A Novel Planar Silicon Waveguide Filter at 45 GHz Based On a Periodic Structure

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Abstract **— A novel planar silicon waveguide two- pole filter at 45 GHz with a 2.5% equiripple bandwidth will be described in this paper. This filter is comprised of a periodic structure of holes that form coupled silicon resonators. We first describe the geometrical, physical and electrical characteristics of the periodic structure, the silicon resonator and the CPW I/O ports applying a Finite Element Method. Then a two-pole filter was designed and simulated at the IRCOM, and fabricated at the Georgia Institute of Technology. Measurements will be presented at the conference.**

I. INTRODUCTION

During the last ten years, many studies have proved that periodic structures present interesting electrical characteristics in microwave and millimeter wave domains. These structures typically consist of periodic arrangements of metallic or dielectric elements. They exhibit frequency regions in which electromagnetic waves cannot propagate. Different domains of applications have been explored with great success such as characteristics improvement and design of active circuits, antennas and planar and voluminous microwave filters [1]-[6]. However, in many cases these devices require high precision mechanical machining or specialized processes to fabricate them.

In this paper, we propose novel one-pole and two-pole planar dielectric waveguide filters on silicon substrate with CPW input/output ports for 45 GHz band applications. The CPW ports used to excite the filters are suitable for flip-chip bonding and therefore allow for a good integration in a planar environment. A micromachining technique is applied to fabricate the experimental devices. This technique allows for high mechanical tolerances and is suitable for mass production.

In the first part of this paper, a global analysis applying a finite element software is performed to characterize the periodic structures and to design the filters. This theoretical study has been developed at the IRCOM laboratory from the University of Limoges-France. Then, in the second part we focus on the fabrication and measurements realized at the Georgia Institute of Technology-USA. At last, comparisons between theoretical and experimental results will be presented at the conference.

II. FILTER DESIGN

All the electromagnetic analyses presented in this section are performed using a finite element software developed in our laboratory. This software permits to solve Maxwell's equations in the frequency domain, in forced or free 3D oscillations. It has already been explained [7] and our purpose is not to describe it herein. However, we note that by applying this software to analyze complex devices, we can establish the [S] parameters between the access ports, the unloaded quality factor (Q_u) and the EM field distribution, taking into account all the electrical and physical properties.

A. Silicon resonator

The purpose of this part is first to analyze the electrical properties of the periodic structures created in a silicon substrate taking into account all the physical and geometrical characteristics. Secondly, resonant elements are defined by locally disturbing the periodicity of the structure [2,3] and then used to design microwave filters at 45GHz. In order to obtain a frequency band gap around 45GHz, we consider the silicon substrate to be metalized on its external faces, as described in figure 1. The thickness of this substrate is equal to 0.430 mm and the dielectric constant is equal to 11.7. As shown in Fig. 1,

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square section (s^2) holes are etched periodically in the substrate. In this case the square lattice period is identical in the two directions. The distance between two adjacent holes is the same and is noted as d.

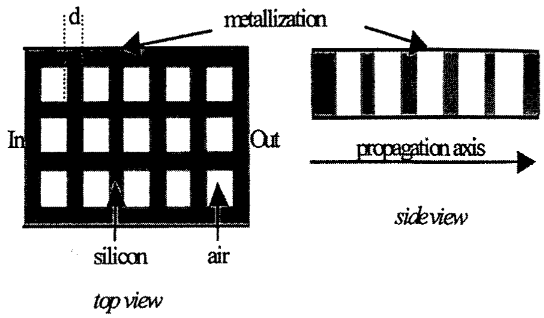


Figure 1: Dielectric structure with periodic hole lattice

As it is well known [1,3], if we create a specific periodic arrangement of holes in the propagation axis of the fundamental mode TE_{10}, the propagation of the electromagnetic wave is disturbed and a frequency band-gap is obtained after optimization, between 40 and 55 GHz as we can observe in figure 2. In this case, the square section s^2 is equal to 0.8x0.8 mm² and the distance d is equal to 0.5 mm.

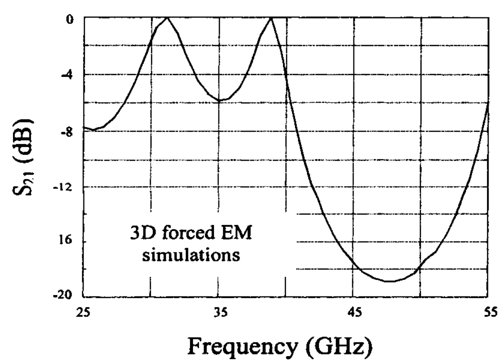


Figure 2: Theoretical frequency band gap

Knowing the periodic structure we now optimize, applying 3D free EM simulations, the dimensions of a resonant element around 45 GHz by disturbing locally the periodicity. Once this is accomplished, this silicon resonator will be used to design the filters. The resonator dimensions are found to be 1.8x3.1 mm². In order to simplify the realization procedure, only the top and bottom sides of the silicon wafer are metalized. As the lateral sides are not metalized, the number of holes around the resonant element has to be carefully defined to confine the EM energy in the resonator as it is shown figure 3. A grid size of 14.8x15.1 mm^2 containing approximately 110 holes is sufficient for good field confinement. In this case, the unloaded Q_u factor has been determined by the FEM taking into account the losses of the structure with the following conductivities: $\sigma_{silicon} = 13.10^3$ S/m and $\sigma_{metallic\ wall} = 5.10^7$ S/m. At 45 GHz, the theoretical Q_u value is equal to 700. For the targeted specifications, it is high enough to obtain satisfying filtering characteristics at these frequencies.

