High Q Micro-machined Cavity Resonator Filter in Low-Cost Silicon Technology

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***Abstract*— This paper demonstrates a two-pole filter based on high Q micro-machined cavity resonators for operation at 20GHz. The filter implements a novel inter-resonator coupling cavity placed above the inter-cavity wall separating the resonators and etched out of silicon using the same KOH-etching process as the one used to realised the cavity resonators. The Q-factor of a single cavity resonator is measured as well as the response of the two-pole filter. The filter presented here constitutes the first development step toward a more sophisticated fixed as well as tunable four-pole filter aiming at the replacement of bulky waveguide filters mounted in a majority of satellite transceivers.**

I. Introduction

Microwave filters are key components implemented in most of micro- and millimetre-wave systems to separate a given spectrum out of a broadband noised signal and have been the focus of many researchers in the past 50 years. However, despite the long effort put into their development, filters remain in many cases a bottleneck in the design of microwave front-ends and the need for compact, easily integrable and low-loss filters still drives the research toward more efficient and low-cost filters [1].

In the special case of band-pass filters, the technology used to realise the filter has to be chosen with particular attention depending on the frequency range, the space available, the technology the filter has to be connected to, and finally, the loss budget allowed for the filter. The insertion loss of a band-pass filter depends to a large extend on the insertion loss of a single resonator, which, of course, has to be as low as possible. The quantity used to assess the performance of a single resonator is the so-called unloaded Q-factor. This quantity is proportional to the amount of energy stored within the resonator divided by the average power dissipated inside the resonator.

The panoply of resonators available to realise band-pass filters is constantly increasing in order to fit the challenging requirements of modern micro- and millimetre-wave systems. On one hand, the filters based on waveguide cavity resonators are bulky and cumbersome to integrate but have very good performance in terms of insertion loss. On the other hand, the filters implementing the classical ladder microstrip resonator are easy to integrate but limited in terms of Q-factor. "In between" there is a number of other solutions. Some of them like Surface Accoustic Wave resonators (SAW) or Bulk Accoustic Wave resonators (BAW) have been proposed to realise very low-loss filters but are limited to the low millimetre-wave range up to the Ku-band. Dielectric resonators overcome the frequency limitation of SAW and BAW resonators and allow the realisation of very efficient filters up to 40GHz but they are quite cumbersome to integrate on a planar PCB. The performance of some common types of resonator are compared versus frequency in Fig. 1.

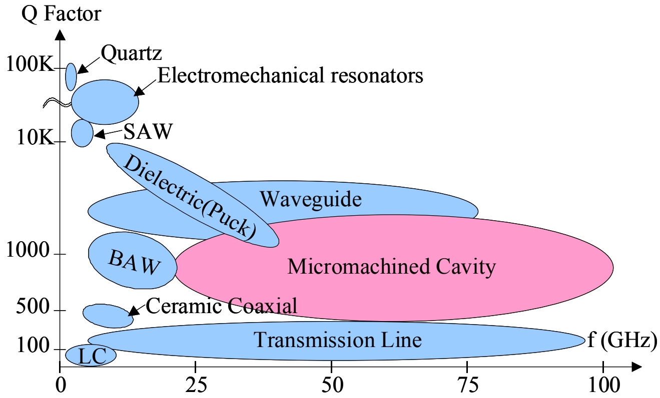

Fig. 1 State of the art of micro- and millimetre-wave resonators (blue) and expected performance of the air-filled micro-machined cavity resonator (pink).

The most popular resonator technologies are represented in blue. None of the conventional technologies satisfies the need for high Q resonators for emerging millimetre-wave applications above 40GHz, excepted the waveguide resonator technology. However, since this solution is becoming costly as the frequency increases and because of the not-so-easy integration of waveguide resonators, some alternative solutions principally based on micro-machining have been proposed. A first solution is the realisation of ladder microstrip resonators on a thin membrane. This evolution of the classic ladder microstrip resonator reduces the dielectric and ohmic losses and some realisations with a Q-factor up to 600 have been demonstrated [2], [3]. An alternative to this is the micro-machining of air-filled metallised cavity resonators. The micro-machined cavities are etched out of silicon using Reactive Ion Etching (RIE) [4], or wet etching TMAH or KOH [5], [6]. Micro-machined cavity resonators are represented in pink in Fig. 1.

