Surface mountable compact Ka-band filter in multilayer micromachining technology

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ABSTRACT

This paper presents a new concept for compact and low-loss Ka-band micromachined bandpass filters for next generation on-board communications. It combines micromachined cavities with multilayer technology to reduce weight and space occupation. A 4th order pseudo-elliptic filter is presented: it is realized by stacking six silicon layers for a reduced footprint. The filter is based on λ/2 TEM Si membrane resonators placed inside shielding cavities and short-circuited at both anchored ends. With respect to conventional cavities based on TE_{101} resonant mode, the footprint of the proposed resonators is reduced by more than 50% at the expenses of a reduced Q factor degradation (<20%). The measurements of the 4th order filter at Ka-band show insertion loss better than 3dB and Q factor above 500 in Ka-band. The filter robustness to manufacturing and the assembly tolerances has been verified on eight samples, showing good reproducibility of the filter response. Environmental tests are on-going to demonstrate the space compatibility of the filter.

I. INTRODUCTION

Micromachined technology is one of the most promising alternative for the realization of low-loss, low-mass and compact Ka-band filters [1] [2]-[5]. Such a technology allows the realization of metallized cavities and suspended membranes in Silicon or SOI (Silicon On Insulator) substrates. Thanks to bonding techniques, the micromachining technology enables as well the realization of multilayer structures for reduced footprint and area occupation [6]- [7]. Finally, this technology allows the realization of surface mountable devices that can be easily integrated in standard printed circuits [8]-[9].
This paper presents the design, manufacturing and testing of a new type of narrow band 4th order Ka-band filter based on the combination of multilayer and micromachined technologies. The filter is based on λ/2 TEM membrane resonators placed inside shielding cavities. They are realized by DRIE (Deep Reactive Ion Etching) of SOI wafers, then stacked, and assembled by thermo-compressive bonding. The first manufacturing run has shown promising results: insertion loss below 3dB and Q factor above 500 has been measured for the 4th order filter in Ka band. The design robustness to manufacturing and assembly tolerance has been verified on eight samples, showing good reproducibility of the filter response. Thermal and mechanical shocks are ongoing to demonstrate the filter space compatibility.

II. DESIGN OF 4TH POLE FILTER

Fig. 1 shows the topology scheme and the 3D drawing of the proposed 4th pole multilayer micromachined filter. It is made of four resonators placed and stacked on two different levels to reduce the footprint and area occupation. Each resonator consists of a λ/2 metal strip realized as a 20µm thick gold-plated silicon membrane suspended inside a shielding cavity and connected to its walls at both ends. All inner surfaces of the two micromachined layers are gold-plated. Similar single cavity resonators have been characterized and presented in [10].

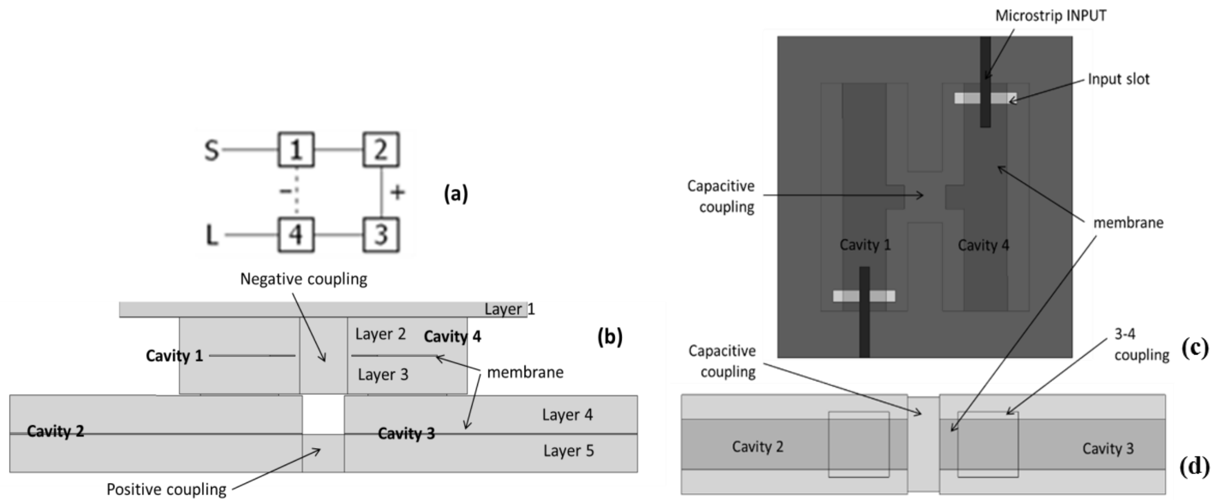

Fig. 1: 4th order filter topology with a negative sign coupling between 1st and 4th resonators (a); Cross section of the 4th order Ka band Filter (b), top (c) and bottom (d) views.

