Integrated MM-Wave MIMO Antenna with Directional Diversity using MEMS Technology

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***Abstract*—This paper presents the design of a fully integrated antenna with directional diversity in the 60 GHz band using MEMS process on high resistivity silicon wafer. This active antenna designed for MIMO systems integrates switches and phase shifters.**

I. Introduction

The 57-64 GHz frequency band will provide Gbit data rates for short-range wireless communications. Indeed this frequency range offers huge bandwidth and, due to the oxygen absorption, improves frequency reuse in cellular networks. Furthermore, array signal processing is a promising approach to enhance the link performance. In addition, antenna arrays are physically small at mm-wave frequencies so that large Multiple Input Multiple Output (MIMO) systems with enhanced capacity could be realized in small volume and implemented in a laptop, a PDA or a mobile phone. Missing line-of-sight radio link can be mitigated by directing beams towards the strongest available multipaths or by transmitting a variety of links toward widely distributed infrastructure antennas.

II. Proposed Antenna

A. Principle

The integrated antenna presented in this paper can be use either for MIMO diversity (transmit / receive diversity) or spatial multiplexing. It includes 2 independent branches. Each branch consists of 5 radiating elements, as shown Fig. 1. These arrays are used to steer the beam in 9 different directions in the half plane facing the array. Therefore, the main beam can be directed to the best direction to radiate or receive with the best signal to noise ratio (SNR). The 9 directions are 0°, ± 14°, ± 30°, ± 48° and ± 84°, referring to the normal to the radiating elements plane. To change the beam direction, we use phase shifters. Between 2 consecutive radiating elements of the same branch, the signal is transmitted through 1 of the 9 possible paths (each path has a different length). The key element of the phase shifters is the switch. At mm-wave frequency, the best solution is to use a micro-electromechanical system (MEMS). Furthermore, in order to have an array as compact as possible with the minimal losses, the whole antenna is built using MEMS process. Thanks to the short wavelength (f=60 GHz) it becomes possible to integrate the whole MIMO array, including radiating elements and phase shifters, on a silicon die of 1cm². In order to direct the beam in only one direction, a metallic plane reflector is added under the substrate. As the antenna will be measured using co-planar waveguide (CPW) probes the whole integrated structure is designed using CPW technique. In addition, CPW allow low mutual coupling between closely spaced lines. The metallic plane backing the substrate has a very limited influence on the CPW as the signal line is about 30 µm wide and the substrate is 675 µm thick. The array has been designed and simulated with *Ansoft HFSS* software. The antenna is covering the 60-64 GHz frequency band.

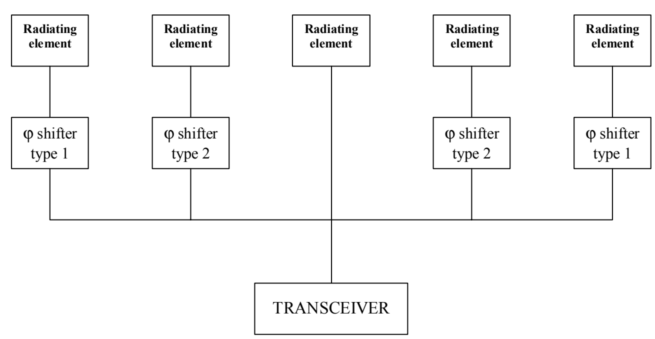

Figure 1. *One of the two branches of the MIMO antenna array*

B. Radiating elements

The radiating elements are rectangular slots with patch stub (Fig. 2). They are fed by CPW, as presented in [1]. The very large band of the antenna presented in [1] comes from the fact that there are several resonance frequencies and therefore, depending on the frequency, the radiation patterns are quite different. As in our application radiation pattern is very important, we designed the antenna to have only one resonance frequency. For this reason the frequency band of our antenna (Fig. 3) is narrower than the one presented in [1].

For each branch, the 5 radiating elements are in-line. The spacing between two consecutive elements is 0.4 wavelength at 60 GHz in free space. In order to decrease the mutual coupling between radiating elements, the previously developed neutralization method [2] will be applied.

