A V-Band CPS Distributed Analog MEMS Phase Shifter

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Abstract — In this work, a new V-band CPS analog distributed MEMS phase shifter has been developed. Since this phase shifter is based on the balanced CPS lines, no extra mode transition structure is required for integration with the balanced circuits using CPS or slot line as well as for packaging in the waveguides. MEMS bridges over the coplanar strip lines are used to control the mutual capacitance between two CPS strip lines, consequently the phase response of the capacitively loaded CPS line. The fabricated phase shifter showed 55º/dB at 40 GHz and 74º/dB at 60 GHz. The return loss is better than 8 dB over a wide frequency range from 1 to 70 GHz. For measurement with CPW-based on-wafer system, a new ultra wideband CPW-to-CPS transition has also been developed, and showed a low insertion loss less than 1.9 dB from DC to 110 GHz.

I. Introduction

Analog and digital phase shifters using coplanar waveguide (CPW) lines loaded with distributed microelectronical system (MEMS) bridges have recently demonstrated broadband characteristics with very low loss [1]-[3]. Another advantage of CPW-based phase shifters is the uniplanarity. Since they use only one side of the substrate, costly through-substrate via hole process can be eliminated, resulting in low cost.

Coplanar strip (CPS) lines are another uniplanar transmission lines of interest. Unlike CPW, they operate in a balanced mode. When the CPW phase shifters are integrated with the balanced circuits based on CPS or slot lines, there is a need for proper transition structure that transforms the unbalanced signals in CPW to the balanced signals. In this case, extra loss is introduced and the bandwidth is reduced [4]-[10]. In this regard, CPS phase shifters are much preferred for balanced circuits. Furthermore, CPS phase shifters can be easily integrated with standard waveguides, which are standard medium at mm-waves, since both structures support balanced signals and the transition from waveguide to CPS can be easily achieved using tapered uniplanar finlines. However, no MEMS phase shifters based on the CPS structures have been reported up to now. In this work, a V-band CPS distributed MEMS phase shifter has been developed for the first time, In addition, a new wideband CPW to CPS transition has also been developed for on-wafer measurement of the CPS phase shifter using CPW-type probes.

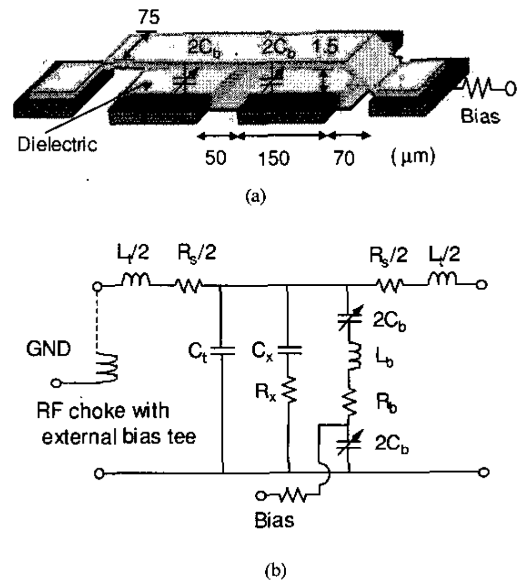

Fig. 1. (a) Schematic and (b) equivalent circuit of the unit cell of a CPS phase shifter with a MEMS bridge.

II. PROPOSED STRUCTURE AND DESIGN

The CPS MEMS distributed phase shifter consists of a high impedance CPS line (Z_0 =110 Ω, width=150 μm, gap=50 μm), capacitively loaded by the MEMS bridges periodically located alongside the line as shown in Fig. 1(a). MEMS bridges are suspended 1.5 μm above the

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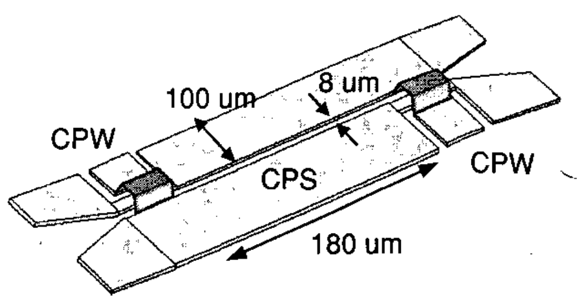


Fig. 2. Schematic of wideband CPW to CPS transition (back-to-back) for on-wafer measurement.

coplanar strip line and supported by the posts on both sides. Bias voltage is connected to the MEMS bridge through a 5-KΩ NiCr resistor while the CPS line is connected to DC ground by external bias tee. A 0.3 μm–thick SiN layer is deposited on top of the strip lines under the MEMS bridge to prevent DC short. With the application of the bias voltage between the strip lines and MEMS bridge, the bridge is pulled down closer to the strip lines, resulting in the increase in the mutual capacitance between two strip lines of CPS. This has the effect of changing the phase velocity of the CPS lines, which can be effectively used to control the electrical phase shift of the lines with the fixed physical length.

