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MEMS-BASED MINIATURE X-BAND PHASE SHIFTERS

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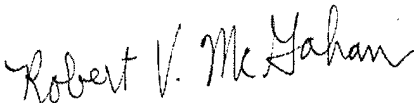
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14. ABSTRACT

The focus of this work was to drive the size and insertion loss of MEMS based phase shifters to an absolute minimum. The work is based on single pole, 4-throw (SP4T) MEMS switches. These novel switches were then applied on the development of low-loss, miniature 2-bit and 4-bit phase shifters. All designs are carried out on 8-mil thick GaAs substrates, a similar substrate typically used for X-band amplifier designs. Measurements indicate an insertion loss of -0.6 dB at 10 GHz for the 2-bit design, and excellent linear phase response and return loss from DC to 18 GHz. The chip area is 9.6 mm2, and is the smallest reported to-date. The 2-bit phase shifter performed well from DC-18 GHz, with -0.8 dB insertion loss at 18 GHz and a return loss of < -10.5 dB over DC-18 GHz. The 4-bit phase shifter based on SP4T switches resulted in a measured average insertion loss of -1.1 dB at 10 GHz, and a linear phase shift response from DC to 18 GHz. The chip area is 21 mm2. This is the highest performing 4-bit phase shifter to-date at X-band, using any technology.

15. SUBJECT TERMS
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1. Summary

This final report covers the period of June 2000 to July 2002 under the contract of Miniature X-Band Phase Shifter Development, John Turtle, Program Monitor. The focus of this work was to drive the size and insertion loss of MEMS based phase shifters to an absolute minimum. The work is based on single pole, 4-throw (SP4T) MEMS switches. These novel switches were then applied on the development of low-loss, miniature 2-bit and 4-bit phase shifters. All designs are carried out on 8-mil thick GaAs substrates, a similar substrate typically used for X-band amplifier designs. This could allow one to implement such a phase shifter directly on the same substrate as current amplifier technology.

Both 2 and 4-bit phase shifters were designed by University of Michigan and fabricated by Rockwell. Measurements indicate an insertion loss of -0.6 dB and at 10 GHz for the 2-bit design, and excellent linear phase response and return loss from DC to 18 GHz. The chip area is 9.6 mm2, and is the smallest reported to-date. The measured losses agree very well with ADS-Momentum simulations. The 2-bit phase shifter performed well from DC-18 GHz, with -0.8 dB insertion loss at 18 GHz and a return loss of <-10.5 dB over DC-18 GHz.

The 4-bit phase shifter based on SP4T switches resulted in a measured average insertion loss of −1.1 dB at 10 GHz, and a linear phase shift response from DC to 18 GHz. The chip area is 21 mm2. The 4-bit phase shifter performed very well from DC-16 GHz with a return loss of < -10 dB. The rms phase error at 10 GHz was less than 2 degrees for the 4-bit design. This is the highest performing 4-bit phase shifter to-date at X-band, using any technology.

2. Development and Measurement of MEMS SP4T Switches

For the SP4T-based phase shifters, the concept is to reduce the number of switches in the signal path by half in any phase state, and hence achieve lower loss than conventional switched-line phase shifters using SP2T switches.

Fig. 1 shows the MEMS SP4T switch used in the phase shifter design. The design of the switch network is based on the assumption that only one switch in each SP4T is turned on for any given phase state. Hence, ideally the equivalent circuit consists of three "open" stubs connected between the input transmission line section and an output section with a series switch that is turned on. Since the relatively short "open" stubs are capacitive in nature, both the input transmission line and the transmission line connected to the switch have to be of relatively high impedance to achieve matching. Depending on the port that is turned on, the SP4T switch exhibits either the "near-port" or the "far-port" response, as shown in Fig. 2.

