Optimization of a High-Power Ka-Band RF MEM 2-Bit Phase Shifter on Sapphire Substrate

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Abstract. In this paper, the optimization of a low-loss radio frequency (RF) microelectromechanical (MEMS) 2-Bit Ka-Band monolithic Phase Shifter for high-power application is presented. These micro-strip circuits are fabricated on 0.254mm-thickSapphire substrate and are based on a reflection topology using 3-dB branch line coupler. The insertion loss of the circuit varies from –2 dB for the state (0°) to –2.6 dB for the highest state (225°). The return loss is better than -15 dB and the phase shift is steady within the aimed frequency range [25.7 –27] GHz. Power stress with 1 dB step measurements have been done on a 1-bit 45°cell . No significant phase change has been observed in down-state for an input power variation from 0 dBm to +32 dBm. In up-state only 3.3° deviation is recorded.

Index Terms: Microelectromechanical systems (MEMS), phase shifters, switches, high-power.

1. Introduction

With the progress of the MEMS technology , new antenna solutions are arising, achieving reconfigurability at moderate cost. It could be an answer to new needs for Space telecoms with Flexible Payloads (coverage flexibility, frequency resource flexibilities and power flexibility) [1].

Microwave and millimetre-wave phase shifters are essential components in phase array antennas for telecommunication and radar applications. Low loss and high frequency phase shifter has been presented in reference [2] or [3] but those works did not address power handling capabilities. Other works such as [4] present phase shifter designs using high power MEMS switches but not necessarily suited for Ka band application nor constant phase shift response versus frequency requirement [5], [6].

This paper proposes an optimized Ka-Band 2-bit phase shifter careful design using capacitive MEMS switches with high-power handling capabilities. This phase shifter has been designed for the particular need of Ka-Band phase array antennas which use ferrites as a reference solution. Two bits only are necessary in our application with the respective values of 45° and 180°. The circuit has been designed within the frequency range [25.7-27] GHz, and the operating power requirement is 4.6W CW. Thus, the RF power applied to MEMS switches is 3dB less than the circuit input power.

Manufacturing of the devices has been performed at XLIM laboratory. Design, probing and measurements were carried out at TAS.

The measured performances of the Ka-Band 2-bit phase shifter are presented in [9] and main results are recalled in section 3. In this paper, back simulations and optimization have been done in order to achieve an accurate response and get the correct phase shifts within the frequency range (see section 4).

2. Circuit Design and Fabrication

In addition to the 2-bit 45°/180° phase shifter (Figure 1), a 1-bit 45° (Figure 2) and a 1-bit 180° phase shifters (Figure 3) have been also designed. The three circuits have been fabricated on a 254 µm-thick Sapphire substrate.

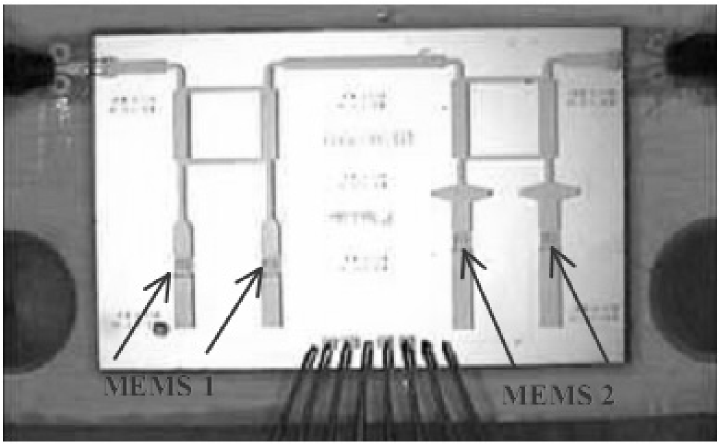


Fig. 1. 2 bit Ka band phase shifter.