Micro-machined cavity resonators have the advantage of being particularly suitable for millimetre-wave applications from 20GHz up to 100GHz and constitute a high Q, easy-to-integrate alternative to the excellent but difficult-to-integrate waveguide resonator. Additionally, they offer tuning and trimming possibilities [7], which are not so easily achievable in most other technologies. This represents obviously a great advantage for the realisation of frequency agile band-pass filters, which are of particular interest for implementation in modern reconfigurable millimetre-wave systems.

In this paper, a two-pole Tchebycheff filter for 20 GHz satellite communication based on KOH-etched micro-machined cavity resonators is demonstrated. The implementation of the micro-machined cavity resonators is completed by the use of a novel KOH-etched coupling cavity placed above the cavity resonators allowing for an inductive coupling of the two resonators. The configuration of the filter allows for an excellent compromise between low insertion loss, high integrability, and low fabrication cost. Finally, thanks to the well known and robust KOH-etching process of silicon used to realise the cavities, very good fabrication tolerances and repeatability are expected.

II. DOUBLY TERMINATED MICRO-MACHINED RESONATOR

The micro-machined cavity resonator used to realise the filter presented here implements the same principle as a conventional waveguide resonator using the resonance of the fundamental TE_{101} mode of a rectangular cavity. The resonant frequency of the TE_{101} mode is given by

$$f_{TE_{101}} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} * \sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2} \qquad (1)$$

where c is the speed of light, μ_r and ε_r are the relative permeability and permittivity of the medium filling the cavity, and a and b are the length and width of the rectangular cavity, respectively. In order to maximize the Q-factor, the ratio of the volume enclosed inside the cavity to the total area of the cavity walls has to be maximised. This is done by taking a square cavity with a=b. The length and width of the cavity are about 1cm to achieve a resonance of the cavity resonator at 19.95GHz. The dimensions have to be slightly corrected to take into account the effect of the non perpendicular sidewalls of the cavity due to the KOH-etching process used to realise the structure. The height of the cavity resonator depends on the desired Q-factor. For the application targeted with the filter presented here, a Q-factor of 1000 is required; it corresponds to a cavity depth of 1mm for Au-covered cavity walls.

The structure is realised with two silicon wafers: a bottom wafer containing the cavity resonator and a top wafer closing the cavity on its upper side. The top wafer contains the input and output coupling structures. The couplings are realised by inductive coupling of a microstrip line realised on top of the top wafer through a coupling slot realised in the ground plane on the back side of the top wafer [6]. For measurement purposes and for easier integration, a coplanar-to-microstrip line transition using radial stubs has been implemented. These transitions are de-embedded using TRL-calibration in the subsequent measurements. A cross section of the doubly terminated cavity resonator is shown in Fig. 2.

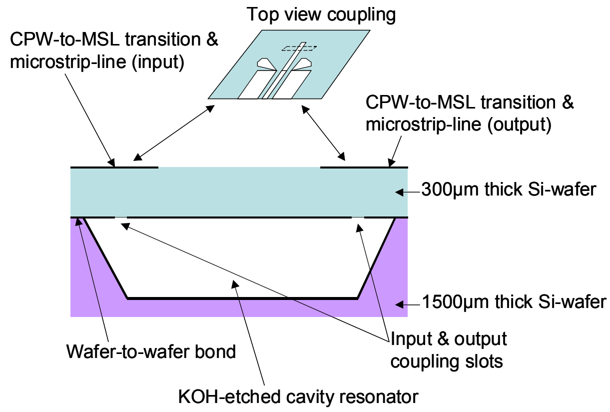

Fig. 2 Cross section of the doubly terminated cavity resonator

The two silicon wafers are 300µm and 1500µm thick for the top and bottom silicon wafer, respectively. The top wafer is chosen to be of high resistivity silicon to minimize the losses in the input and output microstrip lines and in the coupling regions above the coupling slots. The cavity resonator is covered with 3µm of Au, which is more than 5 times the skin depth in Au at the operating frequency. The complete metallisation of the cavity prevents the electromagnetic field from penetrating into the silicon and especially in the bottom silicon wafer, which can be of low-cost low-resistivity silicon. Finally, the two silicon wafers are bonded together by Au-Au thermo-compression, which ensures the cavity to be hermetically sealed. For this reason, the volume inside the resonator can be filled with inert gas or dry atmosphere to prevent any oxidation of the metal inside the cavity if it is not Au and formation of condensed water or moisture on the walls of the cavity. The etching of the 1000µm deep cavity resonator requires about 22 hours of etching time.