The bias lines are narrow (5 μm wide) gold lines that are deposited in the same step as the top bias electrodes on the bridge. The DC ground is provided by the bottom bias electrodes, which are connected to the backside of the substrate by 130 μm diameter dry-etched via-holes. The return loss of the SP4T switch is about −14 dB up to 20 GHz, and −20 dB up to 14 GHz, with an associated insertion loss of −0.43 dB at 20 GHz and −0.21 dB at 14 GHz. At 10 GHz, the return loss is −25 dB and the insertion loss is −0.14 dB.
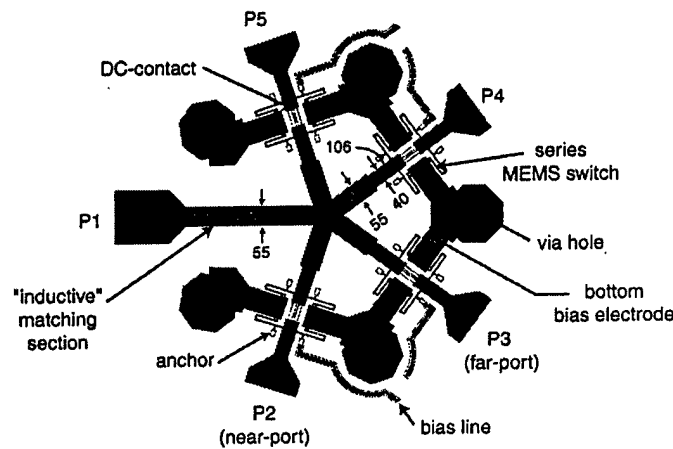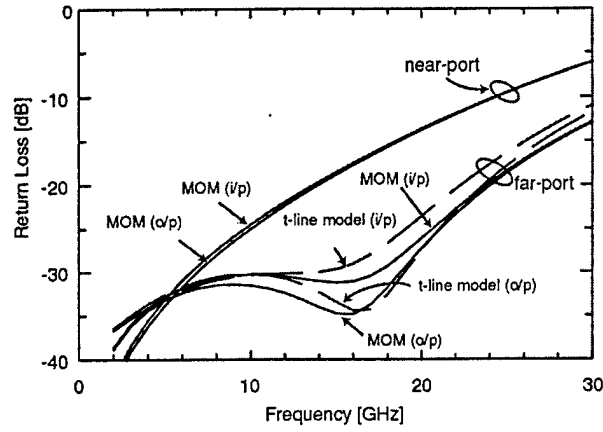

Fig. 1: UoM/Rockwell SP4T MEMS switch based on series switches (all dimensions are in μm).

(a)
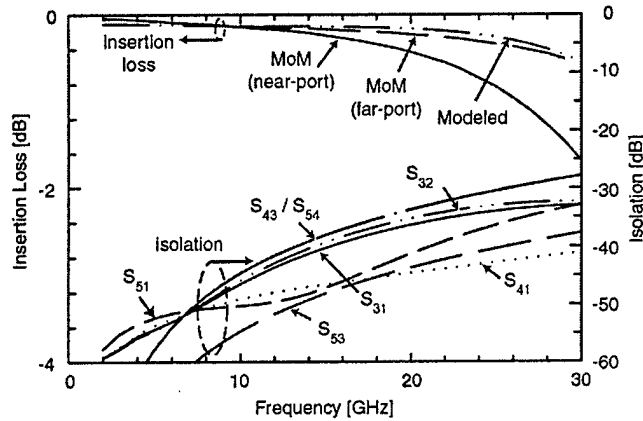
(b)

Fig. 2: Simulated (Momentum (ADS) and transmission line model) performance of the SP4T MEMS switch: (a) return loss and (b) insertion loss and isolation.

The SP4T switches are fabricated using Rockwell's proprietary fabrication process on 8-mil GaAs wafers. Measurements of the stand-alone SP4T switch are available at up to 3 GHz. It is seen that at least –45 dB isolation is obtained up to 3 GHz, and the insertion loss is only -0.1 dB, corresponding to a switch resistance of less than 1 Ω. The isolation and the insertion loss are comparable to the Momentum simulation in Fig. 2.