They operate as a λ/2 TEM resonator, thus the second resonant frequency is twice the first one (f_0) and both depend only on the resonator length. The simulated Q factor is about 500 for cavity height of 625μm. With respect to conventional micromachined TE_{101} mode cavity resonators, the TEM resonators exhibit wider spurious-free band, lower sensitivity to manufacturing tolerances and smaller footprint [2]-[4]. The Q decreases less than 20% for layer thickness below 1mm. With respect to [10], the new resonant cavities have vertical lateral walls since they are not realized by using TMAH (tetramethylammonium hydroxide) etching but DRIE process. The latter, combined with SOI technology, allows higher control of the cavity dimensions and depth as well as easier shaping of the coupling elements between resonators. To realize the 4th pole filter, the resonators are placed on two different levels and coupled as shown in Fig.1: cavities 1-2 as well as cavities 3-4 are coupler vertically whereas the couplings 2-3 and 1-4 are realized horizontally. Each cavity is obtained by bonding two SOI wafers, 625μm thick each. The top Layer1 is used as a lid for the 1st and the 4th resonators and as a substrate for the input/output microstrip lines.

The HFSS full-wave simulations including all loss contributions are shown in Fig. 2: the fractional bandwidth is 1.7%, the IL < 2.5 dB with in-band flatness < 0.3 dB and the group-delay variation is below 1 ns. The two desired TZs at the bandwidth margins are due to the cross-coupling between the 1st and 4th resonators. Two additional TZs are present, due to a weak direct coupling between the input and the output lines; this explains also the low noise floor (< -55 dB) in the stopband. The spurious-free range is from DC in the lower stopband and up to 58 GHz in the upper stopband. The expected manufacturing yield without tuning is above 55% with no need of tuning elements/ for the tuneless filter. The total filter footprint is 8,9 x 11,6 mm.

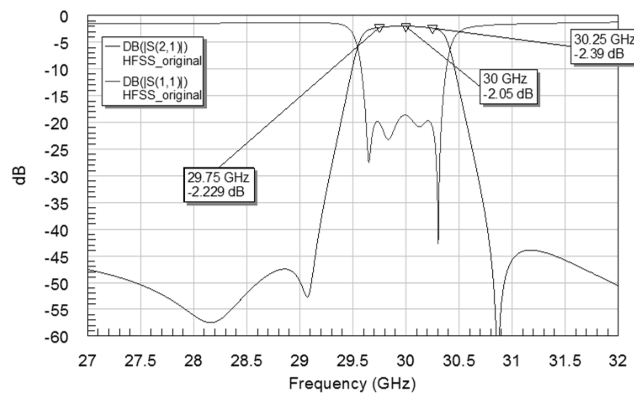

Fig. 2: Simulated insertion loss (in blue) and return loss (in red) of the 4th order Ka band Filter

III. MANUFACTURING

The four pole cavity filters are fabricated by stacking six layers: a base layer, four intermediate SOI layers (for the resonant cavities) and a top layer which provides the RF input and output (Fig. 3). For the fabrication of the single layers essentially two different processes are required: a 6 masks process for the top plate and a 3 mask layer process for the intermediate layers.

The top layer is fabricated on 275 µm thick double side polished high resistive silicon wafers. The through silicon via's (TSV), necessary for the front to back ground connection, are etched from the backside with a 25% Tetra-Methyl-

Ammonium- Hydroxide (TMAH) process. Microstrip input and output RF lines are then patterned on the front side, whereas two slots are defined on the back side metallization. All metallization consists of 2.5 µm thick electro-placed gold layers. Finally, the wafers are coated with a PECVD oxide layer in which the contact holes for the external pads and accesses are etched. The intermediate layers are fabricated on double side polished SOI wafers with a 625µm thick Silicon handle wafer, a 1µm thick buried oxide layer and a 20µm thick Silicon layer. After defining and etching the sealing rings, thermal oxide is grown and the resonators and connection apertures are defined. Next, the cavities are etched with a DRIE process for the full depth of the handle wafer. After, a thermal oxide is grown uniformly on all bare silicon surfaces and the wafers are coated with a gold seed layer on both sides followed by the growth of a 2.5 µm thick electroplated gold.

