# Low-Loss Micro-Machined Four-Pole Linear Phase Filter in Silicon Technology

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***Abstract*—In this paper, a micro-machined linear phase filter for K-band satellite communication is presented. The filter is a four-pole cavity resonator band-pass filter. It is fabricated in silicon using the KOH-wet etching technique, and the filter is assembled by bonding two silicon wafers. The proposed configuration enables the realisation of low-loss and low-cost filters, which are easily integrable, monolithically or in a hybrid fashion, in microwave front-ends. Further, as it is described in the paper, the arrangement proposed for the cavity resonators allows for the realisation of cross-couplings between the cavity resonators, and it makes possible the design of compact linear phase filters. This paper presents the design and the measurement of a single micro-machined cavity resonator, and it describes the design procedure of the four-pole filter. This design of the complete four-pole micro-machined linear phase filter is finally assessed by full-wave simulation.**

## I. Introduction

Band-pass filters are ones of the largest components of present data link millimetre-wave equipments. This is especially true for spaceborne applications like satellite transceivers. In these applications, very low-loss filters are mandatory and waveguide cavity resonator filters have been implemented up to now because of their excellent RF performance. However, these filters, directly machined out of metal, present quite a few disadvantages for on-board use. Their bulkiness and heaviness are bottlenecks, which limit the integration density of the entire system, and they represent a severe cost factor for the transportation into orbit of the complete payload. Also, waveguide filters are more often connected by means of coaxial connectors, which make them cumbersome to integrate onto Printed Circuit Boards (PCB). On the economic point of view, waveguide filters are expensive to manufacture. They require high-precision machining as well as fine tuning made by hand, and the costs are not dramatically decreased for large production scales. In order to overcome these limitations of waveguide filters, one is interested in replacing them by more compact micro-machined filters.

Micro-machined filters are easier to integrate than their waveguide counter-parts, and they are expected to have satisfactory performance in terms of insertion loss. The micro-machined filter presented in this paper is made out of silicon dielectric. It can be easily integrated in a hybrid fashion onto a front-end fabricated in LTCC or in soft Teflon substrate, or even monolithically if the front-end is manufactured in silicon. Furthermore, the interfaces of the filters are planar transmission lines (microstrip or coplanar), and they can be easily connected using flip-chip or bond wires. Finally, micro-machined filters are manufactured using well-established and robust silicon micro-machining techniques. These techniques allow for tight and repeatable fabrication tolerances, and they have the advantage of being cost effective for large production scales.

## II. Privileged Field of Application of Micro-Machined Filters

The micro-machined filter presented below constitutes the first development step of filters intended for integration in satellite transceivers. The performance expected for these filters in terms of insertion loss and power handling makes them suitable for the middle stage of transceivers. This means, after the Low-Noise Amplifiers (LNA), but before the final power amplification stage. In this segment of the transceiver, two major applications can be envisaged. Before the frequency conversion, micro-machined filters could be implemented as post-LNA filters operating in the up-link frequency band (about 30GHz). There, they could filter out the noise generated by the non-linearity of the LNA. However, the number of filters necessary for this task is limited and therefore, the gain in size and weight provided by the replacement of the existing filters is expected to be modest. Another possible use of micro-machined filters is after the frequency conversion. Here, silicon filters could replace advantageously the existing filters required to separate the down-converted signal (approximately 20GHz) into different channels. Also, due to the likely size and weight reduction that could be gained by a higher integration density and a smaller size of the numerous filters necessary at that level, this is the application, which has been chosen to demonstrate the potential of the proposed filter. A schematic of a satellite transceiver indicating the foreseen location of micro-machined filters is shown in Fig. 1.

Hence, the specifications of the micro-machined filter addressed here are the ones of channel partitioning filters implemented in recent satellite transceivers. They aim at the separation of 500MHz-wide channels centred at various frequencies around 20GHz. For the channel centred at 19.95GHz, these specifications are listed in Table I.

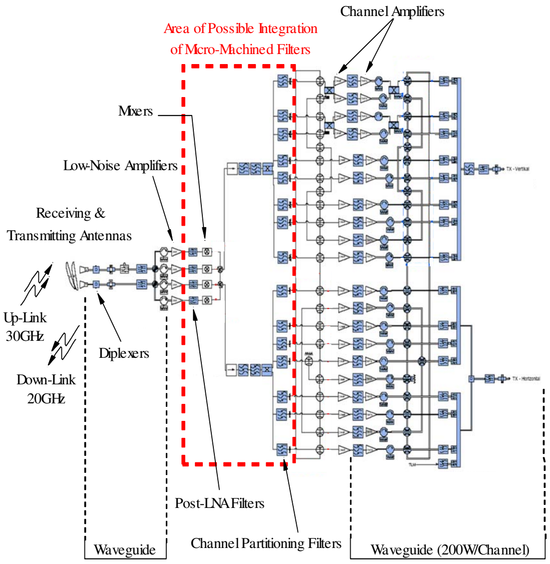


Fig. 1: Schematic of a satellite transceiver for communication link (provided by Tesat-Spacecom GmbH & Co. KG).

