing circuit with a common return path through the main transmission line. The two diodes of a cell are biased in parallel by a common lead. The biasing circuit consists of a high impedance line connected at $\lambda/4$ from the open end of the arms of the cell. RF decoupling is provided by means of two $\lambda/4$ stubs positioned at $\lambda/4$ from the connecting points. A similar circuit is used for decoupling the common return.

One of the problems encountered in designing the circuit was to confine the four cells in a metallic box designed to avoid parasitic resonances in the operating range of 11.7–12.2 GHz. The 3-dB branch-line hybrid coupler was selected to resolve this problem because of its small size and the compactness of its biasing circuit. The composite bandwidth of the four cascaded couplers was increased from 200 MHz to the required 500 MHz by means of stubs positioned each side of each coupler as shown in Fig. 1. A 50-Ω line impedance was chosen for the coupling arms of the coupler in order to obtain a reasonable line width. As a result, the impedance of the main transmission line is 71 Ω. A $\lambda/4$ transformer was added at each end of the circuit to bring the input and output impedances back to 50 Ω. This solution has the advantage of reducing the diode loss by increasing the ratio between the line impedance and the diode series resistance.

The circuit is fabricated by evaporation of a chrome layer 500 Å thick followed by 2 μm of copper. Experiments performed on phase shifters built with different microstrip metallization showed that the transmission loss can be reduced by 10 percent by using copper instead of gold for the circuit metallization. Fig. 2 shows the transmission loss and return loss of the RF circuit without the diodes. The RF circuit is enclosed in an aluminum box whose inside dimensions are 2.000 in × 0.800 in × 0.300 in. These dimensions have been chosen in order to avoid

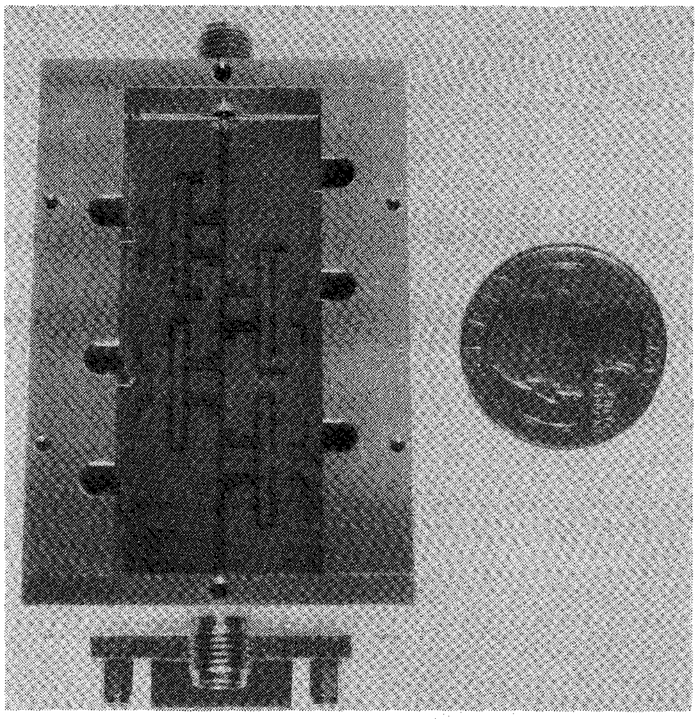

Fig. 1. Photograph of the phase shifter showing the circuit made of four microstrip cells designed to provide phase shifts of 180, 90, 45, and 22.5°, respectively. Each cell is made of a 3-dB coupler and two p-i-n diodes. The four cells are identical except for the position of the diodes and the tuning stubs.

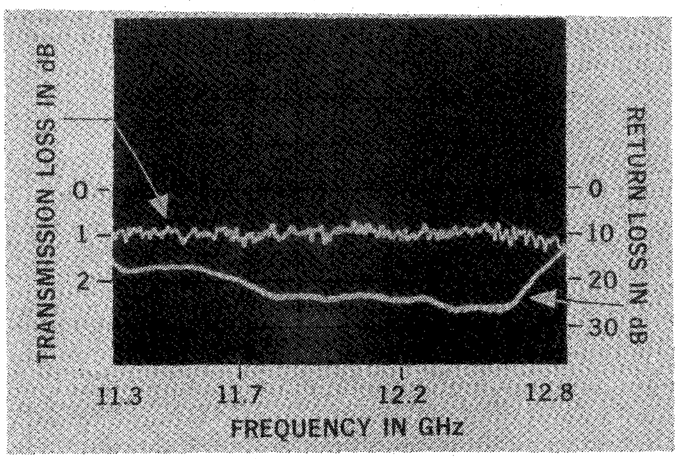

Fig. 2. Transmission loss and return loss of the RF circuit without the diodes for a chrome-copper metallized circuit.

parasitic resonances in the operating bandwidth 11.7–12.2 GHz. The next two resonances occur at 11.3 and 13 GHz. The driver circuit is enclosed on the opposite side of the box with bias pins running between the two sides.

