# A Very-Low-Loss 2-Bit X-Band RF MEMS Phase Shifter

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***Abstract*— A novel low-loss phase shifter, based on RF MEMS series switches and a single-pole four-throw (SP4T) switch design, is presented. The phase shifter is fabricated on a 200 $\mu$m-thick GaAs substrate, and occupies less than 12 mm$^2$ of space. The measured average insertion loss is −0.55 dB, with a reflection loss of less than −17 dB over the 8-12 GHz frequency range. The 2-bit phase shifter performs well up to 18 GHz with an average loss of only −0.85 dB and a near-perfect linear phase shift from DC-18 GHz. This is the lowest loss MMIC-type phase shifter to-date at 8-18 GHz.**

## I. Introduction

RF MEMS phase shifters have been developed using capacitive or DC-contact MEMS switches [1]-[4]. They are characterized by near-zero power consumption and low-loss performance. The MEMS phase shifters are based on traditional switched-line designs using single-pole double-throw switches [1],[3], or reflect-line designs with 3-dB couplers [2], or on switched distributed MEMS transmission-lines [4]. Typical X-band 2-bit phase shifters show a loss of −0.9 to −1.0 dB when integrated on a GaAs or a high-resistivity silicon substrate, although Goldsmith *et al.* attained an average loss of −0.65 dB at 8.5 GHz by integrating the 3-dB couplers on a ceramic substrate. This results in a hybrid-type phase shifter, with increased assembly cost.

The novel design presented in this paper is based on the realization that one can build a very compact, high-isolation single-pole four-throw switch using RF MEMS DC-contact series switches with a very low up-state capacitance. The SP4T switch can be well-matched up to 18 GHz using a short inductive transmission line (t-line). A 2-bit phase shifter can therefore be synthesized using two SP4T switches, with 4 different sections of t-lines and lengths of 0, 90, 180 and 270°, respectively (Fig. 1a). The advantage is that the RF energy passes by two switches instead of 4 as in a standard switched-line design. Another advantage is that if a bit is not used, then the energy does not pass by a "dead" section of transmission-line (Fig. 1b). Compared to reflect-line designs, the SP4T approach does not use a 3-dB coupler and therefore does not suffer from the associated round-trip loss.

## II. Design and Measurements

The design of the SP4T phase shifter is carried out with a three-step approach. First, the SP4T switch is matched using short inductive sections and Agilent ADS/Momentum,

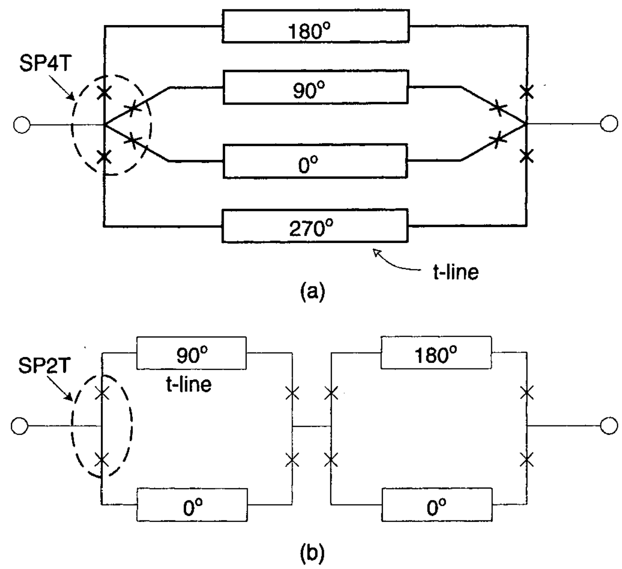


Fig. 1. Two-bit phase shifters based on the (a) SP4T, and (b) SP2T, approach.

and results in excellent performance up to 20 GHz. Second, the four delay lines are simulated using Agilent Momentum as an 8-port network. The resulting S-parameter matrix includes the coupling between the lines and allows us to change the delay line geometry to yield the most compact layout. After several iterations, the SP4T switches are cascaded with the delay lines to yield the overall performance of the phase shifter. Notice that two short open-stubs are placed in the 270° delay line for improved matching in the 8-12 GHz band.