The elementary 1-bit phase shifter is based on reflection type topology [7] [8] which consists of a 3-dB branch line coupler and identical transmission lines at the direct and coupled ports loaded with capacitive MEMS Switch taken from XLIM Technology Basic Building blocks (Figure 5).

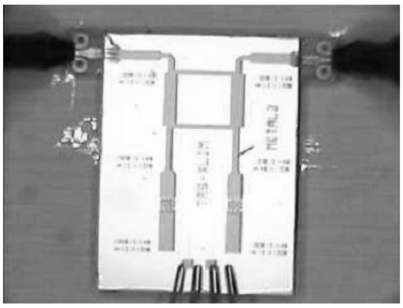


Fig. 2. 1-bit 45° phase shifter.

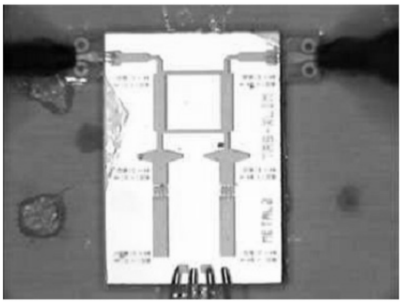


Fig. 3. 1-bit 180° phase shifter.

Fabrication process starts with the deposition of a 60/1500A Cr/Au metal deposition (fig. 5 (a)), followed by a 0.4 µm thick AlN sputtered layer (b).

Next, a 100Kohm.square doped carbon resistive layer is deposited and patterned to provide a low loss bias network of the components. Next, a two steps sacrificial layer is deposited and patterned (c-d), in order to define the areas where the MEMS devices will be separated from the substrate. A second 2.5 µm thick gold layer is then deposited and patterned, to define the MEMS moveable parts (e). Finally, the devices are diced, released (f) and dried in a critical point drying system.

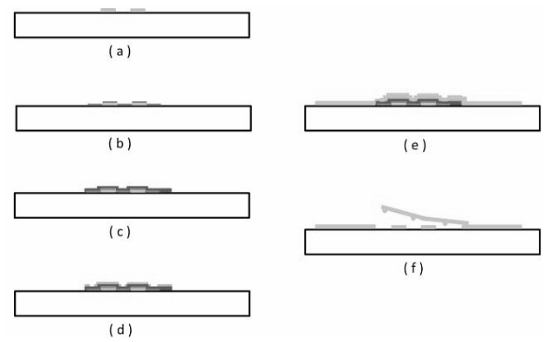


Fig. 4. Fabrication process.

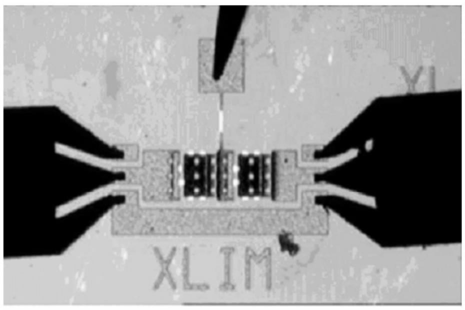


Fig. 5. XLIM elementary capacitive MEMS Switch.

3. Measurements

S-parameters and phase shift of each circuit (1-bit 45° phase shifter, 1-bit 180° phase shifter and 2-bits phase shifter) have been presented in [9]. The three circuits are mounted on a Copper-Tungsten base-plate and are wire-bounded using three parallel wires (length 200µm, diameter 25µm) to JMT© transition (used to transform CPW connection to micro strip).

A. 1-bit 45° phase shifter measured performance

The performance of the 1-bit 45° phase shifter is recalled in Figure 6 and TABLE 1. The input and output reflection losses are better than –11 dB from 25.7 GHz to 27 GHz and the average insertion loss is -0.7 dB for down or up state. The delta fundamental phase state is within 2.3°.

