

Distributed MEMS Tunable Phase Shifters on CMOS Technology for Millimeter Wave Frequencies

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Abstract. The concept of a slow-wave MEMS tunable phase shifter that can be fabricated using the CMOS back-end and an additional maskless post-process etch is presented. The tunable phase shifter concept is formed by a conventional slow-wave transmission line. The metallic ribbons that form the patterned floating shield of this type of structure are released to allow motion when a control voltage is applied, which changes the characteristic impedance and the phase velocity. For this device a quality factor greater than 32 can be maintained, resulting in a figure of merit on the order of 0.85 dB/360° and a total area smaller than 0.065 mm² for a 60-GHz working frequency.

1. Introduction

New applications and services using large amounts of data that tend to saturate the available frequency bands and bandwidths. Telecommunication systems with applications such as high-speed short-range wireless personal area network (WPANs), real time video streaming at rates of several Gb/s (60 GHz), automotive radars (77 GHz), and RF-imaging (frequencies from 60 GHz to more than 140 GHz) are examples [1], [2].

Traditionally, millimeter-wave (mmW) devices are based on monolithic microwave integrated circuits (MMICs), fabricated with Gallium Arsenide (GaAs) due to its higher electron mobility, higher breakdown voltage, and the availability of high quality-factor passive circuits leading to a reduced insertion loss compared to silicon. However, GaAs technology is expensive, which results in prohibitive costs for consumer applications. For several applications, a beam forming architecture will have to be used in order to increase the transmitted and received

power. This is especially important for low-cost fully integrated transceivers, in which the integrated antenna has low efficiency due to the silicon substrate and due to the high absorption of the atmosphere. In such systems, tunable phase shifters are of particular interest, since they are required in networks of scanning antennas for beam forming.

The development of low cost mmW communication system depends on the ability to integrate all the passive elements in low cost CMOS technology. For tunable phase shifters it will be necessary to improve the insertion losses, reduce surface area and increase power limitations comparing the active and passive tunable phase shifters presented so far [3]-[6].

The topology of the phase shifter presented in this paper, using distributed micro-mechanical-electrical systems, could provide an answer to these three problems simultaneously.

2. Tunable Phase Shifter Principle

The tunable phase shifter is based on the slow wave coplanar waveguides (S-CPW) implemented on the classic CMOS Back-End-Of-Line (BEOL) [7], [8]. Normally, the CPW is formed by the thick metal layer (upper most) or combination of several metal layers, in order to increase metal thickness and reduce conduction losses. In these structures a shielding plane, formed by a lower metallic layer, is used to prevent the electric field from reaching the silicon substrate. The shielding plane is made of narrow ribbons that are 200 nm to 600 nm wide and typically 0.5 μm to 1 μm apart that can be connected by metallic vias to the ground plane.

In this type of structure, the capacitance per unit length (C) can be essentially controlled by the distance between the CPW and the shielding plane. By controlling C , it is possible to control the phase velocity $v_\phi = 1/\sqrt{LC}$, where L is the inductance per unit length), thus the phase.

Therefore, by modifying the S-CPW with a post-CMOS maskless etch step, it is possible to remove the insulator (SiO_2) of the BEOL and free the shielding plane, rendering it mobile, as illustrated in Fig. 1. The application of a dc voltage between the CPW and the shielding plane will cause the shielding plane to move towards the CPW, due to the electrostatic force. Thus, the capacitance per unit length will increase, reducing the phase velocity. If a second set of ribbons (DC electrodes) are included underneath the shielding plane, electric voltage can be applied between this set of ribbons and the shielding plane, causing the latter to move away from the CPW, decreasing C . The DC electrodes should have the same dimensions of the ribbons of shielding plane and should be located directly underneath them to avoid blocking the magnetic field.

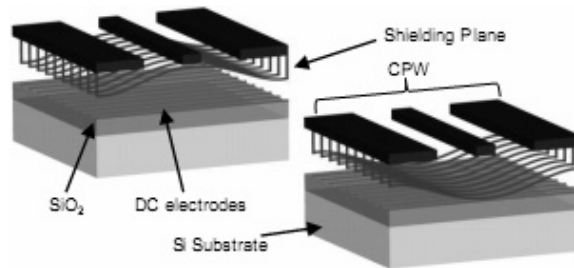


Fig. 1. Distributed MEMS tunable phase shifter principle.