III. Experimental Results

The circuit was first designed at 2.4 GHz in order to facilitate the circuit adjustments and then scaled to 12 GHz. After scaling, only minor corrections had to be made in order to account for the differences of the diode packaging reactance. Diodes from different suppliers were tried. The best results were obtained with Hewlett–Packard beam-leaded p-i-n diodes (HPND-4001) with a

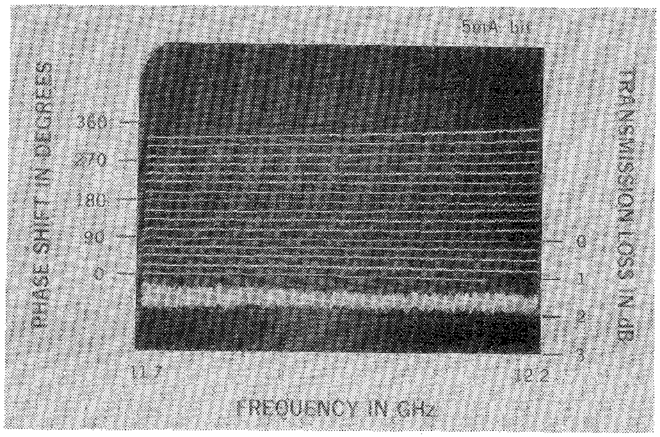

Fig. 3. Display of the 16 phase shift states from 0 to 337.5° by increment of 22.5° over the operating bandwidth. The lower trace shows the corresponding transmission loss varying between 1.8 dB and 1.4 dB over most of the band.

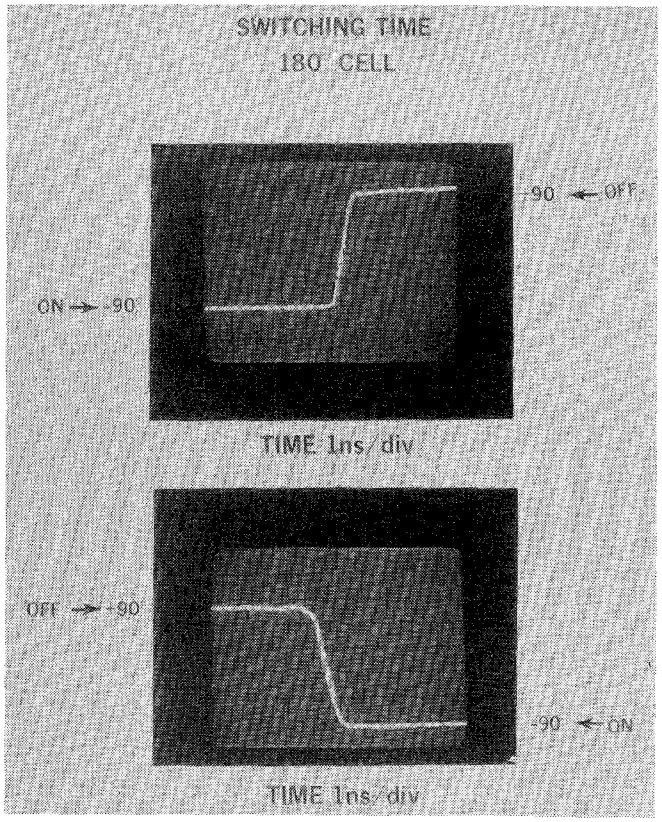

Fig. 4. Photographs showing the switching times of the 180° cell. The switching speed is 0.7 ns for switching off the diodes and 1 ns for switching on the diodes.

capacitance of about 0.07 pF at −30 V and a series resistance of 2 Ω at 10 mA.

Fig. 3 shows the 16 phase states measured over the operating bandwidth. The lower trace shows the corresponding transmission loss which is 1.6 dB ±0.2 dB over most of the bandwidth for a forward current of only 5 mA/cell (2.5 mA/diode) and a reverse voltage of 14 V. The current can be reduced to 2 mA for the 45° cell and to 1 mA for the 22.5° cell with less than 0.1-dB degradation in transmission loss. By increasing the current to 20 mA/cell, the transmission loss can be decreased to 1.3 dB ±0.2 dB.

Switching time was measured with a sampling oscilloscope after phase detection. Fig. 4 shows the switching time for the 180° cell switched from −90 to +90°. The duration is 1 ns for switching on the diodes and 0.7 ns for switching off the diodes. These time durations may be partially limited by the driver circuit which has a switching time of about 1 ns. The dc power consumption of the combined driver [5] and phase shifter was measured when a single cell was pulsed on and off for 1-μs durations with a forward current of 5 mA/cell. At this current level, the total dc power required was 8.75 mW. For the 4-bit phase shifter this indicated an average power consumption of only 35 mW. This may still be reduced to about 28 mW if the 45 and 22.5° cells are forward biased at lower currents as indicated above. Power handling capability has been checked up to 800 mW of RF power, the limit of the available measuring equipment. Analysis indicates that the diode employed should sustain about 1100 mW.

IV. Conclusion

It has been shown that the switching power requirement of a p-i-n phase shifter can be reduced substantially without affecting the RF performance, making its utilization in space array applications feasible. This has been achieved with a low transmission loss of 1.6 dB ±0.2 dB at 12 GHz for a forward current of only 5 mA/cell and a switching time of 1 ns.

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