TABLE I

ELECTRICAL SPECIFICATIONS OF THE MICRO-MACHINED FILTER.

| Parameter | Value |
|---|---|
| Centre Frequency $F_0$ | 19.95 GHz |
| -0.3 dB Bandwidth $\Delta F$ | 500 MHz |
| Insertion Loss $IL$ | <1.5 dB |
| Reflexion $S_{11}$ | <-20 dB |
| Maximal $\Delta TGD$ in 40 MHz (19.7 to 20.2 GHz) | <0.7 ns |
| Out-of-Band Rejection: | |
| 19.6 GHz | <-20 dB |
| 0 to 19 GHz | <-40 dB |
| 21 to 32 GHz | <-40 dB |

In this set of specifications, the out-of-band rejection specified at 19.6GHz aims at filtering the second harmonic of the local oscillator running at 9.8GHz. Further, a maximum variation of the group delay in the pass-band is required to avoid an excessive distortion of the signal passing through the filter.

## III. 2-PORT MICRO-MACHINED CAVITY RESONATOR

Firstly, in order to get an idea of the achievable Q-factor, a weakly coupled cavity resonator has been realised and measured. The cavity resonator is designed according to the principle introduced in [1] and [2]. It is fabricated using two silicon substrates bonded together. The cavity resonator is etched out of the bottom silicon substrate, and it is closed on its top side by a top silicon dielectric. The coupling structures are processed in the top silicon substrate. The input/output feeding lines are microstrip lines realised on top of that same top silicon dielectric. They are coupled to the cavity resonator using metal-free areas called "coupling slots". A cross-sectional view of the 2-port cavity resonator is shown in Fig. 2.

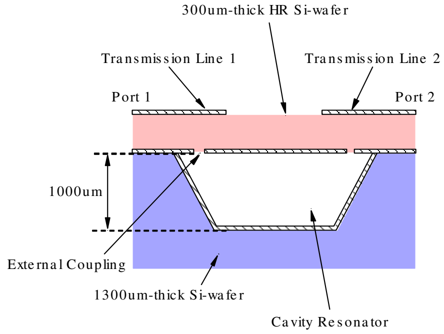


Fig. 2: Cross-sectional drawing of the KOH-etched cavity resonator.

The cavity resonator is squared to maximise the unloaded Q-factor, and its effective length and width (geometrical mean) are 10600µm. It has been measured on-wafer using 150µm-pitch coplanar measurement probes connected to an Agilent E8363B PNA network analyser. The corresponding measured $S_{21}$-parameter is plotted around the resonance in Fig. 3.

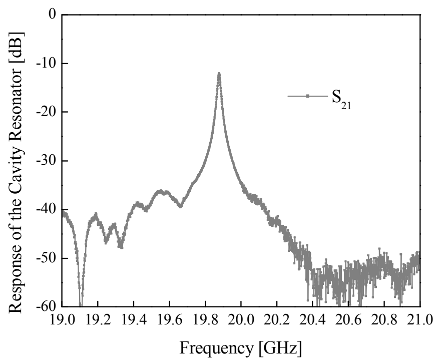


Fig. 3: Measured response of the weakly coupled 2-port micro-machined cavity resonator.

The resonance frequency of the cavity resonator is measured at 19.88GHz. It is 0.36% below the required resonance peak specified at 19.95GHz. Also, the unloaded Q-factor extracted from the measurement using the formulas given in [3] is $Q_u$=1410. It is very close to the unloaded Q-factor of an "equivalent" waveguide cavity resonator theoretically given at $Q_u$=1515.

## IV. FOUR-POLE LINEAR PHASE FILTER

### A. Design

Standard filters like Tchebycheff filters have transfer functions with non-linear phase in the pass-band. Since the group delay is the first derivative of the phase with respect to frequency, these filters have a non-uniform group delay. Hence, for these filters, the signal packets of a broadband signal reach the output of the filter at different times, and the signal is distorted. This situation can be overcome by implementing linear phase filters having, by definition, a flat group delay. In linear phase filters, all components of the input signal are transmitted to the output of the filter at the same time, and the signal travelling through the filter is not distorted. Linear phase filters are realised by designing cross-couplings between resonators, which, initially, are not electrically adjacent. In [4], it is shown that a linear phase filter can be realised when both, the direct and the cross-couplings, have the same sign. Thus, it is possible to design linear phase filters with cavity resonators coupled with direct and cross-couplings all realised with inductive coupling cavities. In the following, a four-pole linear phase filter with one cross-coupling between the first and the fourth resonator is presented. A schematic of the filter is given in Fig. 4.