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Fig. 3: Insertion loss and isolation measurement of the SP4T UoM/Rockwell switch.
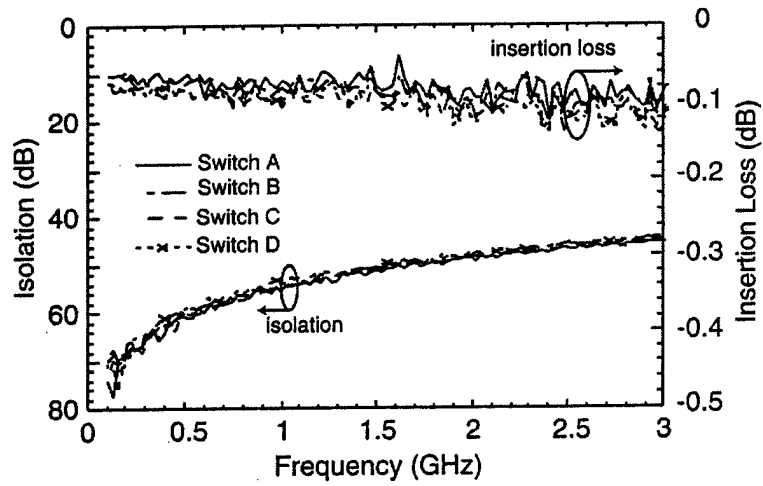
3. X-band 2-bit Phase Shifters based on MEMS SP4T Switches

An X-band 2-bit SP4T-based phase shifter is designed by connecting four delay-lines with electrical lengths of 0/90/180/270° (Fig. 4) between two of the above MEMS SP4T switches.
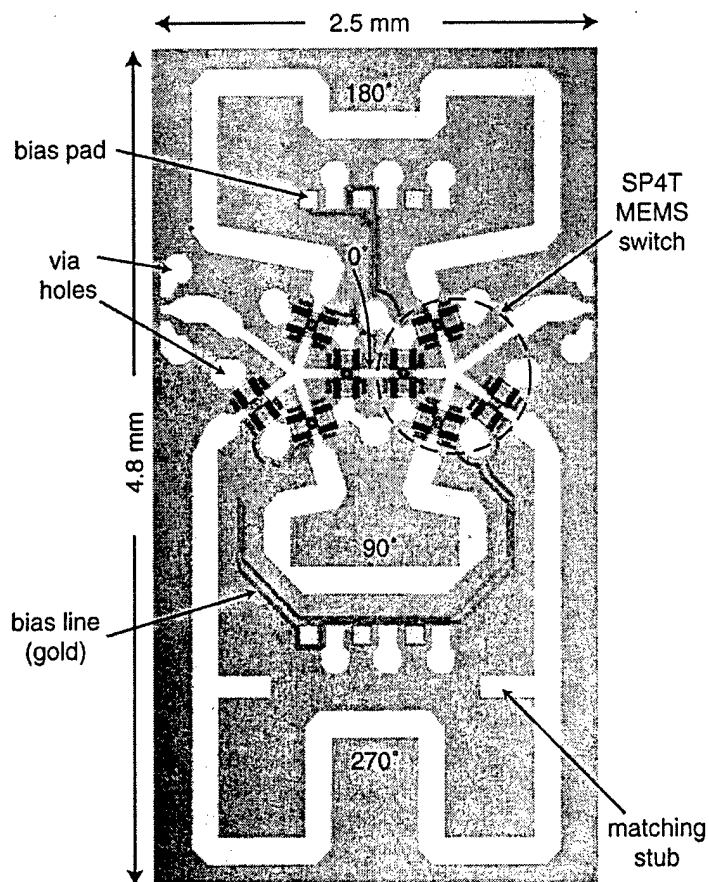
Fig. 4: Picture of the fabricated 2-bit phase shifter based on two SP4T MEMS switches.

The delay-lines are meandered to achieve a compact design while not causing too much coupling (–30 dB max) between any two lines. The SP4T switches are oriented such that the electrical length of the 0° line is almost zero, since this results in the shortest possible delay-lines for each phase state. For the 90° and 180° phase states, the miter fractions for the transmission line bends are adjusted for the best return loss (< -20 dB). In the case of the 270° delay-line, it is necessary to include two short stubs (W=120μm, L=300μm) to achieve –20 dB return loss in X-band. The 5 μm-wide gold bias lines are routed and

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combined into four sets of bias pads. These bias pads are placed between the delay-lines, so as to avoid transmission line cross-overs.