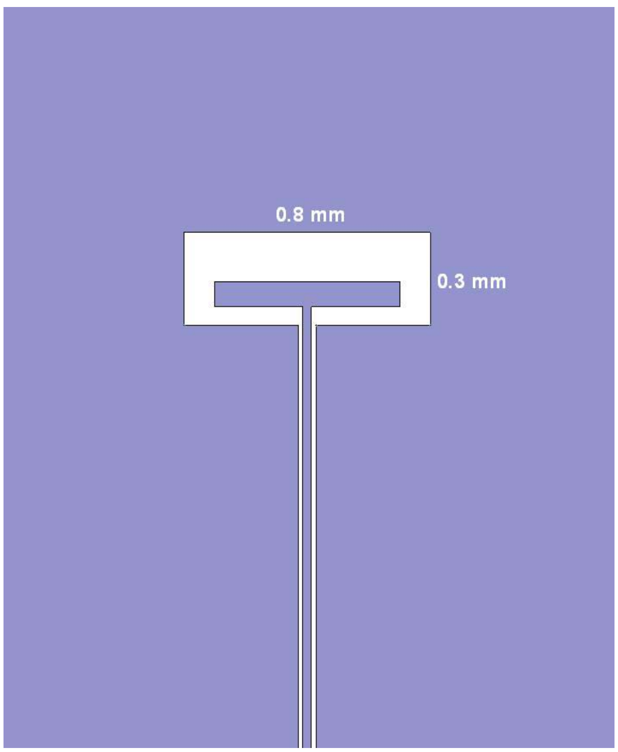

Figure 2. *Elementary radiating element*

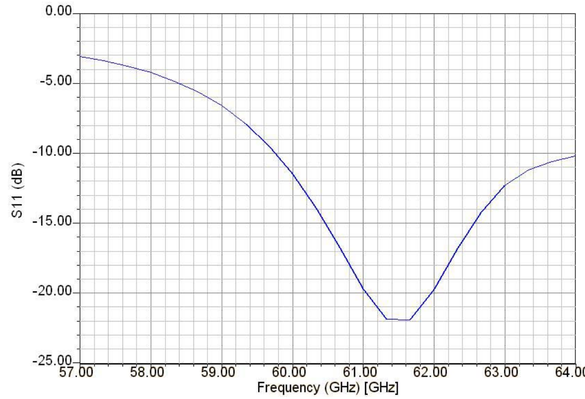

Figure 3. *Return loss of the elementary radiating element*

C. Switches

The use of MEMS switches allows low losses, high linearity and small consumption comparing to PIN diodes or FET. The architecture of the structure is presented in Fig. 4. The movable membrane is made of a 2-µm thick polysilicon conductor layer placed between two 0.35-µm thick silicon nitride layers and is situated under the 7-µm thick gold CPW lines. This original topology will simplify the MEMS packaging and will increase reliability. The switches are electro-statically actuated and use the upper silicon nitride layer as a dielectric. The second silicon nitride layer allows polysilicon discontinuity on the same membrane. Moreover, both silicon nitride layers ensure a perfect compensation of the residual stress in the moveable structure. Two silicon dioxide layers are used as sacrificial layers. The switches have a collapsing voltage of 10 V. The circuit is processed on a high resistivity silicon substrate (4 kΩ-cm). Even if AsGa material is better for RF systems, [3] shows that the advantage of AsGa over high resistivity silicon is decreasing above 60 GHz. Furthermore, the processing cost is reduced by a ratio of 10 when using silicon wafer comparing to the use of AsGa. The simulated insertion losses for the MEMS switches are down to 0.1dB and the isolation are higher than 20dB on the overall bandwidth.

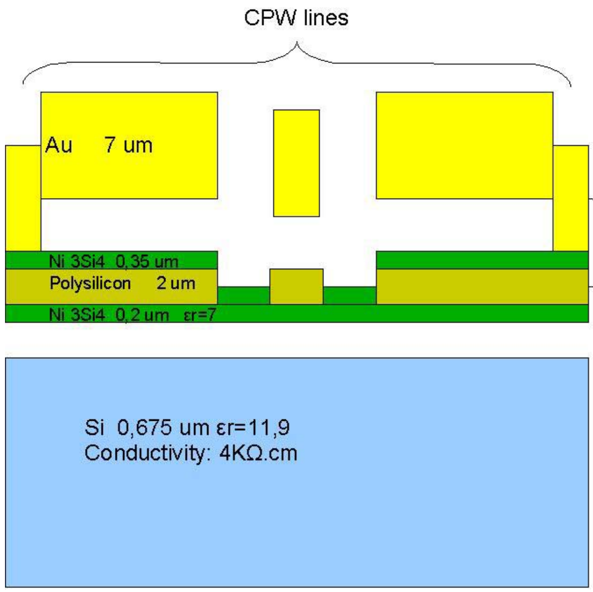

Figure 4. *Side view of the MEMS switch topology*

D. Phase shifters

In order to have the smallest attenuation implied by the single pole multiple throw structures, the central radiating element is used as a phase reference and we apply symmetrically positive and negative phase shifts on the other elements, as shown in Fig. 1. The maximal length of the delay lines is 2.5mm.