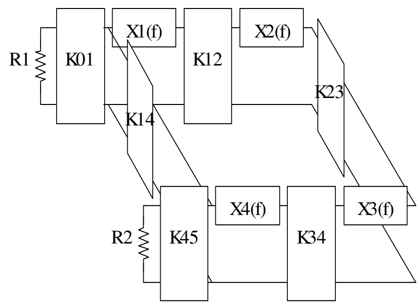


Fig. 4: Schematic of the four-pole linear phase filer.

The filter is designed with four resonators coupled with three direct couplings K12, K23, and K34, and one cross-coupling K14. As previously mentioned, both, the direct and cross-couplings, have the same phase and are inductive. The filter is realised in the same architecture as the one presented in [2]. In the present case, however, the filter is realised with four KOH-etched cavity resonators arranged in a square (Fig. 5).

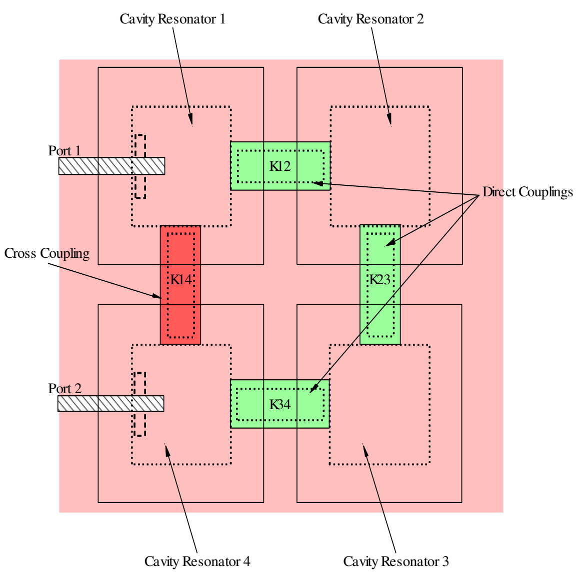


Fig. 5: Top view of the four-pole linear phase filter.

The direct couplings as well as the cross-coupling are implemented using KOH-etched coupling cavities. A cross-sectional view of the filter showing the different features, coupling structures and cavity resonators, is depicted in Fig. 6.

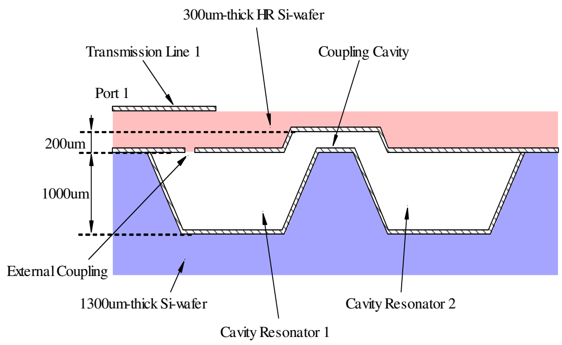


Fig. 6: Cross-sectional cut view of the four-pole linear phase filter.

The input/output couplings of the filter are realised using aperture-coupled microstrip lines similar to those of the single cavity resonator presented in the previous section. For inter-resonator couplings, the magnitudes of the coupling coefficients are controlled by the relative widths of the coupling cavities. In the same way, the strength of the input/output couplings is determined by the size of the coupling slots.

The coefficients of the four-pole filter are determined according to the method proposed in [5]. The coupling coefficients between the resonators as well as the electrical parameters of the linear phase filter are summarised in Table II.

TABLE II

ELECTRICAL PARAMETERS OF THE FOUR-POLE LINEAR PHASE FILTER.

| Coupling Coefficients | | Electrical Parameters | |
|---|---|---|---|
| Parameter | Value | Parameter | Value |
| $k_{01}$ | 0.0315 | $Q_{e,1}$ | 30.18 |
| $k_{12}$ | 0.0281 | $\frac{X_{1,2}}{Z_0}$ | 0.1037 |
| $k_{23}$ | 0.0187 | $\frac{X_{2,3}}{Z_0}$ | 0.0682 |
| $k_{34}$ | 0.0281 | $\frac{X_{3,4}}{Z_0}$ | 0.1037 |
| $k_{45}$ | 0.0315 | $Q_{e,2}$ | 30.18 |
| $k_{14}$ | 0.0057 | $\frac{X_{1,4}}{Z_0}$ | 0.0208 |

The electrical parameters of the linear phase filter, normalised inductances $X_{i,j}/Z_0$ and external Q-factors $Q_{e,1/2}$, are calculated from the coupling coefficients $k_{ij}$ using the equations given in [3].

