W band 2 Bit MEMS Based Digital Phase Shifter

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***Abstract*—2 bit MEMS digital phase shifter has been implemented using IHP's MEMS switch embedded 0.25 µm SG25H1 SiGe BiCMOS technology for W band 77 GHz The implemented phase shifter covers 0-67.5° with 22.5° phase increments in 4 states. Input/output impedances of all 4 states are matched below 14dB return loss with 8 GHz bandwidth. Maximum of 4° (RMS) phase error with insertion loss of 8.8 dB is measured at 77 GHz for 2 bit phase shifter. The fully BiCMOS embedded low-loss and small size MEMS switches enable an overall compact and low-loss phase shifter design.**

***Index Terms*— Millimeter-wave (mm-wave) ICs, MEMS switch, MEMS phase shifter, automotive radar.**

I. Introduction

Phase Shifters are the key components of receiver systems where antenna arrays are required to have electronic beam-steering feature in satellite communications and radar systems. Recently, there is an increased interest of use of radar for automotive applications and 5 GHz bandwidth around 77 GHz is allocated to be used in collision avoidance mitigation-warning systems and cruise control mechanisms [1]. Therefore, this widening field of applications increased the need to high quality phase shifters. The advancing SiGe BiCMOS technologies allow realization of this need by integrated radar chipsets which offer a high level of integration, decreased cost and comparable performance to other technologies.

As the operation frequency increases, so does the free space path loss. Power levels at amplifier outputs decreases and systems with the conventional receiver topologies fail to acquire enough power at the receiver terminals. This emphasizes the importance of the design of low-loss phase shifters which enables increased gain at the receiver terminals and helps improving beam formation by increased received signal level, [2]. Using BiCMOS technology, one could implement the radar system on a single chip with integrated antenna arrays and phase shifters due to small wavelengths in W-band frequencies.

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RF-MEMS switches designed with BiCMOS processes have already proven its low insertion loss performance at very high frequencies which is around 0.5 dB [3] and attracted designers to work on components with MEMS switches. Earlier digital phase shifter designs which have longer transmission lines suffers from the disadvantage of distributed MEMS switch topologies built on large chip sizes [4-5]. On the other hand, without having process integrated switches, as done in previous works, increased loss is observed after combining with active circuits. In this paper, the design of switched transmission line based low-loss digital phase shifter with RF-MEMS switches integrated with the BiCMOS process is reported and measurement results are analyzed.

II. MEMS Based Phase Shifter Design

The design of digital phase shifter is based on a single phase shifting cell which is attained by using two different transmission lines selected by MEMS switches. As shown in Fig. 1, two different transmission line sections are connected to SPDT (single pole double throw) structure to obtain a differential phase shift given by;

$$\Delta\phi = \beta(d2 - d1) = 2\pi(d2 - d1)/\lambda \quad (1)$$

where β is propagation constant of the microstrip transmission line, λ is wavelength and d1 & d2 are the lengths of the transmission lines. Adjusting microstrip line lengths and combining additional delays coming from RF MEMS switches allow one to design a phase shifter block for the desired phase shift.

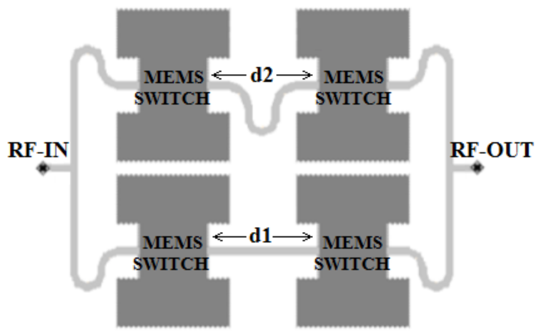

Fig.1. Differential phase shifter cell using MEMS.