The delay-lines are designed using ADS Momentum simulation assuming 2 μm gold metallization. The delay-lines are first designed individually and then fine-tuned after a combined simulation is performed to include inter-line coupling. The combined S-parameters are then cascaded with the Momentum S-parameters of the SP4T switches and a final adjustment is carried out.

The simulated and measured performance of the X-band 2-bit phase shifters is shown in Figs. 5 and 6.
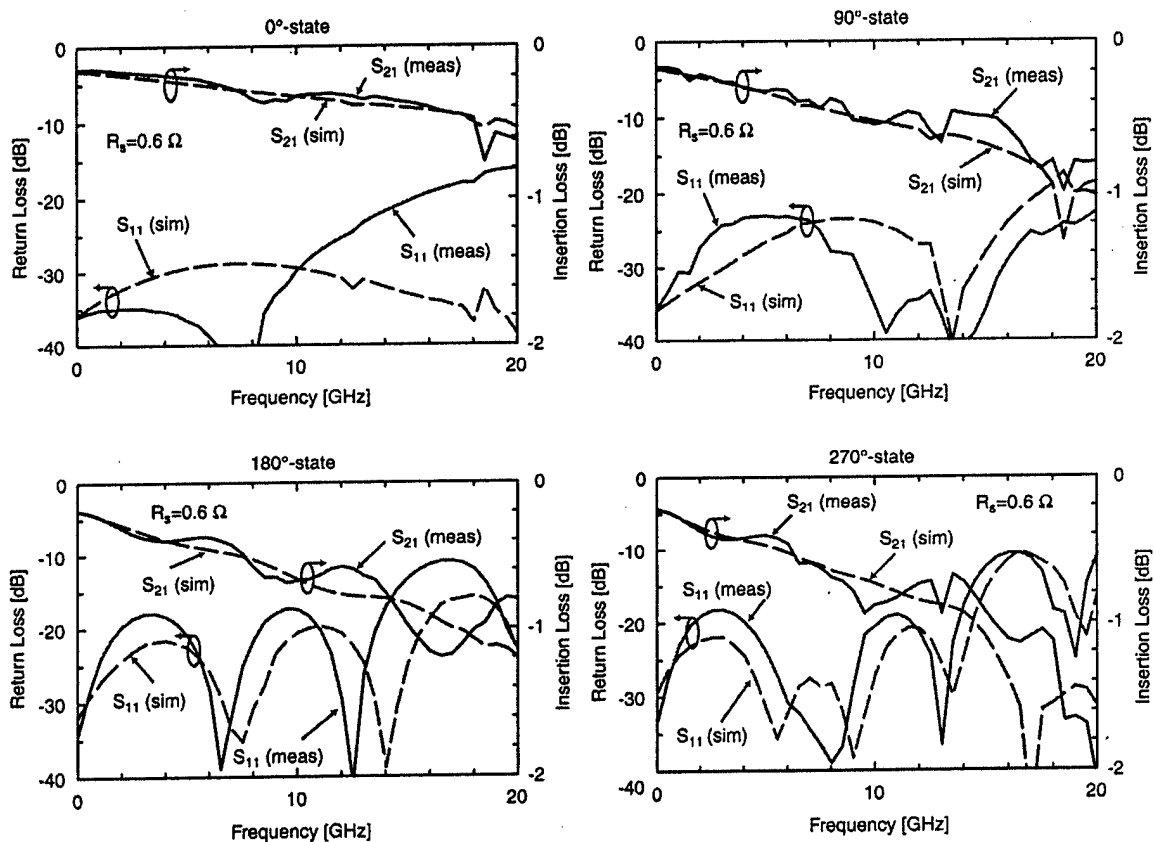

