Piezoelectric Tuned LTCC Bandpass Filters

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***Abstract*— A piezoelectrically tuned second order LTCC bandpass filter with 46% measured tuning range is presented. The filter incorporates a novel parallel-plate capacitor which is tuned by a piezoelectrically moved electrode. The center frequency of the filter shifts from 1.28 GHz to 1.8 GHz with a preserved insertion loss and quality factor.**

***Index Terms*— Bonding, ceramics, piezoelectric materials, tunable filter, varactors.**

I. Introduction

With the growing number of wireless services and frequency bands, the complexity, size and cost of front ends is increasing while their performance starts to suffer from the insertion loss of the additional cascaded stages and switches in the signal path [1]. Therefore, frequency agile components which adapt themselves to the actual mode of operation, promise cost-efficient, highly functional front end terminals with reduced component count [2]. Particularly, the need for tunable bandpass filters has fostered a number of design and material approaches [2]–[4], [6]–[14]. However, there is still a severe gap between the tuning range needed from a system point of view and that achieved by physical devices. It is furthermore desirable, that the tuning mechanism affects only the filter frequency but no other transmission and reflection characteristics within the whole tuning range [3]. Moreover, for small size and reliable performance simple materials and structures should govern the device design.

A varactor with high quality factor and large tuning range would permit frequency filtering as demanded by system specifications. However, the design and manufacture of such analogue filters is not trivial and has not yet been satisfactorily achieved to date due to the lack of a high quality tuning element. This situation calls for new approaches in device concepts as well as materials and processing technologies.

Recently, we presented the design of a piezoelectrically driven variable capacitor with wide tuning range [4]. The device is tuned by moving the top electrode of the parallel plate structure with a piezoceramic cantilever. When applied as a shunt capacitor in a coupled microstrip-line LTCC bandpass filter, the center frequency of the filter is tuned from 1.1 GHz to 2.6 GHz with 200 V control voltage. The filter exhibits low insertion loss of 3±1 dB throughout this tuning range.

As dictated by general filter theory and technology, the quality factor and the selectivity can be improved at the expense of the insertion loss, e.g. by adding further circuit elements or resonators. This paper treats the measurement and characterization of a two-pole "second-order" filter designed and fabricated to yield a performance superior to the former first-order version. The selectivity is improved by 10 to 15 dB and the quality factor of the capacitor by a factor of 2 for a 150 nm gold metallization on the cantilever.

II. Second Order Filters

The layout of the two-pole filter comprises four coupled microstrip lines as shown in Fig. 1. In contrast to the first order filter, there are now two inner microstrip lines, but as before, they are divided into two sections. The sections RF1A and RF1B are formed by the bottom metallizations

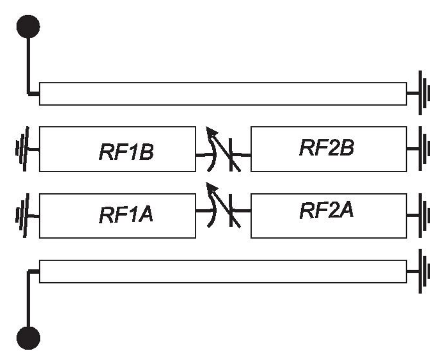

Fig. 1. Layout of the 2-pole tunable filter.

of two piezoelectric cantilevers A and B, respectively, [5] which are shortened to ground at one end and form the upper movable electrode of two variable capacitors with the other end. The other sections RF2A and RF2B of these lines are screen-printed on a low temperature cofired ceramics (LTCC) substrate. They simultaneously form the fixed bottom electrodes of the capacitors.

In zero-bias state, the air gap of each capacitor vanishes and the capacitance assumes its maximum value. In this case, the electrodes are separated by a high-K dielectric layer. Under bias, the upper electrode bends up and opens an air gap thus causing a steep drop in capacitance. A wide tuning range is achieved due to this specific feature. The filter was designed on the basis of established theory [[6], [7]].