The 2 bit phase shifter design which occupies an area of 2mm x 0.9mm is shown in Fig. 2. The design consists of two phase shifting blocks which provides 0-22.5-45-67.5 degree phase shifts (4 states in total) using four different paths between RFin and RFout ports. Each path includes two RF-MEMS switches to achieve better isolation and small phase shifts with the microstrip lines in between switches. The symmetric placement of switches and use of quarter wavelength microstrip lines before the intersection points improve the impedance matching and cancel out the undesired reflections. With IHP's SG25H1 technology, 130µm of microstrip line length corresponds to 22.5 degree, so that the difference of line lengths in between the switches in 22.5 & 45 degree phase shifting blocks become 130µm & 260µm respectively (Eqn. 1). Furthermore line width is kept 15µm in order to achieve 50 Ohm characteristic impedance (Z_0).

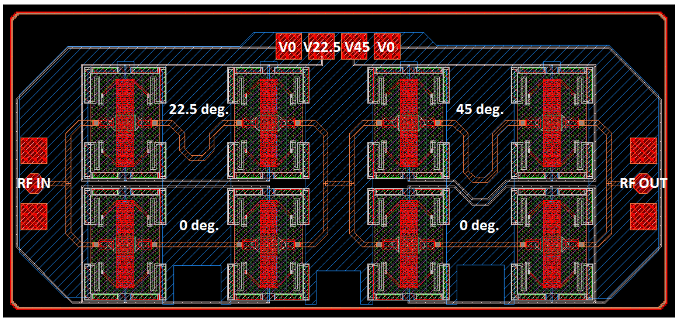

Fig.2. Layout of 2 bit phase shifter cells – 0-22.5-45-67.5 degrees

TopMetal2 layer with 3µm thickness, which is the upper most metal layer of the technology, is used for RF signal paths to maintain the lowest possible transmission line loss. While Metal1 layer at the bottom is used as ground plane to realize a microstrip line, DC voltage is brought to DC electrodes of MEMS switches from the paths placed in Metal2 layer. The distance between the signal line and the ground plane (TopMetal2 to Metal1) is 9.74 µm.

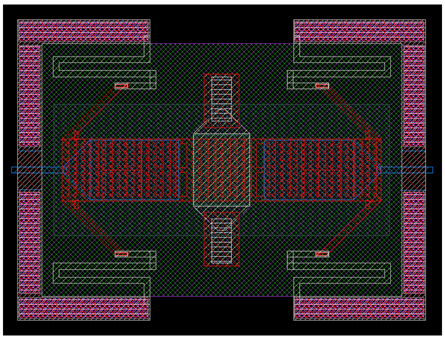

Fig.3. RF MEMS Switch Chip Photo

In order for a certain phase shifting path to be isolated, the two RF-MEMS switches (shown in Fig. 3) in that path are brought to '*down*' position by applying 40V from the DC electrodes while others are kept in '*up*' position with no voltage applied. The voltage creates a high electrostatic force between membrane in Metal3 layer and electrodes in Metal1 layer, which results in downward movement of membrane towards the DC electrodes of switch. Therefore an increase in capacitive coupling between RF signal path and membrane occurs. This coupling is almost 5 folds of the original situation of switch without movement; hence the RF signal is shorted with the membrane which is connected to ground through the ring encapsulating it.

The RF-MEMS switch used in this work is embedded into the back-end-off-line (BEOL) of the BiCMOS process. The RF-MEMS switch models are extracted from the S-parameter measurements and combined with full layout for simulations. As shown in Fig. 4 below, the switch ensures almost 25 dB isolation in the '*off state*' and 0.5 dB insertion loss in the '*on state*' with input and output terminals matched to 50 Ohm at the operation frequency.