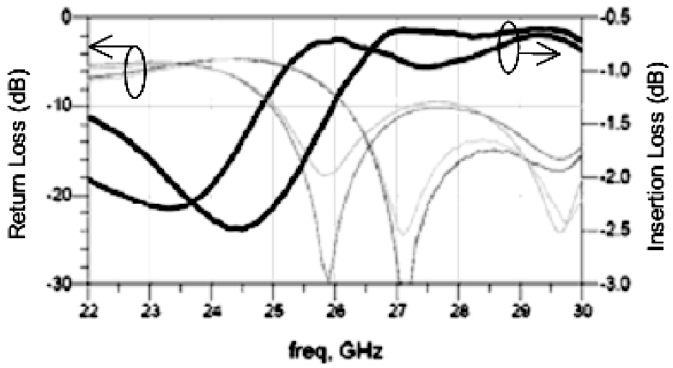


Fig. 6. 1-bit 45 ° phase shifter performance.

Table 1. 1-bit phase data at 26.4 GHz

Phase State	45.0
Measuured	42.7
Delta	-2.3

For this design, we note that, in down-state, insertion loss and phase shift measurement is reproducible. Phase shift response is very close to simulation results (Table 1). Nevertheless, we observed that phase shift value decreases after few actuations down to a stabilized value of 25° due to the influence of charging effects phenomena.

The input power hardness has also been characterized. Figure 7 shows relative AM/PM curves in up- and down-states for three frequency points in the band of interest.

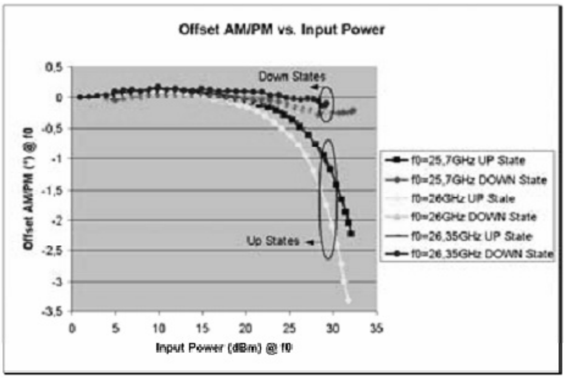


Fig. 7. AM/PM measurement of 45° phase shifter.

Measurement results show a good sturdiness of both the design and the RF-MEMS for an high input power range. The worst case AM/PM variation is 3.3° in up-state and 0.3° in down-state. The input power was voluntarily limited to +32 dBm in order to avoid probes damage.

B. 1-bit 180° phase shifter measured performance

The performance of the 1-bit 180 ° phase shifter is drawn in Figure 8. The input and output reflection losses are better than –10 dB from 25.7 GHz to 27 GHz and the average insertion loss is –1.5 dB for down or up-state.

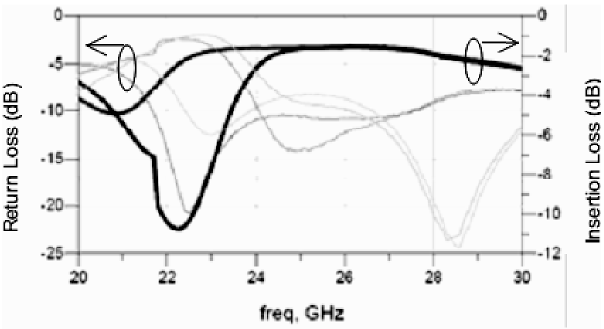


Fig. 8. 1-bit 180 ° phase shifter performance.

On this circuit, input and output matching performance is deteriorated compared to simulation results. Insertion losses are 0.8 dB poorer than simulation. The measured phase shift at ambient temperature is 170°, for an aimed 180° value.

However this performance is obtained at 23 GHz instead of 26.5 GHz indicated a shift in frequency.

After twelve hours at hot temperature (75°C) in environmental chamber, the 170° phase shift value has been now measured at 120°. Charging effect phenomena of the dielectric of the MEMS Switch, not totally reset during a thermal stage, has an influence on the phase shift variation. It shows that packaging is here needed to have reproducible results.