The coupling slots used in input and output of the filter are 500µm-wide H-shaped apertures. They are placed 1358µm away from their respective adjacent cavity resonator side-wall. The coupling cavities are 200µm-deep, 2000µm-long and the inter-cavity wall is 100µm-thick. All dimensions are given in the bonding plane. In order to determine the width of the coupling cavities and coupling slots allowing for the appropriate coupling coefficients, full-wave simulations have been performed for the two coupling structures alone. For inter-resonator couplings, the simulated structure includes the KOH-etched coupling cavity, a part of the two cavity resonators, and the structure is terminated by two waveguide ports. For the input/output aperture coupled microstrip lines, the simulated structure is terminated by a microstrip line port on one side, and by a waveguide port at the other end. For design purposes, the coupling coefficients have been calculated from the simulated $S_{21}$-parameter, and the results have been interpolated with 4th order polynomials. The corresponding design equations are given by

$$L_s = 0.45474213 - 0.8156731*10^{-2} \cdot Q_{e,1/2} + 0.111371768*10^{-3} \cdot Q_{e,1/2}^{\ 2}$$
$$- 0.69203132*10^{-6} \cdot Q_{e,1/2}^{\ 3} - 0.13573153*10^{-8} \cdot Q_{e,1/2}^{\ 4}$$

$$W_{cc} = 0.14530567 + 7.82100111 \cdot (X/Z_0) - 106.48527295 \cdot (X/Z_0)^2$$
$$+ 741.60230038 \cdot (X/Z_0)^3 - 1785.57893576 \cdot (X/Z_0)^4$$

In these formulas, $L_s$ is the length of the input/output coupling slots, and $W_{cc}$ is the width of the coupling cavity. In these equations, the two design parameters $L_s$ and $W_{cc}$ are normalised to the width of the cavity resonator, and they are dimensionless. Finally, the complete filter has been optimised using the full-wave commercial simulator EMPIRE.

### B. Characterisation

The response simulated for the complete four-pole filter is plotted in Fig. 7, and the corresponding group delay is shown in Fig. 8.

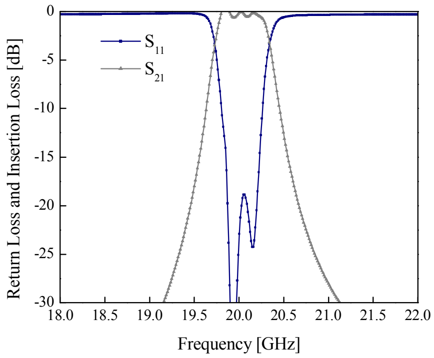


Fig. 7: Simulated response of the four-pole linear phase filter.

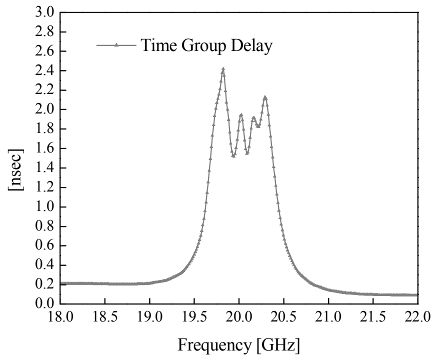


Fig. 8: Simulated time group delay of the four-pole linear phase filter.

The simulated filter response is centred at 20.038GHz, which is about 0.44% above the centre frequency of 19.95GHz required for the filter. The filter has been deliberately designed with a centre frequency above the targeted one. This has been done in order to compensate for the frequency shift observed between simulation and measurement for the 2-port single cavity resonator. The in-band ripple of the simulated response is approximately 0.65dB, and the bandwidth at that same level is 0.464GHz (2.3%). The overall variation of the group delay in the pass-band is 0.9ns. However, within any 40MHz channel of that pass-band, the maximum variation of the group delay ($\Delta TGD$) does not exceed 0.4ns, which is below the variation of the group delay of 0.7ns allowed for the filter.

## V. Conclusions

In this paper, a four-pole linear phase filter designed for low-cost micro-machined silicon technology has been presented. The filter is designed with four air-filled cavity resonators coupled in such a way that the group delay of the response has a satisfactory flatness in the pass-band. Based on the same process, a single cavity resonator fabricated in a first process run has been measured with an outstanding unloaded Q-factor of 1410. The development of the four-pole micro-machined filter presented in this paper constitutes the first steps of a longer study aiming at low-cost, low-loss, and easily integrable filters for the next generation of K-band satellite transceivers.


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