Considering a commercial CMOS process such as AMS 0.35 μm , the top metal layer M4 can be used to form the CPW, while M3 is used for the shielding plane and M2 for the DC electrodes.

In order to obtain an improved performance of the phase shifter, the CPW dimensions were optimized using HFSS (ansoft) for a nominal (without actuation of the shielding plane) characteristic impedance of 70 Ω and a maximized quality factor. This nominal value of 70 Ω leads to the optimal condition in order to obtain a minimum Voltage Standing Wave Ratio over the whole range of phase variation.

The optimized CPW transmission line has a 15- μm wide center conductor, 12.5- μm wide ground conductors that are 55 μm away from the center conductor. Further, according to the design rules of the AMS 0.35 μm technology, the M3 metal layer (shielding plane layer) is 1 μm below the CPW (M4). The minimum feature of this technology is 0.6 μm , which is used for the width of the ribbons. The thickness of the M3 layer is also 0.6 μm . The ribbons are spaced 1 μm apart in order to maximize the quality factor. The DC electrodes are located 0.64 μm below the shielding plane.

The pull-in voltage for the ribbons of the shielding plane can be calculated using [9] that takes into account the fringing field capacitance and the induced axial stress due to the non-linear stretching. Assuming a Young's modulus and Poisson's ratio for aluminum, 70 GPa and 0.35 respectively, and no residual stress in the M3 layer, pull-in voltages between the central conductor and shielding plane and between the shielding plane and the DC electrodes were calculated to be 7.7 V and 5.7 V, respectively. This value is a first estimation for this structure, since the material properties for the AMS 0.35 μm are not known and will have to be determined for a more rigorous analysis. However, this first estimation is promising, indicating that a low voltage can be used to command the phase shifter.

3. Performance of the Phase Shifter

As indicated by [9], the shielding plane will collapse onto the central conductor and DC electrodes at approximately $0.4 \cdot d_0$, where d_0 is the initial gap. For this reason, a continuous phase shift is not possible.

Nevertheless, by connecting the ribbons in groups, it is possible to obtain several bits of phase shift. The ribbons can be connected underneath the ground strips, where they are anchored, and do not influence the quality factor of the phase shifter. Each group of ribbons can be in three distinct positions: at rest, attached to CPW (UP position) or attached to the DC electrodes (DOWN position).

In practice, each group of ribbons should not be longer than the wavelength of the RF signal divided by twenty. At 60 GHz, this leads to approximately 25 μm for the S-CPW described in this paper. Therefore, each group of ribbons should be divided into sections of 25 μm distributed along the transmission line.

Taking into account these considerations, the performance of the proposed tunable phase shifter was analyzed by 3D finite element simulations using HFSS (Ansoft). The deformation of the ribbons in the UP and DOWN position was approximated to the deformation of a fixed-fixed beam with a concentrated load at the center [10]. A thin (40 nm) SiO_2 insulator was considered over the entire structure to prevent DC short circuits. This thin insulator can be deposited after the structure is released.

Table 1 shows the performance *i.e.* quality factor (Q), characteristic impedance (Z_c) and effective relative permittivity (ϵ_{reff}) of the tunable phase shifter for the three distinct positions.

Table 1. Performance of tunable phase shifter

	Q factor	Z_c (Ω)	ϵ_{reff}
UP	32.6	25.7	75.8
Rest	36.7	68.9	11.7
Down	38.8	80.3	8.8

In Table 1, it is possible to see that the quality factor is around 32 and 39 no matter the position of the shielding plane. This result was corroborated experimentally with fixed shielding planes using standard CMOS technology [2].

Further, the effective relative permittivity, ϵ_{reff} , varies from 75.8 to 8.8. These strong variations allow a significant phase shift with quite small changes in Z_c , because the inductance of S-CPW transmission lines is constant and does not vary with the position of the shielding plane position. The characteristic impedance varies from 25.7 Ω to 80.3 Ω . This leads to a Voltage Standing Wave Ratio lower than 2, *i.e.* a modulus of the return loss S_{11} better than 10 dB.