Fig. 5: Simulated and measured performance of the X-band 2-bit phase shifter based on MEMS SP4T switches: insertion and return loss for each state.
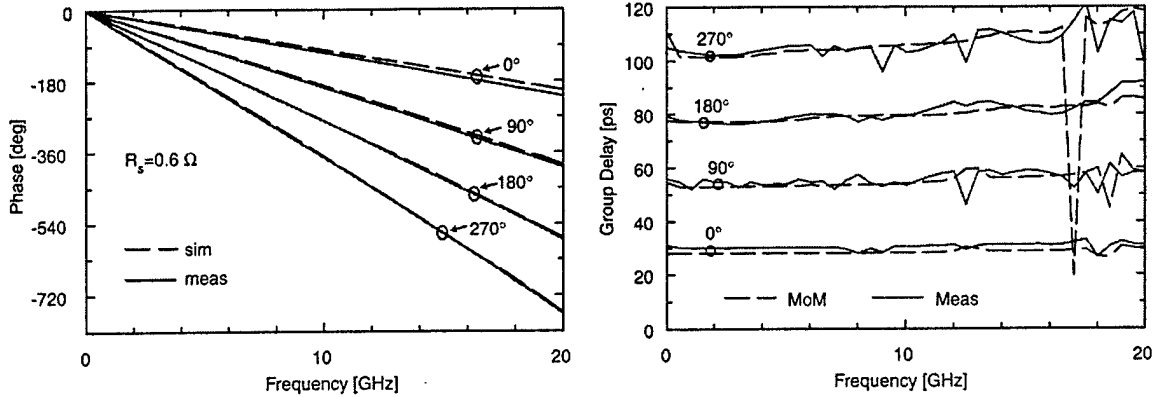
Fig. 6: Simulated and measured performance of the X-band 2-bit phase shifter based on MEMS SP4T switches: phase and group delay for each state.

The measured and curve-fitted insertion loss of the phase shifter is shown in Fig. 5. The "curve-fitting" is identical to the original simulations except with Rs=0.6 Ω instead of 1.0 Ω. The minimum and maximum measured loss within the 8-12 GHz design frequency range are -0.31 dB (0°, 11.5 GHz) and -0.94 dB (270°, 9.5 GHz) respectively, giving a measured loss of -0.62 ± 0.31 dB over all phase states at 8-12 GHz. The associated return loss is better than −17 dB. The variation in insertion loss across the different phase states are inherent in designs using different lengths of delay lines to achieve the phase shift.

The measured insertion loss is better than −1.2 dB from DC-18 GHz (average loss at 18 GHz is −0.85 dB) with a return loss of better than −10.5 dB. Momentum simulation indicates that there is a "dip" in the insertion loss response at around 17 GHz due to off-path resonance. This is also evident in the measured response, but it is shifted to around 20 GHz.

Fig. 6 shows the measured and simulated phase response of the 2-bit phase shifter. The differential time delays as computed by taking the negative gradient of the phase versus frequency response, are 0, 23.9, 49.5 and 73.1 ps respectively, which correspond to a differential phase shift of 0, 88.2, 182.6 and 269.7° at 10.25 GHz (phase accuracy of ±2°). The measured group delay response shows good flatness versus frequency, indicating a true-time delay response from DC-18 GHz.

The 2-bit phase shifter measures 4.8 mm x 2.25 mm, corresponding to an area of 11 mm². The SP4T requires an additional 270° line that is not found in designs based on SP2T switches. Even with this size penalty, careful routing of the transmission lines results in the 11 mm² area, which is as compact as other state-of-the-art MEMS phase shifters, while having a lower expected insertion loss.

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4. X-band 4-bit Phase Shifters based on MEMS SP4T Switches