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III. Device–Specific Fabrication Process

The new filter has been fabricated using the same fabrication process as for the first order version, a simplified representation of which is shown in Fig. 2.

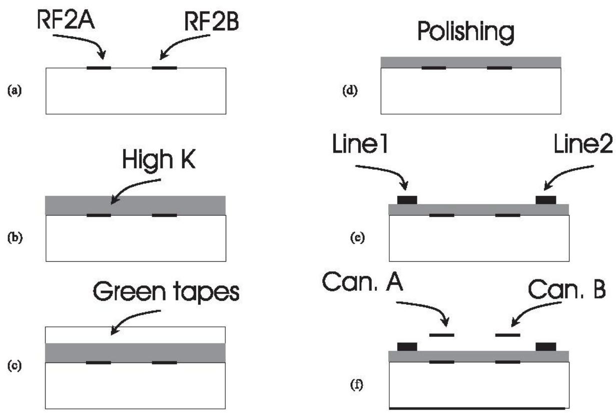

Fig. 2. Simplified fabrication process for the second order.

Using standard LTCC green tape technology, the two inner line sections RF2A and RF2B are screen printed in a first step onto a ceramic green tape. Their width, spacing and lengths are 1 mm, 1.5 mm and 6 mm, respectively. By lamination of a suitable number of tapes a ceramic multilayer substrate is formed for 1.2 mm sintered thickness (Fig. 2a).

A proprietary high-K tape of permittivity 65 (loss tangent 0.002) is included as a cover layer in the lamination process (Fig. 2b). Furthermore, standard green tapes are added on top to balance shrinkage misfits and thermal stress during sintering (Fig. 2c). They also serve as sacrificial layers in the final polishing prior to cantilever assembly.

After co-firing at 850°C, the bottom surface is slightly polished to form a reference plane for the main polishing process of the top surface. Polishing ensures a planar surface and assembly of the piezoelectric elements without gaps. Gaps would result in reduced capacitance even in the bias-free state and would thus reduce the tuning range of the filter. The sacrificial material is removed completely, and polishing continues until the desired thickness of the high-K tape of 10 μm is reached (Fig. 2d). The remaining thickness is periodically controlled during the process at special test windows.

The coupled microstrip lines 1 and 2 with a width of 0.25 mm and a length of 11 mm as well as the ground metallization are subsequently screen printed on the top and bottom surfaces, respectively and post-fired (Fig. 2e). The distance between the inner and outer lines is 0.25 mm.

The piezoelectric cantilevers are finally placed in their position on the surface such that they make the closest contact to the high-K layer possible. A suitable cavity is used at the fixed end to accept an electrically conductive epoxy glue for mechanical fixture and electrical ground contact of the 150 nm thick bottom metal of the cantilevers. Their width and length are 1 and 7 mm, respectively (Fig. 2f). Since the tunable capacitor is formed between the LTCC and the piezoelectric element, the assembly process of the two components is crucial and boundary conditions were optimized:

- The commercial two-component epoxy [15] was chosen to exhibit sufficient processing time, low curing temperature, low shrinkage and good electrical conductivity.
- A specially designed assembly tool was employed (Fig. 3). The cantilever and the LTCC substrate are placed on a metal plate in correct relative position and fixed by a screw such, that they touch each other as close as possible. The plate is then turned upside down, now standing on its four legs.

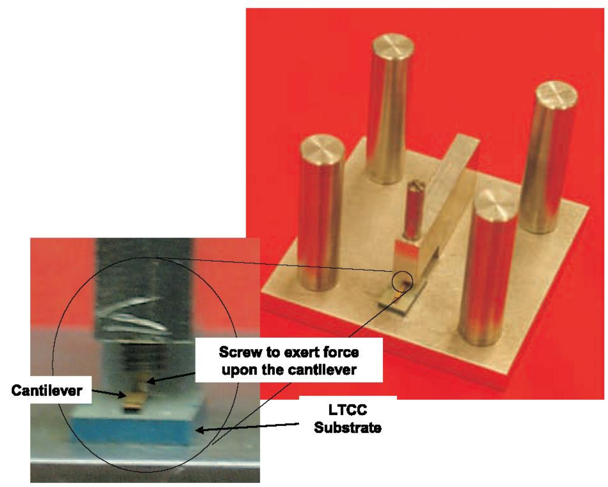

Fig. 3. Structure used to fix the cantilever to the LTCC substrate during the assembly process.

