A 4-Bit Miniature X-Band MEMS Phase Shifter Using Switched-LC Networks

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Abstract — **A compact 4-bit true-time-delay MEMS phase shifter fabricated on 8-mil GaAs substrate is described. Miniaturization of the phase shifter is achieved using phase shift networks based on semi-lumped LC circuits and a compact SP2T switch configuration. Trade-off in size and loss is performed to achieve a phase shifter with an area of 7 mm^2 and an average insertion loss of -1.47 dB at 9.4 GHz. The phase shifter has a measured return loss of < -10.5 dB over 8-12 GHz and an RMS phase error of 2° at 9.4 GHz.**

I. INTRODUCTION

As commercial and military systems increasingly move towards smaller, more intelligent and more mobile systems, the demand for low-cost, light-weight and high performance antenna designs is increasing. Passive phased arrays is an enabling technology for such new systems due to the relative simplicity in hardware design [1]. Unfortunately, the losses of conventional multi-bit phase shifters designed using diode or HEMT switches have been prohibitively high for such purpose [2], [3]. Over the past few years, X-band MEMS phase shifters that demonstrate very low losses have appeared [4], [5], [6], [7], [8]. However, these components are relatively large due to the large area occupied by the long delay lines. Besides, in a multi-bit design, it is difficult to optimize the space occupied by the different phase bits with varying sizes. This was partially solved by using SP4T MEMS switches [9], but a 4-bit phase shifter still occupies an area of 21 mm^2. Further miniaturization of low-loss MEMS phase shifters is desired to achieve a lower component cost, which is especially important for large aperture electronically-scanned antennas.

Miniaturization of FET- and diode-based phase shifters have been attempted in the past using switched low-high pass lumped LC networks, or embedded-FET approaches [2], [3]. Such phase shifters have achieved an extremely small size of only 1-2 mm^2 for a 4-bit design, but the losses associated with the low-Q inductors or transistor series resistance unfortunately result in 5-6 dB losses for a 4- or 5-bit design in the 10-20 GHz range. A different approach is therefore required for the miniaturization of low-loss MEMS phase shifters.

A 2-bit miniature X-band MEMS phase shifter with an area of 5 mm^2 and an average loss of -0.7 dB at 9.45 GHz has been successfully designed and fabricated using semi-lumped LC phase shift networks [10]. This paper is an extension of the same concept to a 4-bit design, and demonstrates that a 4-bit design can be achieved with only a 2 mm^2 increase in area from the 2-bit design, resulting in a phase shifter that is only one-third the size of the smallest known 4-bit MEMS phase shifter [9].

II. DESIGN

A key challenge in the design of the phase shifter is to find a circuit configuration which is not only miniature, but also low loss and broadband (for true-time-delay applications). Otherwise, the attractiveness of using low-loss MEMS switches will be seriously compromised. It is known that a matched lumped-element phase-shift network with up to 90° phase-shift can be implemented using a series capacitor (C) and two shunt inductors (L) in a π-configuration. Such a network was used by Wallace [2] and Campbell [3] in an embedded-FET configuration to achieve extremely compact 4- and 5-bit phase shifters with less than 1.5 mm^2 area. However, the low-Q inductors used accounted for much of the losses in these designs.

A dual form of the above lumped-element phase-shift network takes the form of a series-L, shunt-C π-network, with the phase shift related to the element values by Eq. 1 [10]. This network requires only one inductor and therefore potentially provides a reduction in circuit area.

$$\begin{aligned} X_n &\equiv \omega L/Z_o = -\sin\phi \quad (-90° < \phi < 0) \\ B_n &\equiv \omega C Z_o = -\tan(\phi/2) \quad (-90° < \phi < 0) \quad (1) \end{aligned}$$

With this dual network, it is possible to use the same embedded-FET approach (with series MEMS switches replacing the FETs) to derive very small phase shifters (4 mm^2 for a 4-bit design at X-band). However, very narrow transmission lines (t-lines) are required to achieve a very good return loss, resulting in high insertion losses.

The approach used in this paper is to replace the lumped inductor in Eq. 1 with a lower-loss microstrip transmission line on an 8-mil GaAs substrate. An example is shown in Fig. 1 for the case of the 90° network. Note that two 45° phase-shift networks are used to construct the 90° phase-shift network. This is because such a cascade offers a much wider bandwidth than a single 90° network. In fact, the 45° network is used as the building block for the 45°, 90° and 180° phase bits (Fig. 1).

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For the 22.5° phase bit, a plain transmission line is used as the shunt capacitance required is very small and there is little saving in space even if capacitors are used.