The equivalent circuit model of the unit cell is shown in Fig. 1 (b). In the current CPS design, a loaded line impedance range of 56.5 - 65 Ω has been selected to maintain the return loss below -11 dB up to 70 GHz, and the Bragg frequency is 145 GHz under the condition of the maximum capacitive loading. The choice of the rather high impedance range (> 50 Ω) helps to reduce the conductor loss by avoiding the use of the low-impedance CPS lines, which results in high conductor loss due to the narrow gap between the two lines. The length of the unit cell is 200 μm and zero-bias bridge capacitance seen by the CPS line is 33 fF, which has been calculated from series combination of the two MEMS capacitor (75 μm x 150 μm) between two strip lines and a single bridge. When the gap between bridge and strip lines is changed from 1.5 to 1.0 μm, phase shift of the unit cell simulated using IE3D is about 9.5° at 60 GHz.

In order to test the CPS phase shifter using the standard CPW on-wafer probes, a wideband CPS-to-CPW transition is required. For this purpose, an ultra broadband CPS-CPW transition has also been developed. The back-to-back transition is shown in Fig. 2. It is based on the CPW to Slotline transition [7], but optimized for CPS mode of operation. At the mode transition point, two CPW ground planes are connected together via underpass, and transforms to the first CPS conductor. The CPW center conductor crosses over the underpass in the form of air-bridge and then transforms to the second CPS conductor. Since the structure does not rely on bulky and band-limited resonant components such as λ/4 open or short stubs [4]-[5], it can be realized in a small size and shows ultra wideband characteristics.

The CPS MEMS phase shifter integrated with CPW-to-CPS transitions was fabricated using electroplated gold structures on a 520 μm -thick quartz substrate (ε_r = 3.8). The thickness of the CPW line and the bridge is 3 μm and 2 μm, respectively. The details of the fabrication technology can be found in our previous work [11].

III. MEASURENENTS

Fig.3 shows the photograph of the fabricated V-band CPS distributed MEMS phase shifter with 19 bridges and integrated CPW-to-CPS transitions at the input and output ports. The overall chip size including the bias circuits and transitions is 4.5 mm x 0.8 mm. RF measurements were performed using Agilent 8510XF network analyzer, calibrated using LRRM (Line-Reflect-Reflect-Match) techniques with on-wafer CPW standards. First, a test

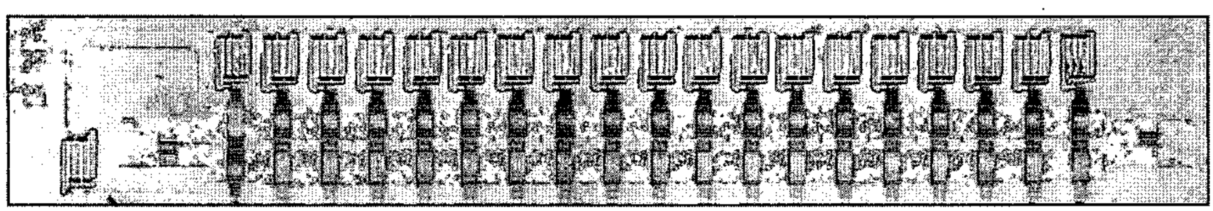
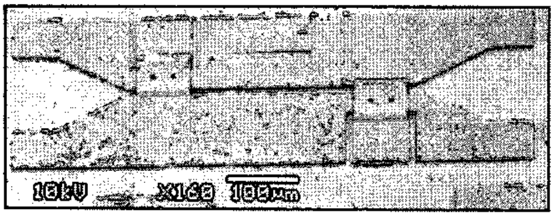
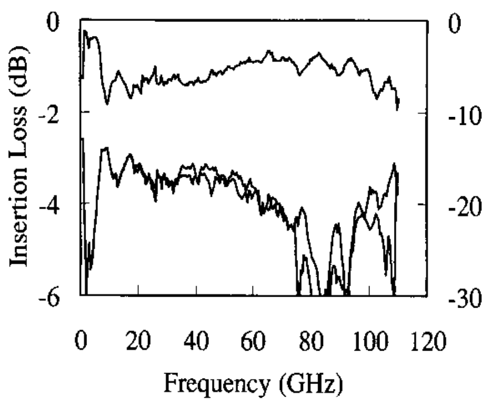