In order to measure accurately the unloaded Q-factor of the cavity resonator, a weakly coupled doubly terminated cavity resonator has been fabricated and the corresponding measured S_{21}-parameter is plotted in Fig. 3.

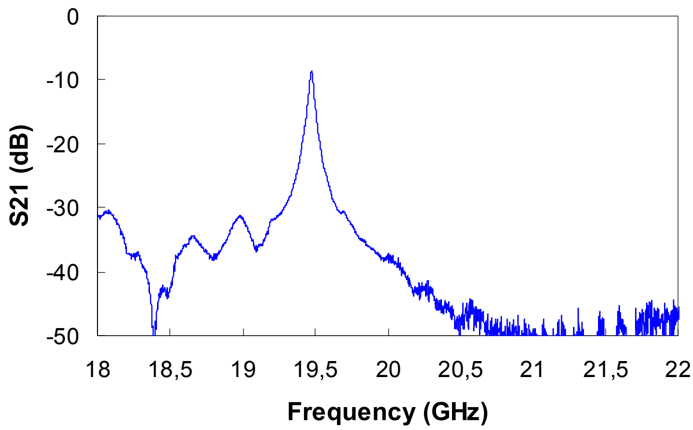

Fig. 3 Resonance Peak of the weakly coupled resonator

The measurement shows a resonance frequency of about 19.5GHz instead of the expected resonance frequency of 19.95GHz. A likely source of inaccuracy is a considerable under-etching of the cavity resonator, which would of course lower the resonance frequency of the resonator by increasing the lateral dimensions of the cavity. This under-etching can be taken into account in further design steps.

The loaded and unloaded Q-factors of the cavity resonator are calculated from the measured S_{21}-parameter using:

$$Q_L = \frac{f_0}{f_{1-3dB} - f_{2-3dB}} \qquad (2)$$

$$Q_U = \frac{Q_L}{1 - 10^{\frac{S_{21}|f_0}{20}}} \qquad (3)$$

where Q_L and Q_U are the loaded and unloaded Q-factors of the cavity, respectively. f_0 is the resonance frequency of the resonator, $f_{1\text{-}3dB}$ and $f_{2\text{-}3dB}$ are the cut-off frequencies 3dB below the resonance peak, and $S_{21}|f_0$ is the value of the S_{21} parameter at the resonance frequency. The unloaded Q-factor extracted from the measurement is 945, which is quite close to the required Q-factor of 1000.

III. Two-Pole Micro-Machined Filter

A two-pole Tchebycheff filter based on the high Q micro-machined cavity resonator has been designed and fabricated for operation at 19.95GHz. The specifications of the two-pole filter are derived from the specifications of the targeted four-pole filter. The centre frequency of the pass-band of the filter is 19.95GHz, which corresponds to the up-link frequency of the targeted satellite communication application. The required band-width is 500MHz, and the in-band insertion loss must be lower than 1.5dB over the entire pass band. The coupling coefficients used for the design of the filter are read from the table related to the design of Tchebycheff filters given in [8]. They are given in Table 1.

TABLE I

Coupling Coefficients of the Two-Pole Filter

Input Coupling: Qe1	71.8
Inter-Resonator Coupling: k	0.023
Output Coupling: Qe2	71.8

Qe1 and Qe2 are the external Q-factors of the cavity resonators connected to the input and output microstrip lines terminated with a 50Ohm impedance and k is the coupling coefficient of the inter-cavity coupling. The input and output couplings are achieved by choosing the adequate dimensions and locations of the coupling slots [9]. The inter-resonator coupling is realised with a so-called coupling cavity in place of the well-known inductive iris often used in waveguide cavity filters and which cannot be directly realised using the KOH-etching process of silicon. The coupling cavity is etched out of the top silicon wafer using KOH-etching and is metallised. It forms a silicon free volume between the two cavity resonators, where the evanescent coupling fields penetrate. They couple to the H-fields of the fundamental TE_{101} mode of both cavity resonators and their magnitude is determined by the dimensions and position of the coupling cavity. In this way the strength of the inter-cavity coupling is completely determined by the height, length and width of the coupling cavity, which can be chosen to meet exactly the required coupling coefficient. A top view and a cross sectional view of the two-pole filter configuration is shown in Fig. 4.