The transmission line in Fig. 1(b) is equivalent to the π-network (L_1, C_1) at the design center frequency. Hence, part of the original shunt capacitance C_t in the lumped element network in Eq. 1 is "absorbed" into the transmission line, and the required impedance (Z) and electrical length (θ) of the transmission line can be computed using Eq. 2. The impedance of the transmission line can, in principle, be chosen arbitrarily within the practical range, as shown in Table I. However, a very high impedance for the t-line, while resulting in a compact circuit, also yields a very narrow line with a high conductor loss, which is not acceptable. Thus, as a design trade-off, the impedance and hence circuit size is increased beyond the minimum possible value to achieve a miniature, yet relatively low-loss design.

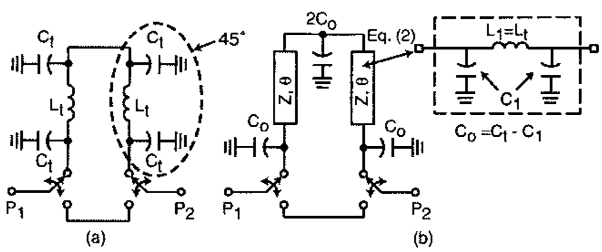


Fig. 1. (a) Equivalent circuit of the 90° phase bit using two cascaded 45° LC phase-shift networks, and (b) its transformation to a semi-lumped network using Eq. 2.

$$1 - \omega^2 L_1 C_1 = \cos\theta$$
$$\sin\theta . Z^2 - \omega Z[Z_o^2(2C_1 - \omega^2 C_1^2 L_1) + L_1] + Z_o^2 \sin\theta = 0 \quad (2)$$

TABLE I
REPLACEMENT TRANSMISSION LINE PARAMETERS AS A FUNCTION OF MIM CAPACITANCE (C_o) FOR A 45° PHASE SHIFT NETWORK AT 10 GHz. THE π-CIRCUIT INDUCTANCE IS CONSTANT AT 562 PH.

MIM Capacitance (C_o)	π-Circuit Capacitance (C_1)	TL Electrical Length (θ)	TL Impedance (Z)
0 fF	131.8 fF	45.0°	50.0 Ω
20 fF	111.8 fF	41.2°	53.5 Ω
63 fF	68.8 fF	32.0°	66.5 Ω
100 fF	31.8 fF	21.6°	95.7 Ω

Agilent ADS Momentum is used to simulate the RF via holes and the microstrip transmission lines of each phase-shift network, and the S-parameters are combined in the circuit simulator with the MIM capacitors, which are simply modeled as RC circuits with $Q = 1/(\omega C_o R) = 40$ at 10 GHz. The phase-shift networks are then connected to compact back-to-back SP2T switches, formed by removing one of the MEMS switches in the reference path and adding two matching stubs for X-band operation (Fig. 2). The input and output t-lines of the series switch A are high impedance (77 Ω) lines, so the two open stubs on each side of the switch form a T-match circuit (shunt-C, series-L) with good match over X-band when switch A is closed. The series MEMS switches used are the standard dc-contact switches developed by Rockwell Scientific [6], which have an up-state capacitance (C_u) of around 1.5 fF and a switch resistance (R_s) of 1-2 Ω. The back-to-back SP2T switch circuit is first simulated using Momentum in the two states (switch A closed, or switches B and C closed). The simulated performance in Fig. 2(b) shows a -20 dB return-loss bandwidth of dc-18 GHz. S-parameters of the SP2T switches and the phase shift networks are then combined to obtain the performance of each complete phase bit (Fig. 3). Each phase bit is designed for better than -25 dB return loss over the 8-12 GHz frequency range. Finally, the complete 4-bit phase shifter simulation is performed by combining the S-parameters of the individual phase bits. Such a piece-wise approach is necessary to result in a reasonable simulation time.