Fig. 3. Photograph of fabricated CPS distributed MEMS phase shifter. Chip size is 4.5 mm x 0.8 mm (19 bridges).

structure with back-to-back CPW-to-CPS transition has been measured. The measured results of the back-to-back



(a)

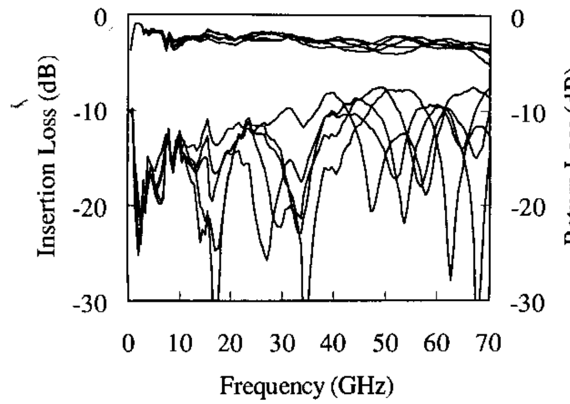


(b)

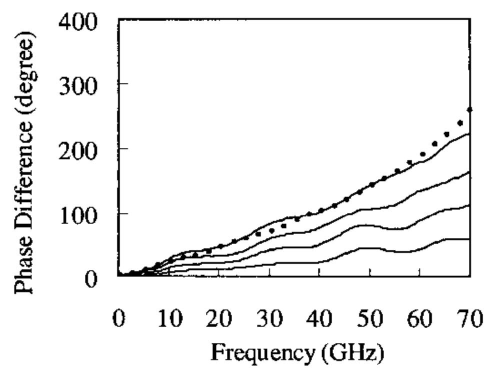
Fig. 4. (a) Photograph of fabricated back-to-back CPW to CPS transition. Layout size is 0.5 mm x 0.2 mm. (b) Measured insertion loss and return loss of wideband back-to-back CPW to CPS transition.

CPW to CPS transition are shown in Fig. 4, together with the photographs of the test structure. The insertion loss is less than 1.9 dB and return loss better than 12.5 dB from 1 to 110 GHz. Over the V-band from 50 to 75 GHz, the maximum insertion loss is as low as much as 1.07 dB with minimum return loss of 16.5 dB. Considering the compact size as well as low loss, this transition can be effectively used for a wide range of interconnections in various uniplanar MMICs.

The whole phase shifter structure with the integrated transitions at the input and output has also been tested in the same set up. Fig. 5 shows the measured results of CPS MEMS phase shifter for bias voltages of 0, 12, 15, 17, 19 V. The pull-down voltage is about 20 V. The data include the effect of two CPW-to-CPS transitions. The overall phase shifter shows an average insertion loss of 2.95 dB over the entire V-band, and the maximum phase shift was 178º at 60 GHz. When the effect of the two transitions are de-embedded from the loss data (0.85 dB at 40 GHz and 0.9 dB at 60 GHz), the CPS phase shifter alone shows 55º



(a)



(b)

Fig. 5. Measured results of CPS MEMS phase shifter for bias voltages of 0, 12, 15, 17, 19 V. (a) Insertion loss and return loss. (b) Phase shift. These data include the effect of two CPW to CPS transitions.

/ dB at 40 GHz and 74º / dB at 60 GHz. These data are slightly lower than the best results of analog CPW distributed MEMS phase shifter, which showed 70º/dB at 40 GHz and 90º/dB at 60 GHz [1]. This is attributed to the enhanced conductor loss, radiation loss, and surface wave leakage inherent to the CPS structure as compared with the CPW [12]. However, for integration with the balanced circuits, the phase shifter of this work will eventually present lower losses than the CPW counterparts since the latter will need transitions that inevitably introduce the transition loss. The measured return loss of the CPS phase shifter is better than 8 dB from 1 to 70 GHz. The return loss can be improved by controlling the gap dimension between the MEMS bridge and the strip lines during the fabrication process.

IV. CONCLUSIONS

A V-band CPS distributed MEMS phase shifter with balanced circuit compatibility has been realized for the first time. The fabricated phase shifter with 19 bridges showed 55º/dB at 40 GHz and 74º/dB at 60 GHz. For wideband measurement with CPW-based on-wafer system, a new wideband CPW-to-CPS transition has also been developed. The does not rely on bulky resonant circuits, and thus be realized in a small size and show ultra wideband characteristics. The insertion loss of the back-to-back transition is less than 1.9 dB and return loss better than 12.5 dB from 1 to 110 GHz. The low-loss micromachined CPS phase shifter is a promising candidate for integration with balanced circuits and waveguides.

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