A 15-to-45 GHz Low-Loss Analog Reflection-Type MEMS Phase Shifter

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Abstract — A low-loss broadband reflection-type phase shifter (RTPS), showing constant phase shift from 15 to 45 GHz, was developed using MEMS technology. The analog phase shifter consists of two cascaded reflection-type phase shifters for 1:3 bandwidth. Air-gap overlay CPW couplers were employed for low-loss 3 dB coupling, and bridge-type MEMS variable capacitors were used for low-loss reflective terminations. The fabricated phase shifter shows the average insertion loss of 3.63dB, and rms phase error of 3.7° from 15 to 45 GHz. Compared with the similar RTPS using GaAs PHEMT varactor diodes, much lower loss is observed together with improved bandwidth.

I. Introduction

Radio Frequency (RF) MEMS (microelectromechanical systems) technologies have been successfully applied to the development of low-loss RF switching devices and variable capacitors [1]-[2]. RF MEMS capacitive switches and variable capacitors have demonstrated significant performance advantages over the conventional electrical PIN diodes and varactors in terms of lower loss, lower parasitics and higher linearity. Due to these advantages, they have been enabling components for low-loss phase shifters, which is a critical circuit for modern radar and communications systems. A number of micromachined phase shifters using MEMS technology have been developed for active phased array antennas (APAAs) [3]-[4]. These phase shifters are based on either distributed loaded lines or switched lines, and thus exhibit linear relationship between the phase shift and the frequency.

Another type of broadband phase shifter requires constant phase over a wide frequency range. Reflection-type phase shifter (RTPS) has been widely used for this purpose. RTPS was first introduced by Hardin [5]. Hardin proposed a simple circuit for the reflective terminations incorporating a single varactor diode. The resulting frequency response of the relative phase shift has a single hump. This hump can produce a maximum bandwidth of approximately 5-10%, for a phase error of ±5° between a 0° and 180° relative phase shift. Attempts to widen the bandwidth of RTPS have been proposed by many authors [6]-[7]. Boire [6] developed a 1:4 bandwidth digital 5-bit MMIC phase shifter and Miyaguchi [7] developed frequency independent 180° RTPS. However, these broadband concepts can only be applied to one phase difference state. Therefore, several broadband RTPS's should be cascaded to implement multi-bit phase shift, which result in excessive loss.

Lucyszyn [8] proposed a novel method for increasing the bandwidth by cascading two matched RTPSs. In this method, the center frequency of the first-stage RTPS hump is set to the low-frequency end while that of the second one is set to the high-frequency end. In this way, flat frequency response could be achieved over significantly wider bandwidth than the simple RTPS. Based on this concept, the authors have developed a wideband cascaded CPW MMIC RTPS [9]. Gate-to-source diodes of GaAs PHEMT have been used as varactors. The MMIC circuit exhibited low phase error of 5.5° over a wide frequency band from 27 to 47GHz. However, the insertion loss was rather high (6.9 dB) due to the large series resistance of the PHEMT diode.

In this paper, we report a low-loss 1:3 bandwidth RTPS using MEMS technology for the first time. The fabricated analog MMIC phase shifter showed extremely flat phase shift (rms phase error=3.7°) and low loss (average loss=3.63dB) from 15 to 45 GHz.

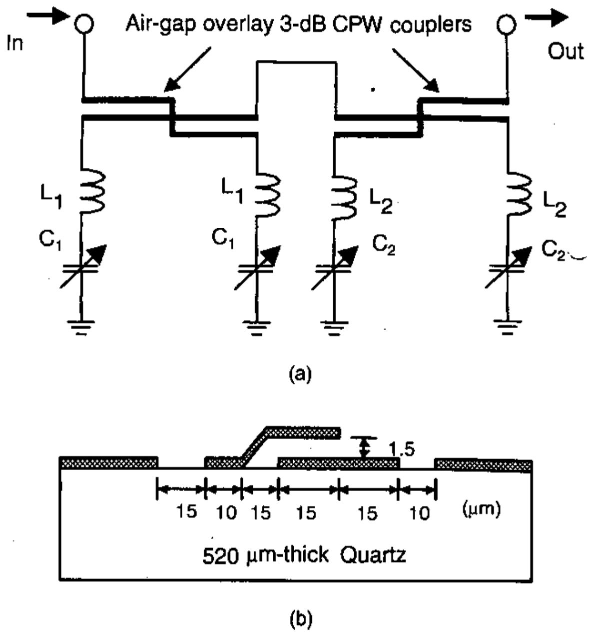

Fig. 1. (a) Circuit schematic of two-stage reflection-type CPW analog phase shifter. (b) Cross section and detailed dimensions of air-gap overlay coupler.