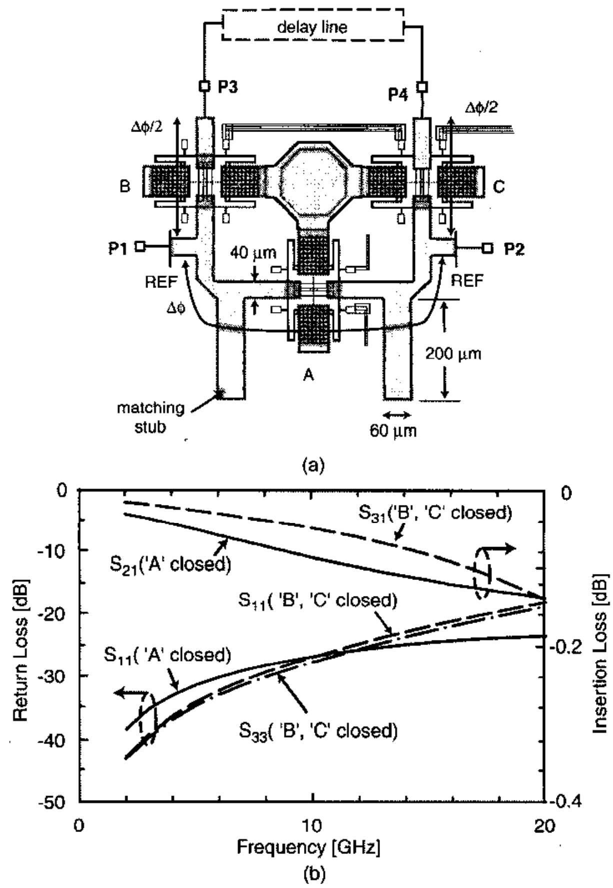


Fig. 2. (a) Layout of the back-to-back SP2T switches, and (b) simulated return and insertion losses, assuming R_s=0 Ω. Insertion loss is increased by $20\log_{10}[2Z_o/(2Z_o + R_s)]$ dB across the bandwidth for non-zero R_s.

A photograph of the complete 4-bit phase shifter is shown in Fig. 4. Comparison of the areas of the individual phase bits with

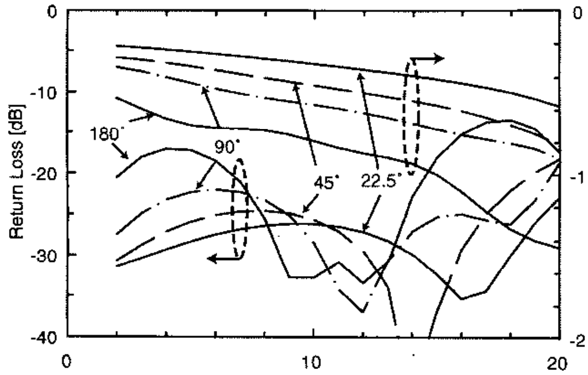


Fig. 3. Simulated return loss and insertion loss of 22.5°, 45°, 90° and 180° phase bits, assuming MIM capacitors with $Q = 40$ and switch resistance $R_s = 1\ \Omega$.

a design using plain 50 Ω transmission lines reveals a space saving of around 30 % for each phase bit. However, in a 4-bit design, it is possible to locate the lower phase bits (which are physically smaller) between the space between the larger phase bits. Therefore, the 4-bit design is only 2 mm^2 larger than the 2-bit version reported in [10].

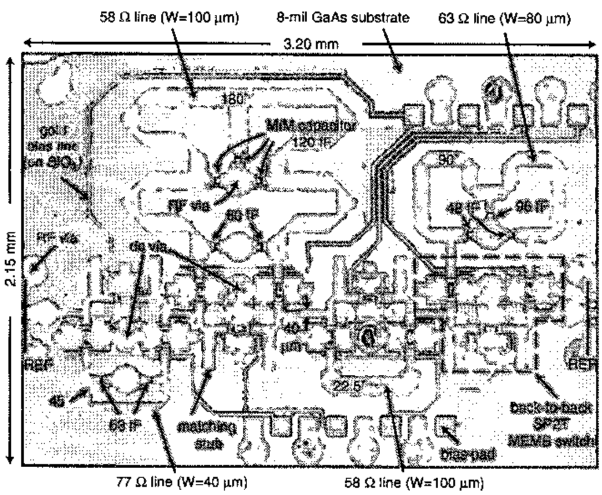


Fig. 4. Photograph of the completed 4-bit miniature MEMS phase shifter.

tion loss is 1.33 dB and 1.64 dB, respectively, and the worst case return loss is −10.5 dB, which is about 3 dB worse than simulation. Measurements and simulations of the insertion loss agree very well up to around 12 GHz, beyond which the measured loss is higher than that of simulation. One possible reason is that the piece-wise simulation approach fails to account for the increased coupling within the compact circuit at the higher frequencies.

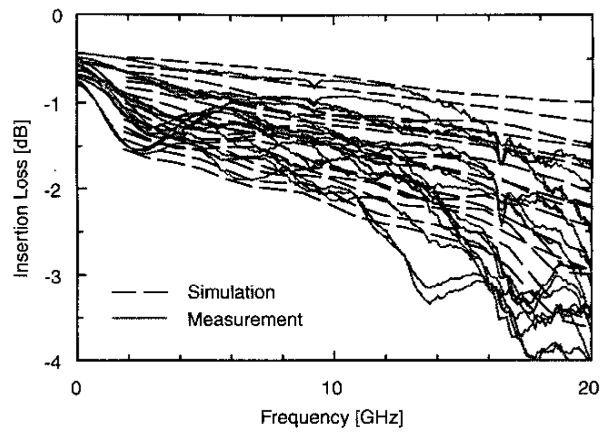


Fig. 5. Measured and simulated insertion loss of the 4-bit miniature MEMS phase shifter.