The SP4T is fabricated at Rockwell Scientific on a 200 $\mu$m GaAs substrate using an RF MEMS series switch described in detail in [5]. The Rockwell Scientific switch has a $C_u$ of 2 fF and an isolation of −38 dB at 10 GHz. A gold-alloy contact metal is used, and the average down-state switch resistance is 1 Ω. Via-holes around the switches are used for dc-biasing, i.e. ground return (Fig. 1a). The overall area of the chip including the biasing network is 12 mm$^2$, making this the smallest RF MEMS phase shifter to-date. A photograph of the fabricated phase shifter is shown in Fig. 2.



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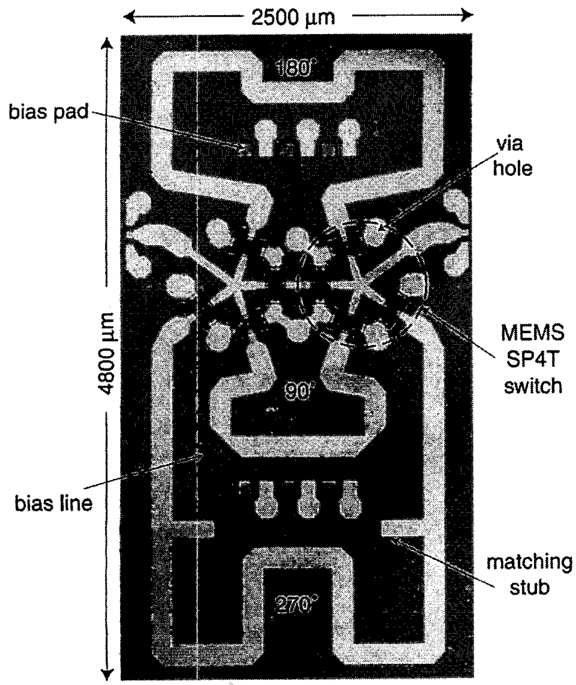
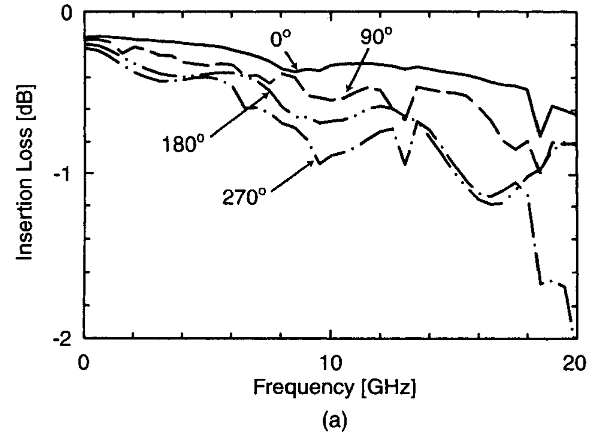



Fig. 2. Photograph of the low-loss SP4T 2-bit phase shifter.

The measurements are calibrated to the probe tip and include the loss of the input and output CPW-to-microstrip transitions. An average loss of $-0.5$ to $-0.6$ dB at 8-12 GHz is obtained, with a reflection loss of better than $-17$ dB in all four states (Fig. 3). The measured differential time delays are 0, 23.0, 49.0 and 72.8 ps respectively, which correspond to a differential phase shift of 0, 90.1, 177.8 and 272.0° at 10.25 GHz (Fig. 4). The measured phase shift is linear up to 18 GHz, making this design a true time delay phase shifter from 10-18 GHz. At 18 GHz, the measured average loss is only $-0.85$ dB, with a reflection loss of better than $-11$ dB. ADS/Momentum simulations agree very well with the measurements (within $\pm0.05$ dB in amplitude and $\pm3$ dB in reflection loss), and are not shown.