The 4-bit phase shifter design (Fig. 7) uses four SP4T switches, and is essentially the above "coarse-bit" design (0/90/180/270°) combined with a 0/22.5/45/67.5° "fine-bit" design. The transmission lines for the coarse-bits are re-routed for a more compact layout. Due to the constraints of the line lengths in the fine-bits, the 0°-line is made longer, and the SP4T switches has to take on a different orientation. The coarse-bits and fine-bits are designed separately for the desired phase shift and very good return loss, and the responses are combined.
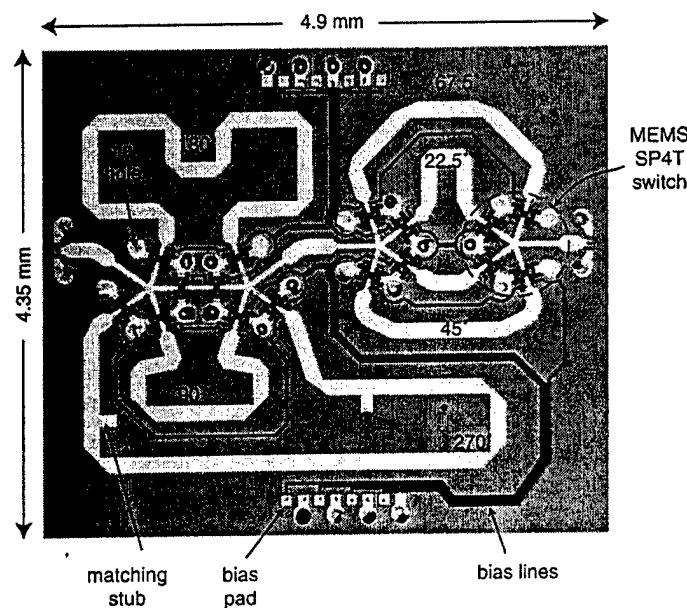

Fig. 7: Picture of the completed 4-bit phase shifter based on four MEMS SP4T switches.
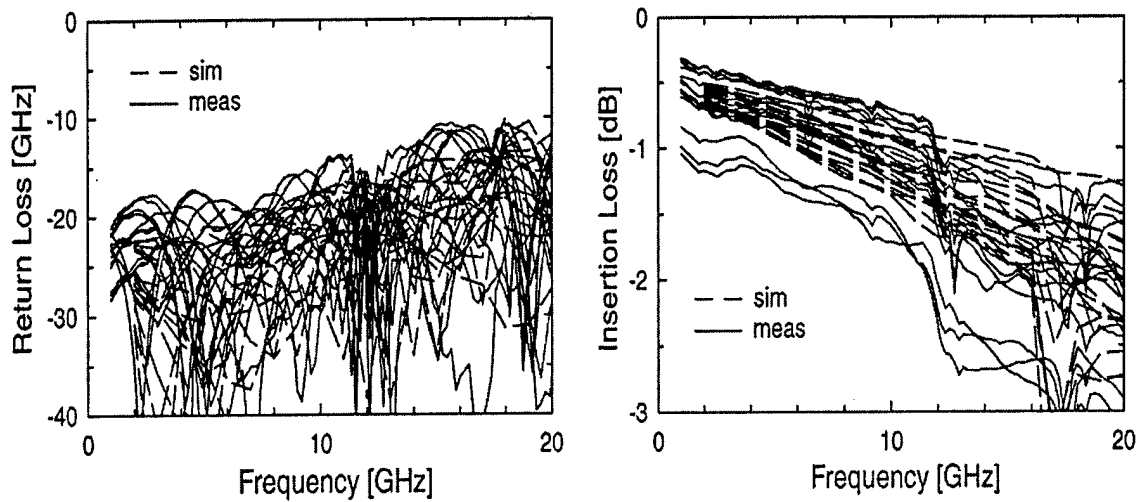
Fig. 8: Simulated and measured return loss (a) and insertion loss (b) of the 4-bit phase shifter.
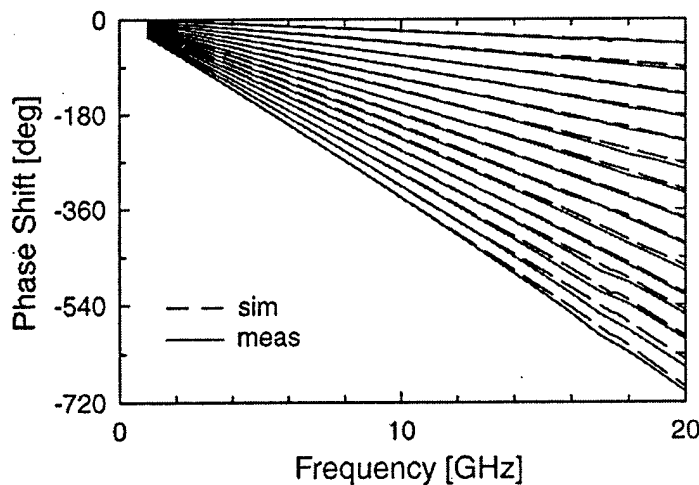
Fig. 9: Measured and simulated phase shift of the 4-bit SP4T RF MEMS phase shifter.