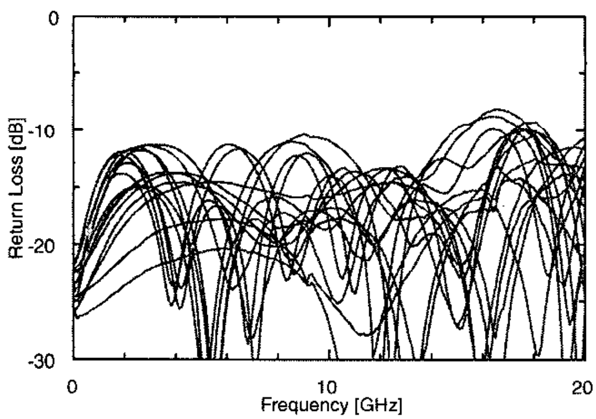


Fig. 6. Measured return loss of the 4-bit miniature MEMS phase shifter.

III. FABRICATION AND MEASUREMENTS

The phase shifter is fabricated using the Rockwell Scientific MEMS process [6]. The MIM capacitors are fabricated in an initial stage, and then protected with polyimide during the fabrication of the MEMS switches. The circuit measures 3.20 mm×2.15 mm (6.9 mm^2) and is only one third the size of the smallest known MEMS 4-bit phase shifter [9].

The 4-bit phase shifter has a measured average insertion loss of −1.47 dB at 9.42 GHz, with an associated return loss of −10.5 dB and an RMS phase error of 2.0° (peak error of +2.7°, −3.3°) (Figs. 5-7). At 8 GHz and 12 GHz, the average insertion loss is 1.33 dB and 1.64 dB, respectively, and the worst case return loss is −10.5 dB, which is about 3 dB worse than simulation.

The center frequency of the phase shifter drifted downwards from the design value of 10 GHz by about 0.58 GHz. This is largely due to the actual MIM capacitor values being larger than design, as shown in Fig. 8(b). Variation in MIM capacitor values can be caused by lateral fabrication tolerance or MIM dielectric thickness variation during fabrication. Fabrication accuracy can be improved in future by replacing the silicon nitride dielectric by air [7], which will result in larger-size capacitors and less sensitivity to fabrication errors.

IV. CONCLUSION

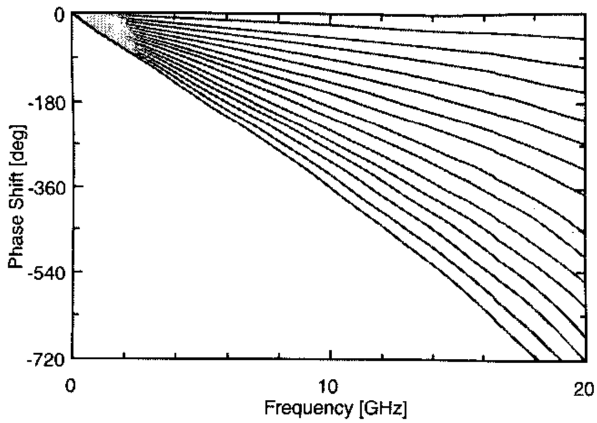
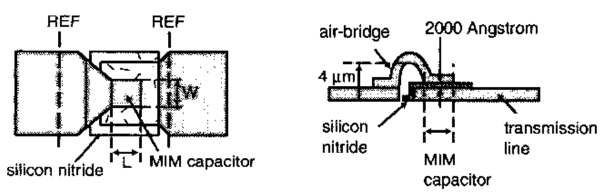


Fig. 7. Measured differential phase shifts of the 4-bit miniature MEMS phase shifter.



(a)

Design (A)	Measured (B)	Ratio (B/A)	Dimension (L×W)
48 fF	82 fF	1.71	10.4×13 μm
60 fF	98 fF	1.63	13×13 μm
96 fF	145 fF	1.51	13.6×20 μm
120 fF	177 fF	1.47	17×20 μm

(b)

Fig. 8. (a) Layout of MIM capacitors, and (b) measured versus design MIM capacitor values.

The semi-lumped approach of designing low-loss phase delay network has been successfully extended to a 4-bit miniature MEMS phase shifter design, resulting in the smallest 4-bit MEMS phase shifter reported to date. A very good average insertion loss of -1.47 dB is achieved, which is only 0.27 dB higher than the lowest-loss 4-bit X-band MEMS phase shifters in the literature [9]. Future areas of improvement include the reduction in the loss variation across the various phase states, and the use of metal-air-metal capacitors to improve fabrication tolerance.

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