C. 2-bit phase shifter measured performances

The performance for two manufactured samples of the 2-bit phase shifter for up and down-states are shown in Figure 9 and Figure 10 for three MEMS switches configuration.

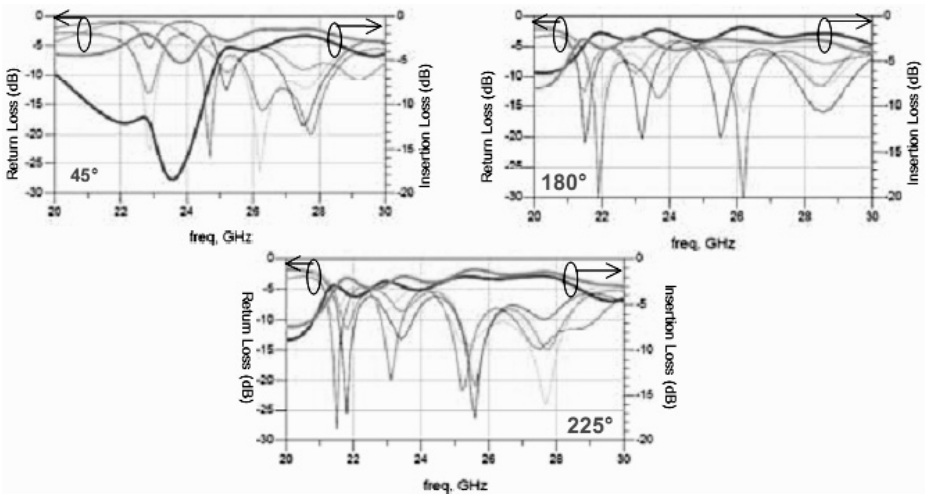


Fig. 9. 2-bit 180° phase shifter RF performances.

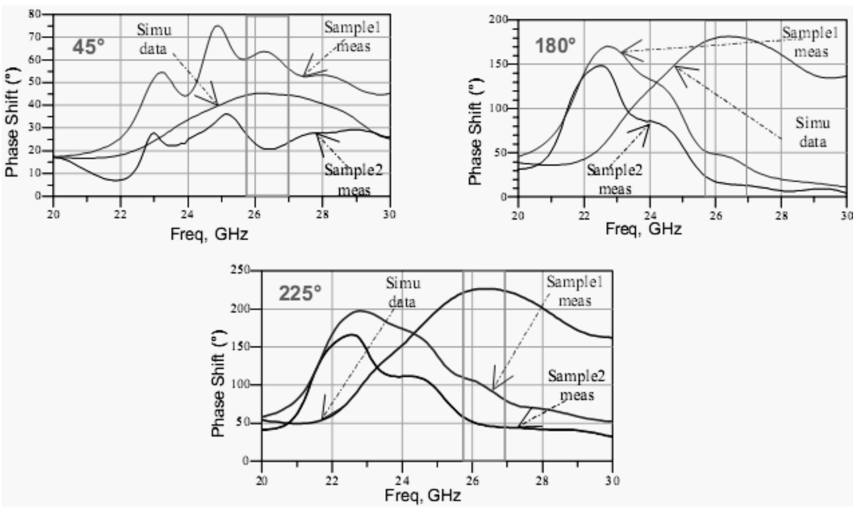


Fig.10. Phase shift performance of the 2-bits phase shifter.

The influence of the 180° cell behaviour could have been recognize on the 2-bit phase shifter measurement. Moreover, it has been noticed that measurement (in particular for phase shift parameter), is not reproducible over several samples. This phenomena could be explain by dispersion on physical parameters of MEMS switches and/or their C_{Down}/C_{Up} ratio.

We observed that:

- The input and output reflection loss are higher than simulation predictions but they are in line with the measurement obtained on the single 180° cell.
- Phase shift curves for 180° and 225° states are shifted by 3 GHz towards low frequencies like the 180° cell.