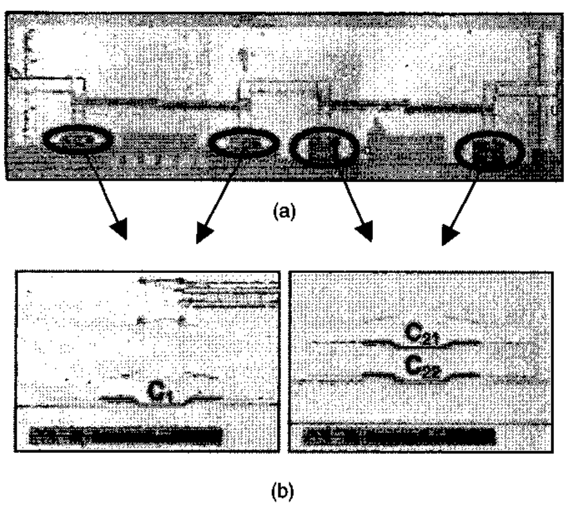

Fig. 2. (a) Photograph of the fabricated two-stage reflection-type CPW analog phase shifter and (b) reflective termination circuits of each RTPS stage.

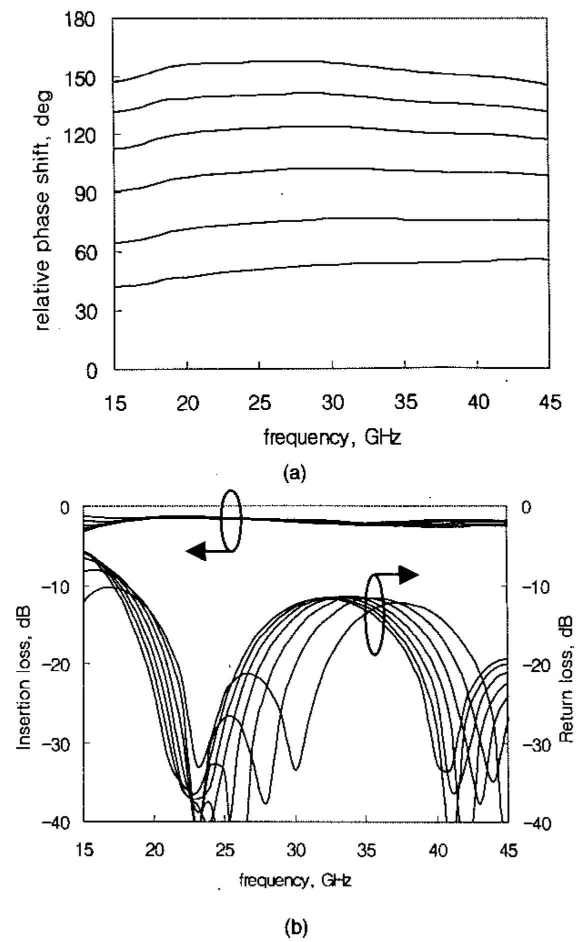

Fig. 3. (a) Simulated relative phase shift responses and (b) insertion loss and return loss responses. Variable-capacitance ratio increases by 0.5 from 1.5 to 4.

II. DESIGN AND FABRICATION

Fig. 1(a) shows the circuit schematic of the 15-45GHz 2-stage cascaded reflection-type analog phase shifter. Air-gap overlay CPW couplers developed by the authors [10] were used for wideband 3-dB coupling. In the overlay coupler, the air-gap offset broadside coupling between two lines offers tight coupling and reduces the conductor loss by redistributing currents over broad surfaces. Compared with the standard Lange coupler, this coupler results in tighter coupling and lower loss. The coupler was designed with the center frequency of 32 GHz. The detailed dimensions of the coupled line structure are shown in Fig. 1(b).

The reactive termination circuit at the two arms of the coupler is a series L-C circuit, where the inductor is realized with a short-section of CPW transmission line and the capacitor is realized with MEMS variable capacitors.

The MEMS variable capacitor is a bridge-type metal-air-metal (MAM) capacitor. MEMS bridges are suspended 1.5∝m above the coplanar strip line and supported by the posts on both sides. It acts as a variable capacitor by applying the voltage between the plates, which generates the electrostatic force to change the distance between the two electrodes. A 0.3 ∝m–thick SiN layer is deposited on top of the strip lines under the MEMS bridge to prevent DC short. The initial (unbiased) C_1 and C_2 (C_1 = 48 fF, C_2 = 96 fF) and inductances L1 and L2 (L1,L2 : Z_0=50□, l=120∝m CPW transmission line) were determined to achieve the phase shift flatness from 15 to 45GHz [8]. When the bridge is pulled down completely, the capacitor becomes metal-insulator-metal (MIM) capacitor, and the maximum capacitance in this case was assumed to be about four times as much as the initial capacitance. Under this condition, the phase shift as much as 156° could be obtained at 32GHz from the simulation. The top plate size for C1 is 80∝m x 100∝m, and two capacitors of this size are used for C_2. (Fig. 2(b)).