Two main architectures have been developed for switched line phase shifters. The first one uses series MEMS switches as in [4]. Switches are located close to the delay line junctions with a complex matching network at the input of the junction. However, to decrease collapsing voltage of the switch, electrodes have to be larger (200um*200um) than in [4] and the spacing between the switches and the junctions has to be increased. In coplanar wave guide technology, these matching problems become very hard to solve.

A second solution developed by [5] uses shunt MEMS switches. In the collapsing state, these switches operate by shorting the signal to ground. They must be situated at a quarter wavelength distance from the junctions. When the switches located at a quarter wavelength from the T-junction are down, delay lines are short circuited. Then, theses lines look like an open circuit at the junction. This solution is better for large MEMS but it implies a minimum delay line length of 180°, which increases the losses.

Our solution is a combination of the two former methods. The principle of the phase shifters is presented in Fig. 2. It is based on 2 similar structures in series, each of them controlled by 4 switches (2 series and 2 shunts). For each structure the signal goes upward, downward or straight. When the signal goes straight, the 2 shunt switches are short-circuiting the signal downward and upward at a distance of $\lambda/4$ from the node so that there are 2 open circuits on these branches at the node, and the 2 series switches are transmitting the signal. When the signal goes upward the shunt switch at the upper part and the series switches are turned off (open circuit), and the shunt switch in the lower part is turned on (short circuit). The same principle appears when the signal goes downward. Then, there are 3 possible ways for each structure, which leads to 9 possible ways as the 2 structures are in series.

The main advantage of this phase shifter comparing to the one presented in [4] is its simplicity. The single pole triple throw do not need any matching network and is fully compatible with CPW lines. In addition, although the number of paths can hardly be increased in practice for the phase shifters presented in [4] and [5], the number of elementary structures composing our phase shifter (two) can be increase without additional complexity and allow more possible paths and therefore more positions when steering the beam of the antenna. The number of positions is given by 3^n, where n is the number of elementary structures (2 in our case).

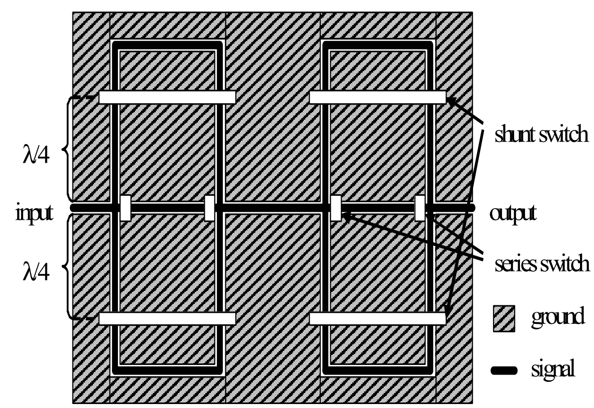

Figure 5. *Phase shifter architecture*

III. Future Work

The antenna will be manufactured using the semi-custom MEMS processing *MetalMUMPS PLUS* from *MEMSCAP* Company. To be tested separately, each elementary part such as radiating elements, switch and phase shifters will be realized independently.

The manufacturing will be over by the end of August 2006.

From September 2006 we will measure the whole antenna system as well as all the elementary parts (switch, phase shifter, etc ...). All these results will be presented at the conference.

IV. Conclusion

The 60 GHz band promises to provide new means to achieve very high data rates for short range communications. With this microwave monolithic integrated circuit (MMIC) structure, our purpose is to prove the viability and to show the advantages of fully integrated MIMO systems using a MEMS process. Naturally, it will remain a lot of challenges until this kind of structure can be use in commercial applications. Path loss is more severe and implementing a highly integrated transceiver in CMOS will be challenging at the very last.

References

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