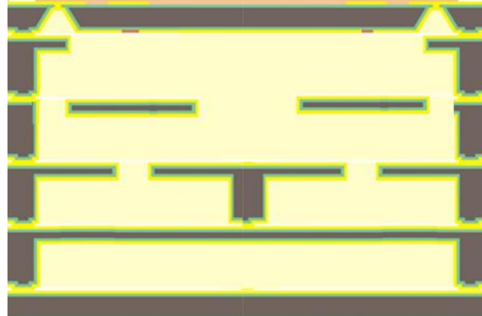

Fig. 3. Schematic cross section of the right half of the filter

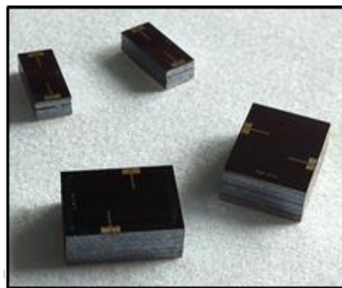

Fig. 4 Fabricated 4th pole filters (in foreground) and single resonator (in background)

Afterwards, the wafers are diced, inspected, cleaned with an oxygen plasma, and assembled in a flip chip bonder. In future production, wafer-to-wafer bonding will be applied to reduce costs. The quality of the bonding was measured with a shear tester: typical shear forces are higher than 4 kg. Fig. 4 shows the assembled 4th order filters and single cavities. Visual and microscope inspections showed that in this first manufacturing run a not correct definition of the etching time has caused an over-etching of all the lateral walls, that turned to be about 60-80µm wider than designed. Consequently, the resonant membranes are about 120-160 µm longer than designed since they are anchored at the cavity walls. In addition, the gold electrodeposited on the bottom of the device layer of the SOI wafers showed very high roughness due to the high roughness of the bottom Silicon interface.

IV. Experimental Results

The Ka band 4th order filters have been characterized on die by using coplanar probes and SOLT (Short-Open-Load-Thru) calibration. Microstrip-to-CPW transitions are included as part of the feeding lines. Fig. 5 shows the measured S-parameters of the manufactured 4th order filter in comparison with back simulations.

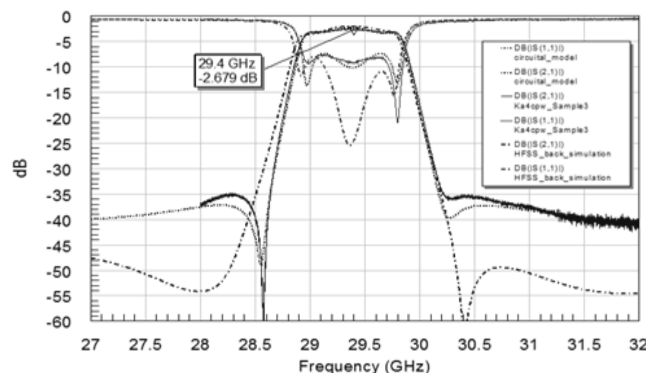

Fig. 5 Comparison among measurements, circuital (AWR) and the HFSS back simulation, accounting for the actual cavities dimensions.

The filter shows insertion loss below 3dB and Q factor above 500, slightly lower than predicted due to the high roughness of the cavity bottom interface. Higher Q can be obtained by increasing the thickness of the electro-plated gold layer. With respect to the expected performance, the filter presents a downshift of about 900 MHz of the resonant frequency and a worse return loss. Both phenomena are result of the over-etching problem that led to longer membranes and larger coupling windows between cavities. This has been verified by circuital and full-wave back simulations. The circuital simulations showed that the main reason for the poor return loss is the higher coupling between cavities 2 and 3 (on the bottom layer). Full-wave simulations have been then performed by moving outwards all silicon walls by 60µm to reproduce the actual cavity dimensions.

The performance repeatability has been verified on eight samples belonging to different wafers of the same lot (Fig.6). The measured performance are very promising and in good agreement with the Montecarlo analysis that was done in the design phase to account for manufacturing and assembly tolerances.

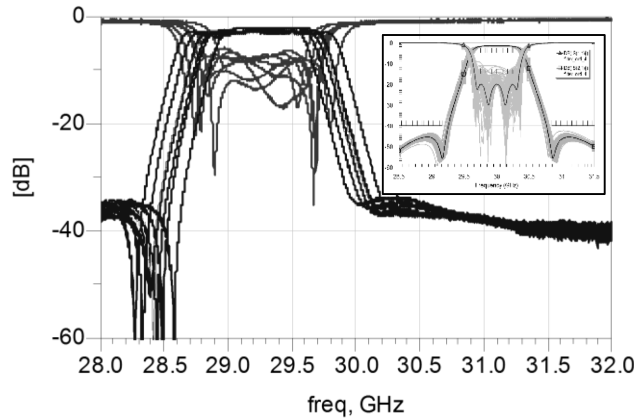

Fig. 6. Measured performance of the eighth samples. Montecarlo analysis is shown in the box.

V. CONCLUSION

A new Ka-band 4th order surface mountable filter has been proposed in multilayer micromachined technology for on-board communication systems. The first prototyping run, based on the use of DRIE technology on SOI wafers, has shown promising results. Insertion loss better than 3dB has been measured in Ka band, with a Q-factor above 500. Qs up to 1000 can be obtained are expected by increasing the metal thickness and the cavity height. Environmental tests are on going to demonstrate the filter space compatibility.

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