The measured results are shown in Figs. 8 and 9. The "curve-fitting" is identical to the original simulations except with Rs=0.6-0.7 Ω instead of 1.0 Ω. The minimum and maximum measured loss at 10 GHz are -0.7 dB (0°) and −1.6 dB (270°) respectively, giving an average measured loss of −1.15 dB over all phase states at 10 GHz. The associated return loss is better than −15 dB at 10 GHz. The variation in insertion loss across the different phase states are inherent in designs using different lengths of delay lines to achieve the phase shift.

Fig. 9 shows the measured and simulated phase response of the 4-bit phase shifter. The phase accuracy is +/-2 deg. at 10 GHz, and is less than 2 deg. rms at 10 GHz. This represents one of the best phase shifters ever developed to-date using any technology. The measured group delay response shows good flatness versus frequency, indicating a true-time delay response from DC-16 GHz.

The 4-bit phase shifter measures 4.9 mm x 4.35 mm, corresponding to an area of 21 mm^2, which is about 5x smaller than the Raytheon reflect-line phase shifter.

5. Preliminary Design of the 2-bit Reflection Phase Shifter

We have performed a preliminary design of the 2-bit 10 GHz reflection phase shifter. This was initially done by connecting 45/90/135°lines to three of the ports of the MEMS SP4T switch in Fig. 1. Since it is possible to omit the switch for the 0°-state, a more compact configuration can be achieved by using an SP3T switch instead of the SP4T switch. Such an implementation using the Rockwell Scientific switch is shown in Fig. 10. The SP3T approach has a better phase linearity and is also less prone to the off-path resonance problem. The return loss of the phase shifter is equivalent to the insertion loss in a typical transmission-type phase shifter. For the 2-bit reflection phase shifter shown in Fig.8, the loss is around – 0.8 dB at 10 GHz, which is comparable to the 2-bit SP4T phase shifter. Note however that these loss values are obtained by cascading the Momentum simulation of the SP3T and SP4T switches to the Libra transmission-line models of the delay lines, and a better loss estimation can only be obtained by using a full-Momentum solution of the entire phase shifter. This will be done together with an optimization of the phase shifter area.

(a)