## III. Extension to 4-Bit Designs

The SP4T design can be extended to 4-bit phase shifters as shown in Fig. 5. In this case, a 0/22.5/45/67.5°-cell is cascaded after the 2-bit phase shifter. Again, the RF energy passes by 4 switches instead of 8 as in a standard switched-line design. This results in at least 0.4 dB less loss. The phase shifter area including biasing networks is 21 $mm^2$ on a 200 $\mu$m-thick GaAs substrate. Simulations indicate an average loss of $-0.85$ dB, with a reflection loss below $-18$ dB at 10 GHz, and a linear phase-shift up to 18 GHz. Measurements will be presented at the conference.



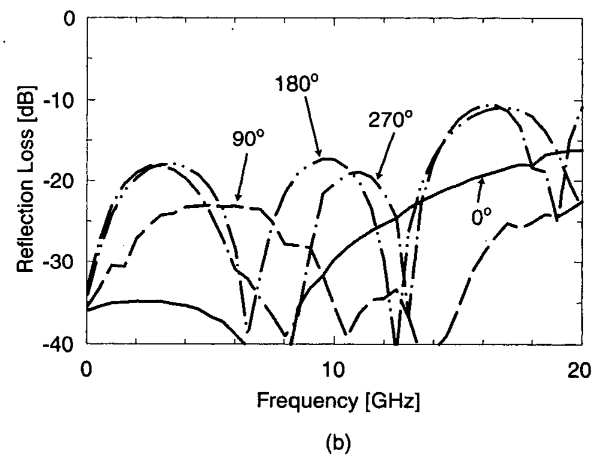




Fig. 3. (a) Measured insertion loss, and (b) reflection loss of the SP4T 2-bit phase shifter.

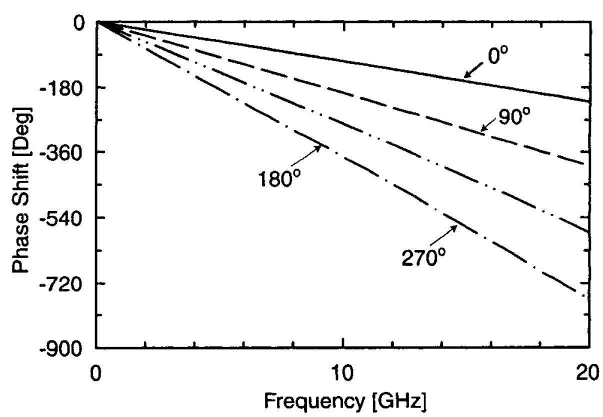



Fig. 4. Measured phase-shift of the SP4T 2-bit phase shifter.

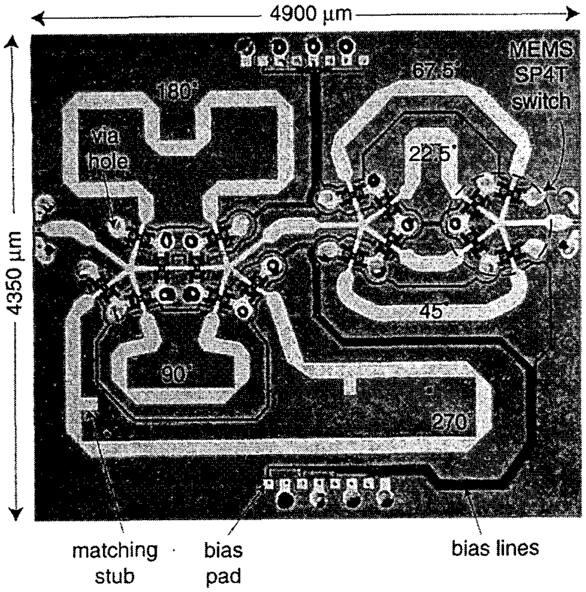



Fig. 5. Layout of a 4-bit SP4T-based phase shifter.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