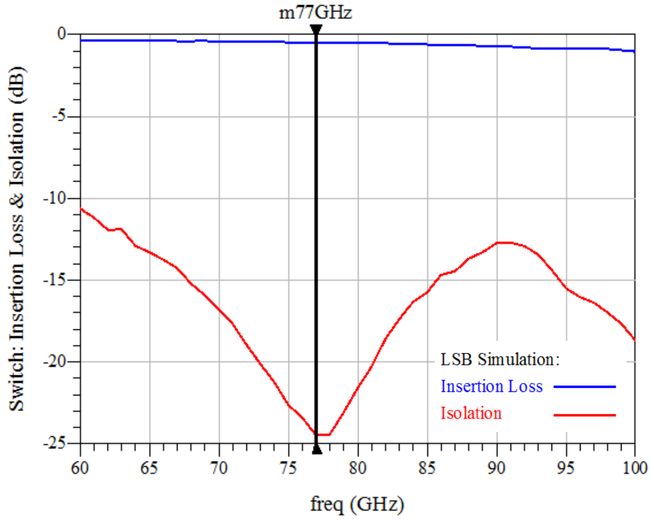

Fig.4. Typical performance parameters of RF MEMS Switch

III. Simulation & Measurement Results

Electromagnetic (EM) simulation of 2 bit phase shifter is performed with Agilent® Advanced Design System software and the layout is drawn using Cadence® for fabrication. Measurement-based MEMS switch models are combined with microstrip lines for full EM layout simulation. Also, parasitic capacitances of input/output signal pads (around 15fF) are included in simulations.

The schematic simulation setup used is accomplished as demonstrated in Fig. 5. The fully EM-simulated layout profile with S-parameter data based SNP blocks of switches is used. Considering the case of having 4 different states in total, one of the paths of each phase shifting block (22.5 or 45 degree) is isolated and the other is not by loading the related 2 port S-parameter file into SNP blocks each time. The figures below, as an example, explain how to attain 45° and 67.5° differential phase shifts respectively in the schematic environment. RF signal follows the paths where switches are '*on*'.

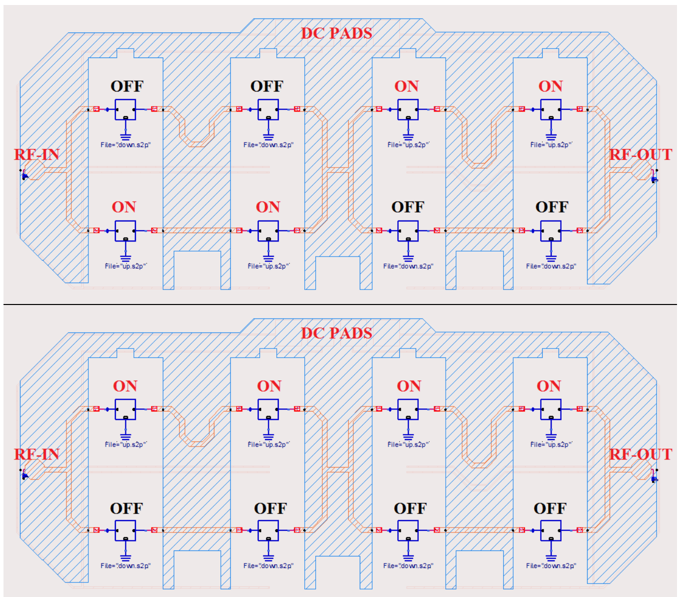

Fig.5. Schematic simulation setup, Top figure: 45° phase shift case, Bottom figure: 67.5° phase shift case

When losses emanating from microstrip lines and MEMS switches are integrated, a simulated insertion loss of 5.6 to 5.8dB, depending on the phase shift state as seen in Fig. 6, is achieved. If measurement results are analyzed, it is seen that insertion loss of phase shifter changes between 8.2 to 8.8dB, which about 2.8dB of loss difference between simulation and measurement exists. This increase results from extra loss of fabricated MEMS switches since microstrip lines that belongs to the longest path has insertion loss of 3.8dB as simulations highlight, so that around 1.2dB of loss remains to each switch whereas 0.5dB of loss is taken into account in simulations.