- The glue is injected through an opening of the metal plate into the LTCC cavity from the back side. The amount is adjusted to just fill the cavity down to the electrode of the cantilever thus assuring a conductive connection of this end of the cantilever to the integrated LTCC electrode. The other end remains freely movable.
- The glue is finally cured for 4 h at 85°C.

Fig. 4 shows a photograph of the finished device. The outer two of the four coupled lines are visible with their ground-signal-ground input and output pads on top of the high-K tape, while buried lines are hidden inside between the ceramic layers. Ground connections are realized by vias to the bottom side of the LTCC. Also indicated are the fixed and movable ends of the cantilevers. The variable capacitors are formed in overlapping areas of 1×1 mm^2

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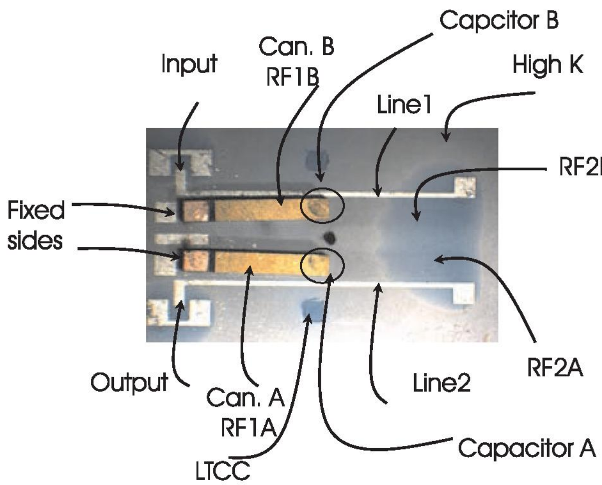

Fig. 4. The fabricated second order filter.

between the cantilevers and the buried lines. Their nominal electrical value is therefore in neutral cantilever position 58 pF at 10 μm dielectric thickness. The overall size of the filter is $12{\times}9$ mm^2.

IV. Filter RF Measurements

The two cantilevers (A&B) have been driven individually and simultaneously in order to achieve equal capacitance values. The measured performance of the filter is shown in Fig. 5. Equalization of the capacitors, a necessary condition for proper filter performance, was possible in a frequency window of 0.57 GHz between 1.23 GHz and 1.8 GHz.

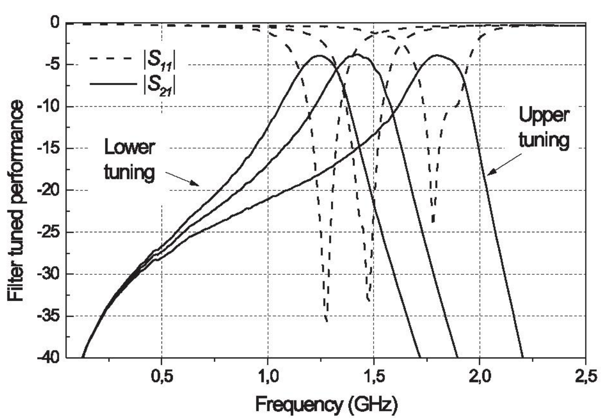

Fig. 5. Measured tuning curves for the second order filter.

The filter exhibits a relative tuning range of 46%. Within this range, its transmission characteristics agree well with simulations employing Sonnet Electromagnetic Software [16] and assuming variable air gaps in the capacitors (Fig. 6). Remaining deviations are attributed to the angular misalignments of the cantilevers in both the vertical and the horizontal planes.