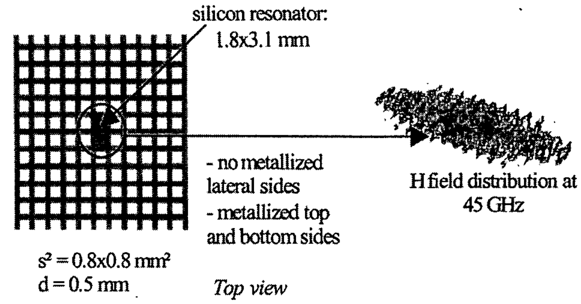


Figure 3: Resonant element description

B. One pole filter

In this section, we define the input/output excitation system of the resonator. It is composed of CPW ports printed on the top face of the substrate as described in figure 4.

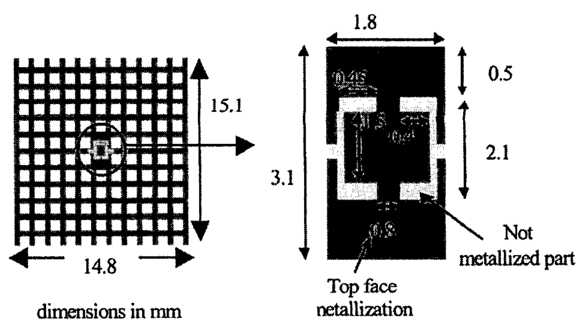


Figure 4: CPW Input/Output port description

Our objective is to validate the CPW port principle applying a 3D forced oscillation EM simulation between the access ports, taking into account the losses defined previously. The theoretical response is shown in figure 5. These results allow us to validate the excitation technique and the good frequency isolation around 45 GHz due to the periodic structure effects.

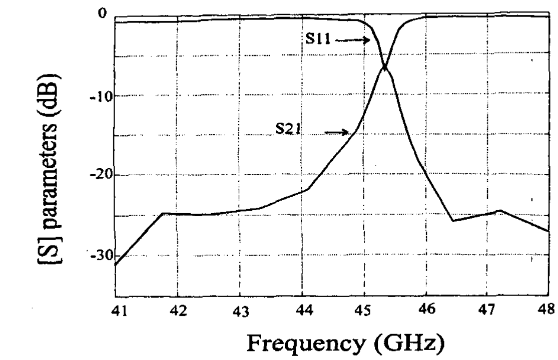


Figure 5: Theoretical response of the one pole filter

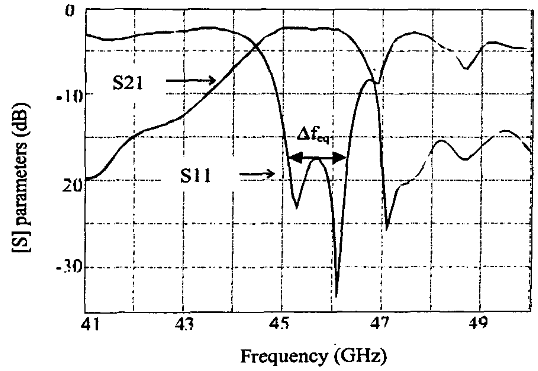


Figure 7 : Two pole filter response

C. Two pole filter

We now design a two-pole bandpass Tchebyscheff filter applying a classical synthesis method. The filtering objectives are the following: a central frequency equal to 45 GHz, a 2.5% equiripple bandwidth Δf_{eq} and a ripple in the band equal to 0.1 dB. Based on these specifications, the CPW I/O ports have been optimized to obtain the theoretical external Q factor equal to 32.5, using 3D forced oscillations EM simulations. Then applying 3D free oscillations, we define the distance between the two resonators to obtain a coupling coefficient K equal to 0.036. The optimized filter design is presented in figure 6.