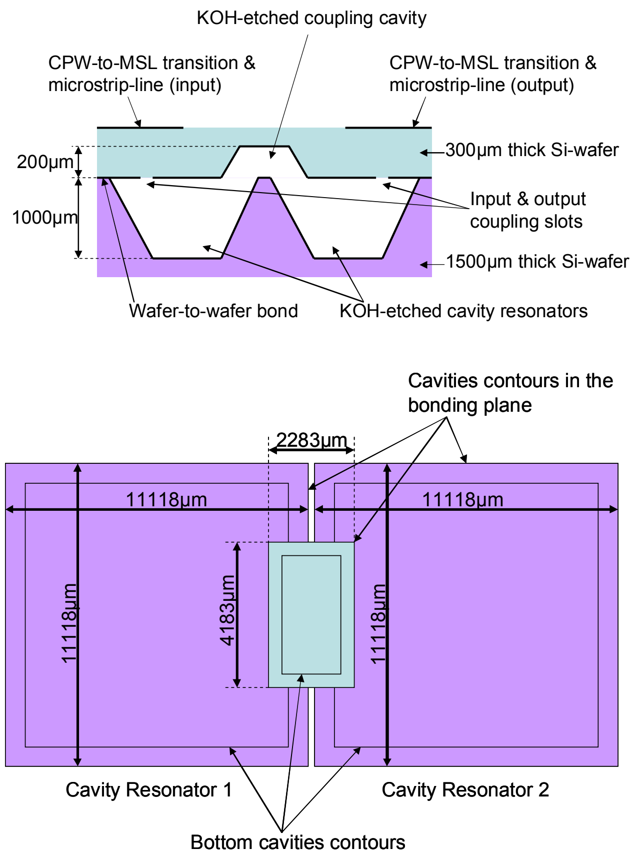

Fig. 4 Configuration of the two-pole filter: side view (top) and top view (bottom)

The fabrication costs of the filter are optimised by using the same KOH-etching process to realise the cavity resonators and the coupling cavity. It represents an advantage in terms of simplicity of the process.

The S-parameters of the filter have been simulated using the commercial 3D FDTD (Finite Difference Time Domain) simulation software EMPIRE and measured using TRL-calibration. Fig. 5 shows the simulated and measured filter response. A comparison of the two filter responses shows a shift of the centre frequency of about 600MHz. It is a similar shift in frequency as it was observed for a single resonator and it is believed to be due to the same source of inaccuracy. The measured -3dB band-width is about 795MHz, which is more than the required 500MHz. This discrepancy between simulation and measurement is attributed partly to the fabrication tolerances of the coupling structures, coupling slots, and coupling cavity. Finally, the measured in-band insertion loss is about 1.3dB, which is reasonable for a two-pole filter easily integrable on a planar PCB.

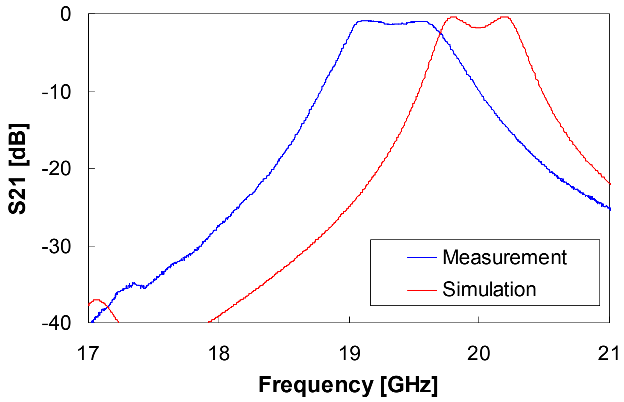

Fig. 5 Simulated and measured response of the two-pole filter

IV. Conclusion

In this paper, a low-loss two-pole band-pass Tchebycheff filter at 20GHz realised in micro-machined silicon technology is demonstrated. The configuration of the filter implementing a novel KOH-etched coupling cavity placed on top of the cavity resonators is presented. The good Q-factor of a single cavity resonator measured at 945 and the low in-band insertion loss of the two-pole filter of about 1.3dB demonstrate good performance for a filter easily integrable on a planar board. With this, the replacement of high-Q but bulky waveguide filters implemented in numerous micro- and millimetre-wave devices seems more realistic. The development of the filter demonstrated in this paper constitutes the first step of a longer study aiming at the development of a low-loss frequency agile four-pole filter to be implemented in satellite transceivers.

Acknowledgement

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