The results showed an average insertion loss of about -2 or -3dB in the operating frequency band, in any case higher than the simulation. This can be due to metal and/or substrate losses underestimation.

3. Feedback Simulation and Optimization

Retro simulations with Agilent ADS circuit software have been done to better explain the discrepancy between measured and simulated results. The design of each function has been optimized for a second run, taking into account substrate and MEMS switches technological parameters uncertainties. We have been keeping in mind that these uncertainties could have a significant influence on the totally circuit performance.

Regarding substrate technological parameters uncertainties, we paid a particular attention to the properties of sapphire substrate (Table 2) and especially its anisotropic permittivity value. Measurement fitting was performed by sweeping the effective dielectric constant value. The best result was obtained with an ε_r of 11.6 (ε_r=11 for the initial design). Thus, this value have been kept for design optimization.

Table 2. Properties of Sapphire substrate

	Value
Crystalline structure	rhombohedral
Tear in a stocking parameter (nm)	0.348
Permittivity: ε_r	9.3 to 11.6(anisotropic)
Tan δ	3.8 10^{-8} at 80K and 10 GHz
CTE(10^{-6}/K)	7

Since the dielectric properties of sapphire substrate are anisotropic, the relative dielectric constant is not a single value but a tensor. It could have an impact on the behaviour of single micro-strip lines by the variation of their local impedance, and could explained frequency shift, high insertion losses, and incorrect phase shift.

Width and length dimensions of each discontinuities as bend or taper elements have been also analyzed and optimized to reduce their sensitivity to variation of effective dielectric constant.

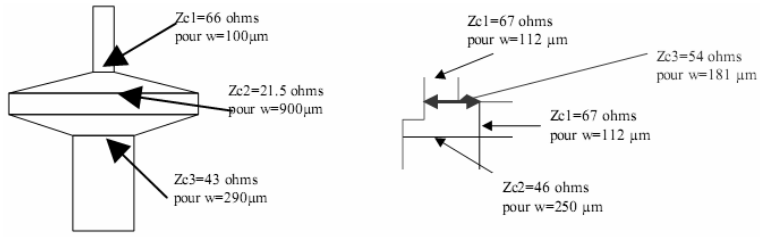


Fig. 11. Layouts of micro-strip elements sensitive to ε_r variation.

For MEMS switches technological parameters uncertainties we have looked a design sensitivity to the dispersion on physical parameters of MEMS switches and /or their C_{DOWN}/C_{UP} ratio which have a direct impact on phase shift value at given frequency.

More attention has been given to improve the 180° cell behaviour. The optimization of this design has been done in order to get better input and output matching performance, better insertion loss and a correct phase shift centred at 26.5 GHz (Figure 14). Thereby, we have taken into account:

• the technological parameters (including tan δ parameter new value),

• the influences of every discontinuity, keeping in mind that they could have a significant influence on the presented impedances, and consequently on the totally 180° cell performance.

Further, the proposed structure of the 1-bit 180° phase shifter design (Figure 13) has been done to be close to the 1-bit 45° phase shifter, whose measured performance and simulated behaviour are similar.

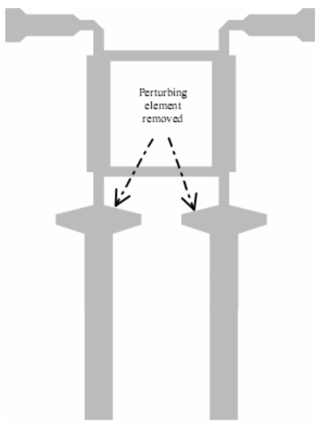


Fig. 12. Previous1-bit 180° cell layout.