(b)
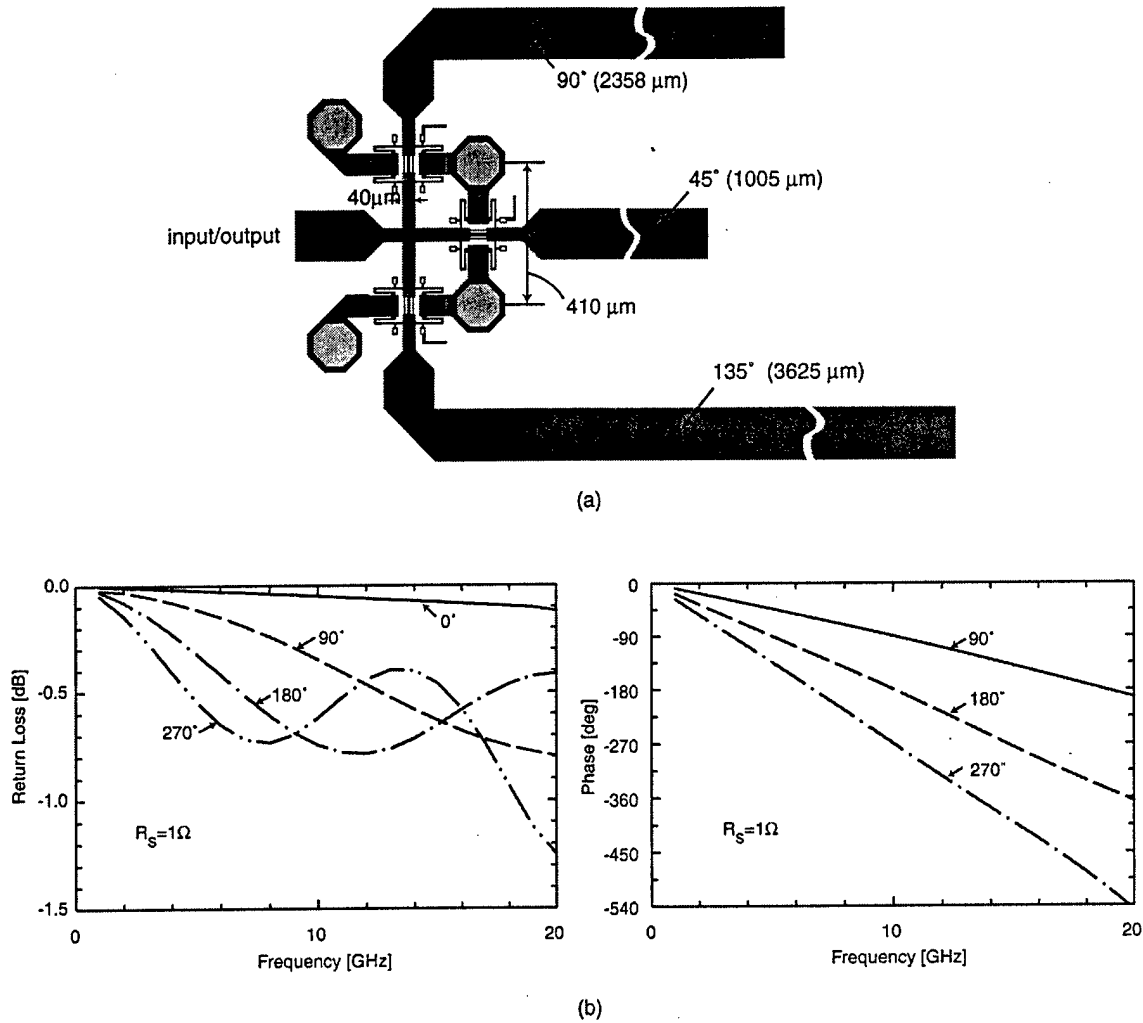
Fig. 10: Preliminary design of the 2-bit reflection phase shifter.

6. Conclusion

We have developed 2-bit and 4-bit phase shifters using RF MEMS switches on GaAs substrates which have shown state-of-the-art insertion loss and phase shift linearity. To our knowledge, the results presented in this report are better than what can be achieved with any other technology to-date. The essential idea is to use an SP4T switch so as to reduce the number of switch stages in the phase shifter, and to design compact transmission-line delay units using advanced electromagnetic simulation.

7. Published Papers:

G.M. Rebeiz, G.L Tan and J.S. Hayden, "RF MEMS phase shifters: design and applications," *IEEE Microwave Magazine*, Invited paper, vol. 3, no. 2, pp. 72-81, June 2002.

G.L. Tan, R.E. Mihailovich, J.B. Hacker, J.F. De Natale and G.M. Rebeiz, "Low-loss 2- and 4-bit TTD MEMS phase Shifters based on SP4T Switches." To appear in *IEEE Trans. Microwave Theory Techn.* Special Issue on RF MEMS, Jan. 2003.

G-L Tan, G.M. Rebeiz, et. al., "Development of very low loss 2-bit and 4-bit monolithic X-band MEMS phase shifters," Invited Paper, *IEEE Antennas and Propagation Symp.*, July 2001.

G. L. Tan, R. E. Mihailovich, J. B. Hacker, J. F. DeNatale, and G. M. Rebeiz, "A Very-Low-Loss 2-Bit X-Band RF MEMS Phase Shifter," *IEEE Int. Microwave Theory and Techniques Symp.*, pp. 333-335, Seattle, Washington, June 2002.

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