The quality factor of transmission lines directly affects the insertion loss of the tunable phase shifter, shown by the figure of merit (insertion loss per degree of phase) given by (1).

$$dB/^\circ \approx 2\pi / 360 \cdot 8.69 / 2Q \quad (1)$$

The phase shifter presented in this paper is based on a transmission line with a figure of merit of 0.85 dB/360 $^\circ$.

For a beam forming application, a phase shift of 180° is required [ref]. The length of the phase shifter required for a 180° phase shift is given by (2).

$$l = \frac{c}{2f \cdot \left(\sqrt{\epsilon_{\text{reff max}}} - \sqrt{\epsilon_{\text{reff min}}} \right)} \quad (2)$$

Where f is the frequency and c is the speed of light. For a tunable phase shifter working at 60 GHz, with ϵ_{reff} between 75.8 and 8.8, the total length of the proposed structure would be 436 μm . These results were obtained for a 150- μm wide phase shifter, which leads to a total area smaller than 0.065 mm^2 .

Today, the state of the art CPW has a quality factor of 15, for a transmission line made on SOI HR substrate with 65 nm technology [3]. If the quality factor of varactors are taken into account (lower than 6 at 60 GHz [5]), this would lead to an overall quality factor of 4.2 for the entire phase shifter. This gives a figure of merit of 6.5 dB/360°. Further, due to the low $C_{\text{max}}/C_{\text{min}}$ of the varactors, the length of the transmission line would have to be $2\lambda g$ (about 4 mm) to achieve a 360° phase shift.

This would require a silicon area of 4 mm \times 0.1 mm = 0.4 mm^2 , considering a CPW or microstrip transmission line 100- μm wide.

As described above, the proposed tunable phase shifter shows a significant improvement in performance and consumes considerably less silicon surface. Further, no varactors are needed to achieve the required phase shift, thus the power handling limitations are considerably higher.

4. Sample Fabrication and Preliminary Results

As mentioned, a maskless etching process is used to free the shielding plane that is embedded in silicon dioxide (SiO_2) in order to allow it to move under the application of an electric field. The SiO_2 is removed from selected areas of the structure using the silicon nitride (Si_3N_4) passivation layer of the conventional CMOS process as mask. The SiO_2 is etched with HF vapor at ambient temperature. To avoid condensation of the HF vapor, the samples are kept at 40°C, preventing the metallic layer (aluminum) to be etch away. By controlling the etching time, it is possible to free the shielding plane while maintaining the second set of ribbons attached to the SiO_2 .

The maskless etching process of the oxide layer has already been demonstrated by other teams [4] and do not pose a major problems, as seen in Figure 2. In this figure, it is possible to see several sets of ribbons that can be used to form the shielding plane. The ribbons shown here are 50 to 200- μm long and 0.6 or 2- μm wide. No deformation due intrinsic stress can be seen. Different metal levels (M4 and M3) from AMS 0.35 μm CMOS process were used to obtain the ribbons. Metallic vias are used to anchor the ribbons to a lower oxide layer that is not removed in the etching process.

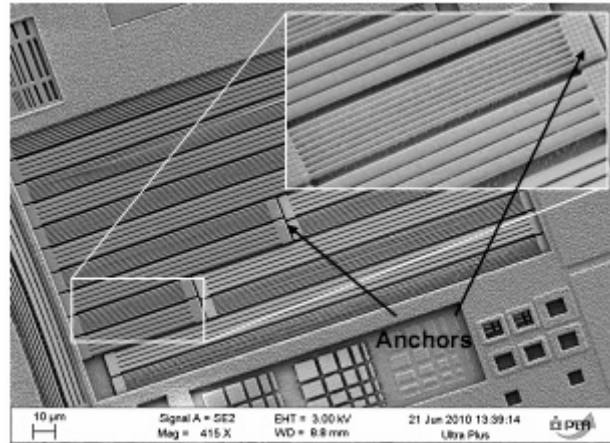


Fig. 2. Ribbons with different dimensions (50 to $200\ \mu\text{m} \times 0.6$ or $2\ \mu\text{m}$) released using HF vapor.

6. Conclusion

A new concept of millimeter wave phase shifter using CMOS technology was proposed. The expected performance can consider the eventual integration of phase shifters for controlling scanning antennas, which generally represents a major technological breakthrough. The "price" to pay is a maskless post-CMOS etching step.

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