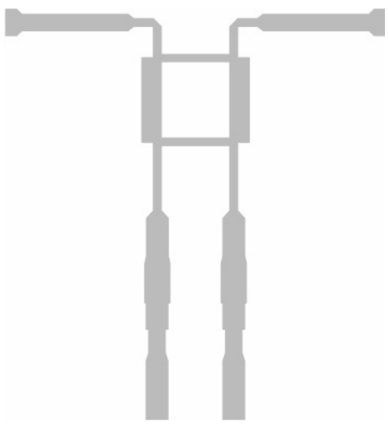
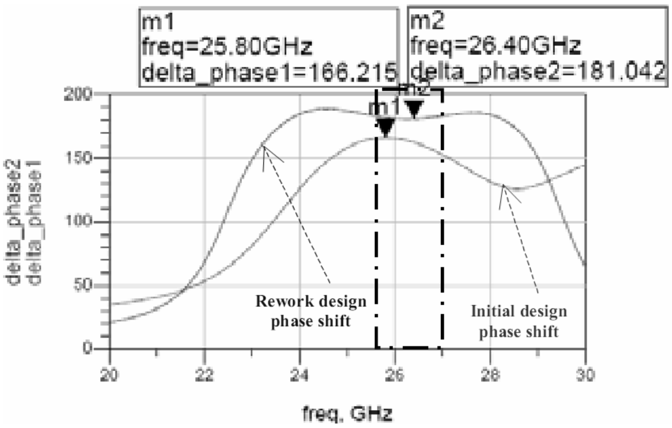


Fig. 13. 1-bit 180° cell optimized layout.

Simulated performances are very encouraging for the phase shift parameter. It can be seen on Figure 14 that, a flat phase shift value within the operating range can be expected.



Fig, 14. Phase shift of optimized 180° device.

Figure 15 and Table 3 show the simulated result of the 2-bit phase shifter optimized design.

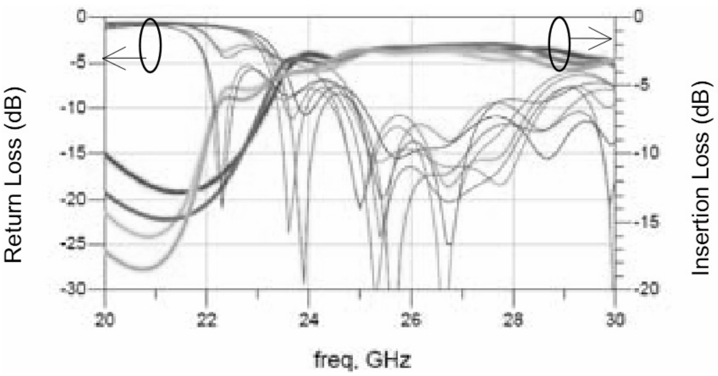


Fig. 15. 2-bit phase shifter performance.

Table 2. 2-bit phase shifter simulated phase shift value

Phase State	45.0	180.0	225.0
Simulated data @26.4 GHz	40	175	216
Delta	-5	-5	-9

The insertion loss of the phase shifter at 26.5 GHz varies from -2 dB for the state (0°) to -2.6 dB for the highest state (225°). The return loss is better than -15 dB for all states within the [25.7-27] GHz frequency range.

5. Conclusion

A 2-bit Ka-Band monolithic phase shifter with XLIM elementary MEMS switches for high power applications has been designed and on-probe measured. The average insertion loss of the circuit is -2.3 dB with a return loss >10 dB within the aimed frequency range [25.7-27] GHz. Power handling capability of a 1-bit 45° phase shifting cell over a wide input power range shows a good behaviour. No self actuation of RF-MEMS has been observed up to an input power of +32 dBm which confirms the interest in XLIM capacitive MEMS technology for power applications.

Taking into account technological parameters uncertainties which have a direct impact on device behaviour and phase shift parameter, back simulations have been done. Redesign of corrected and optimized 45° 1-bit, 180° 1-bit and 2-bit phase shifters have been achieved. Manufacturing of these MEMS based phase shifters will be performed by XLIM laboratory.

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