Fig. 3 shows the simulated phase shift and S-parameters of the cascaded 15-45GHz RTPS. In Fig. 3 (a), each curve from the bottom corresponds to the capacitance values that are increased from 1.5 to 4 times the initial capacitance in steps of 0.5. As can be seen from Fig. 3 (a), the relative phase shift is flat over 15-45GHz with maximum rms phase error of 4°. Insertion loss is less than 3.4dB from 15 to 51GHz and the input and output return losses are better than 10dB from 18 to 51GHz. Fig. 2(a) is the photograph of the fabricated CPW analog reflection-type phase shifter. The chip size is 1.2 mm x 4.6 mm.

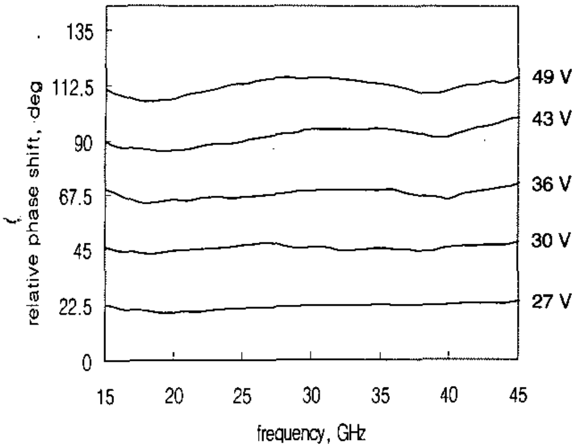

Fig. 4. Measured relative phase shift from 15 to 45 GHz. Applied biases at each phase state are specified at the right-hand side of the graph.

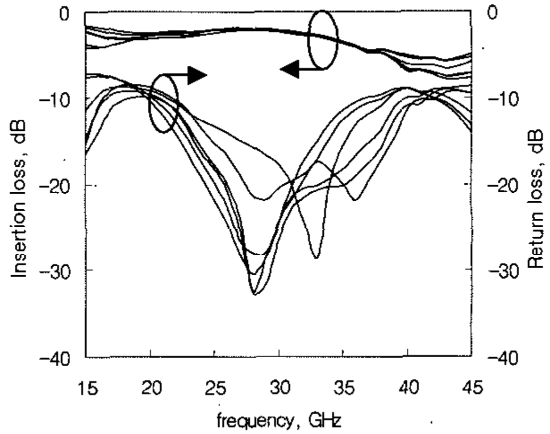

Fig. 5. Measured insertion loss and return loss responses.

III. MEASUREMENTS

Fig. 4 shows the measured relative phase shifts of 15-45GHz RTPS as a function of frequency. The bias voltage for variable MEMS capacitors varied from 0V to 49V. The pull-down voltage is around 47 V. Measured relative phase shift increases by 22.5°, and the maximum rms phase error is 3.7°. The phase shift can be increased to 123° at 32GHz by applying the bias voltage higher than the pull-down voltage. Compared with the simulation result in Fig. 3, the measured result shows smaller phase shift range. This is attributed to the reduced C_{max}/C_{min} ratio after fabrication, which is estimated to be about three instead of four. The initial air-gap dimension as well as the thickness of the SiN dielectric layer appears to be the sources of the problem.

Fig. 5 is the measured insertion loss and return loss of the phase shifter at each phase state from 15 to 45GHz. The average insertion loss is 3.63dB between 15 and 45 GHz. For the same frequency range, the measured return losses are better than 8dB. Compared with the similar RTPS using the GaAs PHEMT varactor diodes that showed average insertion loss of 6.9 dB between 24 and

47 GHz [10], noticeable advantage is observed in terms of the loss and bandwidth.

IV. CONCLUSIONS

A micromachined wideband reflection-type analog phase shifter showing constant phase shift from 15 to 45 GHz has been designed, fabricated and tested. This analog phase shifter employs two cascaded reflection-type phase shifters to achieve 1:3 bandwidth. The MEMS variable capacitors and the offset air-gap overlay couplers help to reduce the insertion loss considerably compared with conventional RTPSs using the semiconductor varactor diodes. This work clearly shows the advantage of micromachined phase shifters for low-loss ultra broadband applications.

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