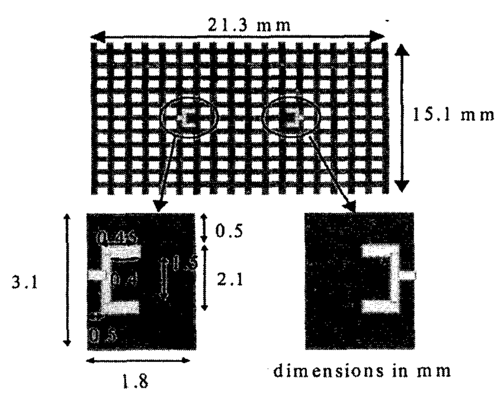
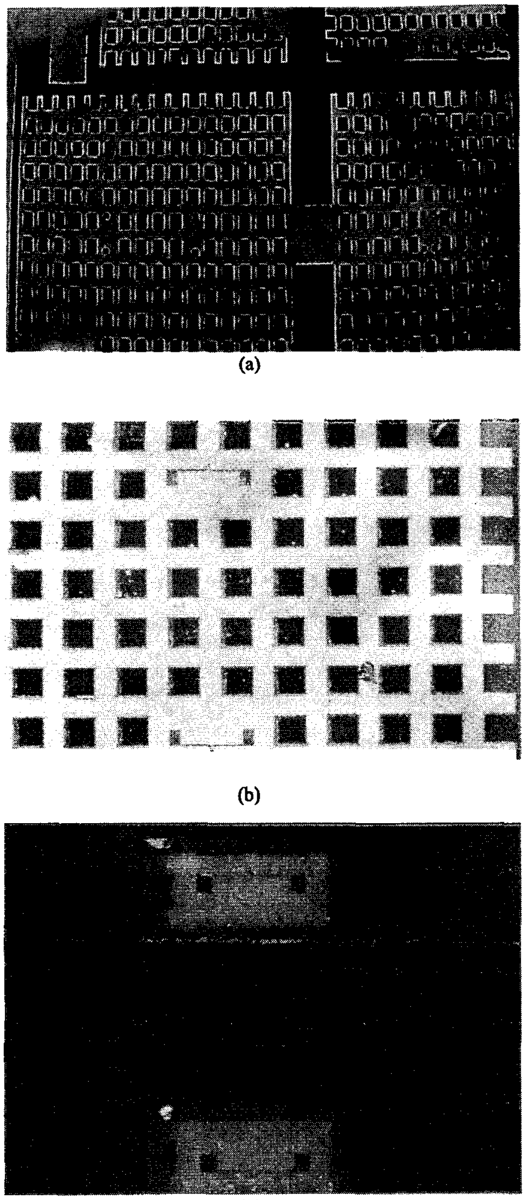


Figure 6 : Tchebyscheff two pole filter

Once the optimized filter design is done, a 3D forced oscillation EM simulation is applied (taking into account the losses as described previously) to obtain the S parameters. Results are shown in figure 7. As we can see the filtering objectives are satisfied. The predicted insertion loss is around 2.5 dB across the pass band.

III. FABRICATION

The one- and two-pole filters were fabricated on very high resistivity (ρ>5000 Ωcm) silicon wafers to reduce significantly the dielectric loss that can lower the quality factor of the resonators. The metallic periodic grid was fabricated first by using standard lithographic techniques and gold electroplating to a thickness of approximately 3 μm (Fig. 8a). The next step was to remove the silicon from the rectangular holes defined by the grid. This was achieved by using a laser micromachining technique. More specifically, a YAG laser with a wavelength of 355 nm provided the energy required to locally melt the silicon (Fig. 8b). The procedure yields a negligible amount of tapering as the laser beam penetrates through the material, providing an almost vertical wall profile. The laser is coupled to extremely accurate x and y stages that allow "direct-write" patterns to be cut over an area of 22" x 26" with a positional accuracy of less than 15 μm. Once the laser micromachining was done, two additional silicon wafers of lower resistivity were metalized to provide the top and bottom metal planes needed for the filter operation. These wafers were bonded to the laser micromachined wafer using silver epoxy glue that was cured at 120° C for 20 minutes, as well as other bonding techniques. The final structure consisted of a total of three stacked wafers. In order to measure the response of the filters the top wafer had access windows that allowed RF microprobes to contact the CPW lines and excite the resonators (Fig. 8c). These windows were created by wet etching micromachining techniques (TMAH water based solution). A thermally grown layer of oxide was used as the masking layer. Alignment marks between the top and middle wafers facilitated the bonding process. Measurements will be taken using an Agilent 8510 vector network analyzer and a Cascade wafer probe station using an SOLT calibration technique.



(a)

(b)

(c)

Figure 8:a) One-pole and two-pole metalized filters before the silicon etching, b) two-pole filters after the silicon etching and c) micromachined access windows for probing.

IV. RESULTS AND CONCLUSIONS

In this paper, we present a novel planar silicon waveguide two- pole filter at 45 GHz with a 2.5% equiripple bandwidth. This filter is based on a periodic structure comprised of holes and coupled silicon resonators. The geometrical, physical and electrical characteristics of the periodic lattice of holes, the silicon resonator and the CPW I/O ports have been first described applying the Finite Element Method. In a second part, a two-pole bandpass Tchebyscheff filter has been designed. The design methodology has been validated and the filter presents satisfying theoretical characteristics. Fabrication and experimental characterization is currently under way. Original results are encouraging. Measurements will be presented at the conference. Bonding and assembly issues will also be discussed.

ACKNOWLEDGEMENTS

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