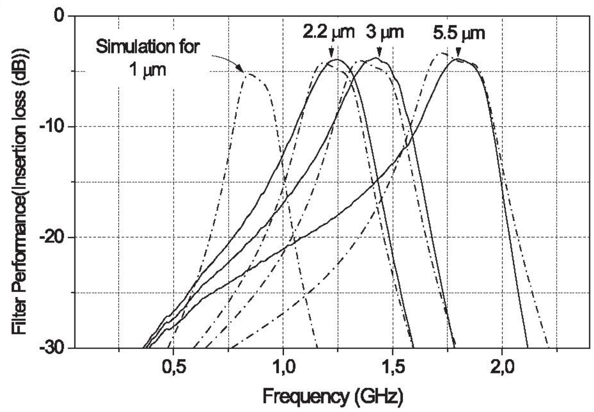

Fig. 6. Measurements and simulations of the second order.

A. Tunability in the Second–Order

After the connection of the voltage sources to the electrodes of the cantilevers, the filter performance for zero bias is shown in Fig. 7. The bias on the cantilever B was increased to shift the return loss S_{22} down to match S_{11}; the matching case is the low frequency curve of Fig. 5. In this case, the behavior of the microsystem shows, that cantilever B has reached its lowest position and touches the LTCC surface. This situation also determines the lower limit of the tuning range. The upper limit is given by the maximum bend of the piezoelectric bimorph in the present assembly.

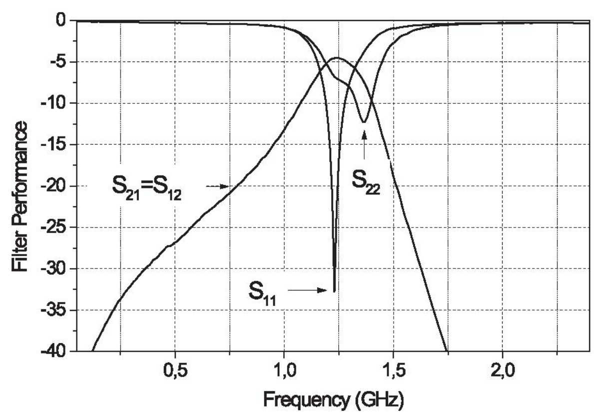

Fig. 7. zero–bias measurements.

B. Attenuation

The attenuation of the filter outside the passband is superior to that of a single-pole design by 10 to 15 dB as shown by the comparison in Fig. 8. This results in improved selectivity and isolation.

V. Conclusion

A second-order piezoelectrically tuned LTCC bandpass filter was presented, in which two piezoelectric cantilevers

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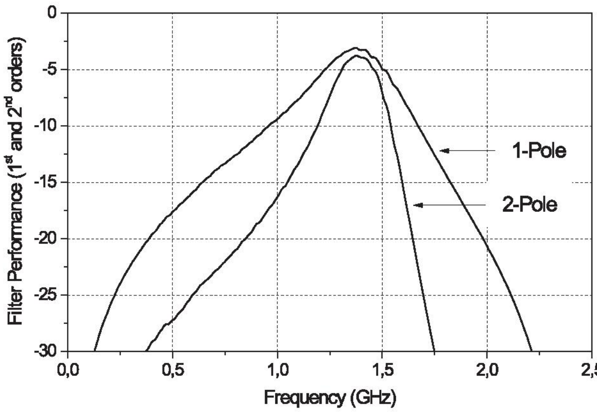

Fig. 8. Comparison: measured attenuation for the first [4] and the second orders (current work).

replace sections of two coupled resonator lines of a conventional untuned filter so that the tuning function consumes no extra space. The two piezoelectric elements particularly form two tunable terminating capacitors by varying the vertical electrode spacing. The tuning range is enhanced by the combined effect of a high-K ceramic layer and the variable air gap. The bandpass filter exhibits a wide tuning range from 1.28 to 1.8 GHz with constant insertion loss of 4 dB and return loss better than -20 dB. The attenuation is improved by 10 to 15 dB in the second-order design as compared to the first-order version.

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