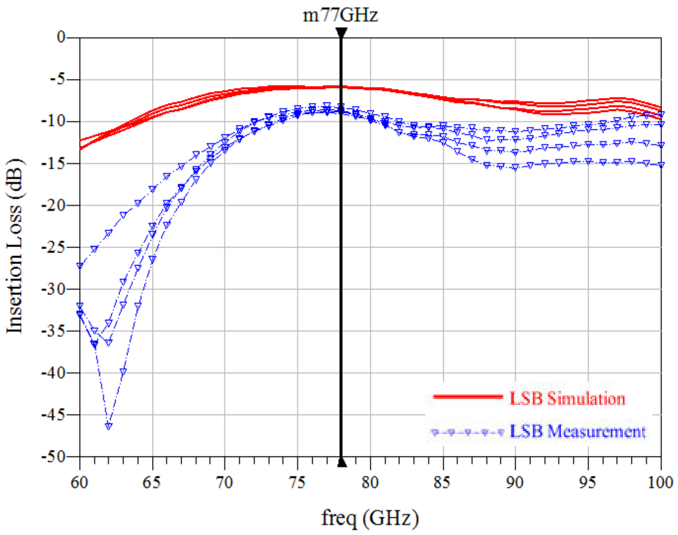

Fig.6. Insertion loss of simulated and measured phase shifter

In Fig. 7 simulated and measured return losses of the 2 bit phase shifter are plotted for 4 different states. It is observed that all states have return losses 14dB and below at the frequency of operation within 8GHz bandwidth.

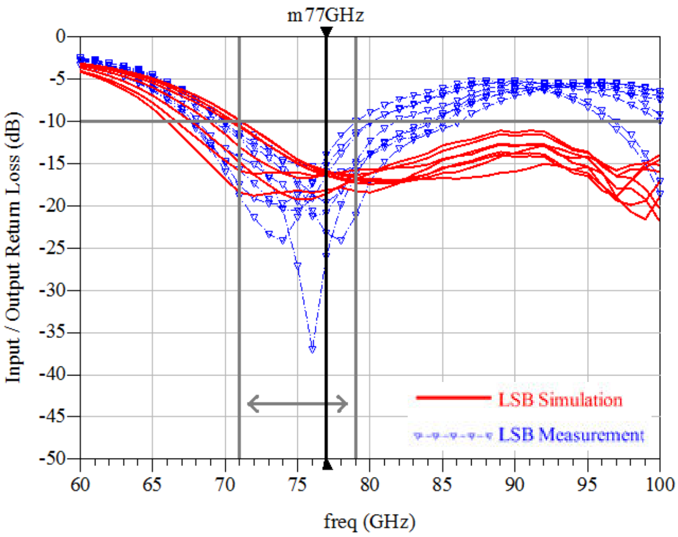

Fig.7. Return Loss of simulated and measured phase shifter

Finally phase error (rms) performance is also seen in Fig. 8. In this case, the simulated phase error for the phase shifter is found as 1 degree at 77GHz whereas measurements point to a 4 degree phase error. In order to overcome the excess phase error, microstrip lines between MEMS switches could be adjusted.

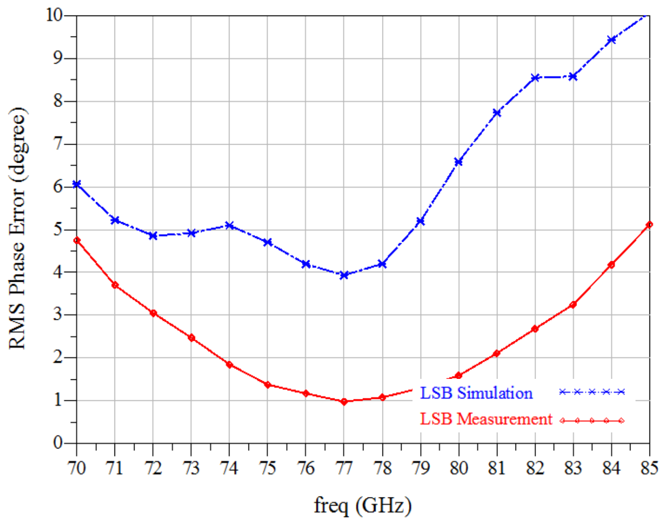

Fig.8. Simulated and measured phase errors (RMS)

IV. Conclusion

In this paper, the design of the 2 bit phase shifter using MEMS switched microstrip lines is presented. Fully BiCMOS embedded RF-MEMS switch technology is used to realize the mm-wave phase shifter. Measurement results show that the phase shifters are well matched over the frequency of 71-79 GHz and have losses of 8.5dB on average for 2 bit phase shifters at 77GHz. The simulated phase error (RMS) is about 4 degrees. The results show that the fully BiCMOS embedded RF-MEMS switch based phase shifters are very promising to implement single chip phase array systems at mm-wave frequencies.

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