Wide Piezoelectric Tuning of LTCC Bandpass Filters

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***Abstract*— The increasing number of frequency bands and services in wireless communications is causing a demand for analogue active and passive frontend components with wide bandwidth or tuning range, respectively. Similar to micro-electromechanical systems (MEMS), this work presents a parallel plate capacitor with multilayer dielectrics and piezo-electrically movable top electrode as an advantageous tunable element with no addition of any lossy material. 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 and low insertion loss of 2 to 4 dB. The analysis of the device by full-wave simulation reveals a potential tuning range from 0.8 GHz to 2.8 GHz when the thin-film processability of the LTCC surface is properly controlled.**

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

I. Introduction

The need for tunable front-end components is particularly arising due to the increasing number of wireless services and associated frequency bands [1]. A single filter with a wide voltage-controlled tuning range would enable radio manufacturers to reduce costs by using a single frequency-agile device instead of a series of fixed frequency filters [2]. A variety of tuning-concepts has therefore been investigated over the years as described in [3]-[4]. Particularly noticeable are semiconductor varactor diodes [5], MEMS capacitors [6], paraelectric capacitors [7]-[9], and piezoelectrically controlled circuits [10]. All of these approaches come with their individual benefits and draw-backs in terms of power consumption, speed, reliability, microwave losses or drive voltage level.

Here we present a novel approach combining low temperature cofired ceramics (LTCC) for microwave passive integration with piezoelectric actuator technology. As in the case of a MEMS tunable capacitor [6], the tuned component is a multilayer capacitor comprising a lower electrode on the LTCC surface, a high-K dielectric intermediate layer, and a top electrode, which can be raised by the piezoelectric element in order to open an air gap between the electrode and the high-K dielectric. The resulting continuous decrease in capacitance causes a large shift of the center frequency by 1.5 GHz of the bandpass filter. The present filter design focuses on the demonstration of feasibility, tuning range, and device compactness. Although no optimization was done for power consumption, tuning speed, drive voltage, filter attenuation, and insertion loss, the approach already demonstrates low insertion loss due to the absence of lossy materials. The single actuator concept is also expandable to higher-order filters with more complex characteristics.

II. Tunable Bandpass Filter Design

A filter with three coupled microstrip lines as shown in Fig. 1 was chosen as a demonstrator. One of the two sections of the center line is identical with the bottom metallization of the piezoelectric cantilever, which is shortened to ground at one end, and on the other end it forms the upper-movable electrode of the variable capacitor. The second section of the line is on the LTCC substrate, thus forming the bottom-fixed electrode of the capacitor (see Fig. 2). The bending of the cantilever is effected by applying a DC high voltage to the top electrode of the cantilever.

The piezoelectric cantilever is a commercially available lead-zirconate-titanate (PZT) bimorph [11], which has a bottom metallization of 80 nm gold. Its dimensions are 7 mm length, 1 mm width, and 0.48 mm thickness. It can be integrated into the LTCC coupled line filter to bend both upwards and downwards by proper biasing. Tolerances due to angular misalignment can be compensated by voltage bias.

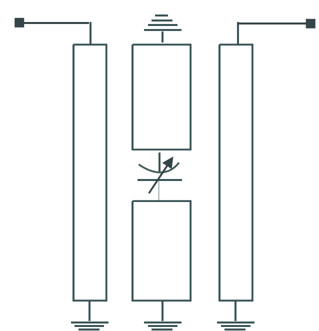

Fig. 1. Tunable bandpass filter circuit.

In [12] a PZT thick film has been cofired on LTCC substrate; in contrast to this approach we have use hybrid integration and assembly of the two components.

In zero-bias state, the air gap width becomes zero and the capacitance assumes its maximum value. In this case, the electrodes are separated by a high-K dielectric layer. With bias, the upper electrode is raised and the capacitance decreases due to the air gap. Like in MEMS devices, the capacitance variation is due to movement of the electrodes and not due to change in material parameters. Like in MEMS devices also, piezoelectric tuned filters exhibit a high quality factor. Piezoelectric actuators exhibit proven reliability and life time. Also, sticking of the contact surfaces has not occurred in piezoelectric tuned filter.

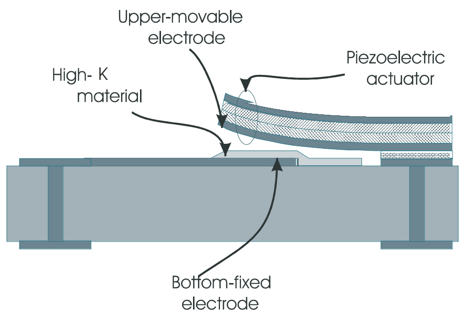

Fig. 2. Schematic of the piezoelectrically tuned varaible capacitor.

The capacitance value is approximately calculated by the well-known parallel plate formula [13]

$$C = \frac{\epsilon_0 \epsilon_{reff} A}{d} \quad (1)$$

$$\epsilon_{reff} = \frac{1}{\frac{d_{air}}{d} + \frac{d_{high-K}}{d\epsilon_r}}. \quad (2)$$

where ϵ_0, ϵ_{reff}, A and d are the vacuum permittivity, the effective permittivity of the air plus the high-K dielectric layer, the area of the capacitor, the high-K dielectric thickness, the air gap size, and the electrode distance (the high-K dielectric thickness plus air gap), respectively.

For the initial design, the zero bias state resulting in the maximal capacitance is considered. In this state, the capacitor area and coupled line lengths are designed for the centre frequency of the filter pass band equal to 0.55 GHz. The thickness of the dielectric material in the capacitor is given by the technology (e.g. 10 μm). The tuning range depends on the capacitance variation of the piezoceramic cantilever capacitor according to (1). A typical filter performance as simulated by Sonnet 8.52 is shown in Fig. 3. Matching is maintained throughout the tuning range, but the attenuation is limited to 10 to 15 dB for this simple filter structure. The vertical displacement of the cantilever tip, i.e. the air gap width d_{air}, is given by the relation

$$d_{air} = 3d_{31}(\frac{L}{t})^2 V. \quad (3)$$

where d_{31}, V, L, t are the piezoelectric constant of the material 230 pm/V, the applied voltage, the length 7 mm and the thickness 0.13 mm of the cantilever, respectively. The required displacement of 20 μm is achieved by 10 V bias.

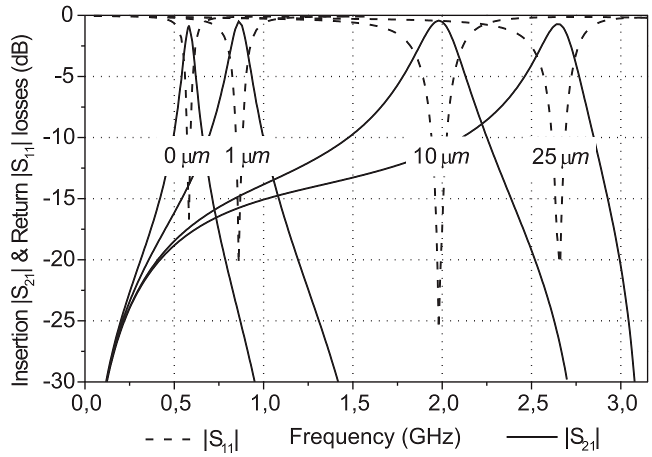

Fig. 3. Simulated tuning of the bandpass filter by the variable capacitor.

For small air gaps the filter center frequency depends strongly on the control voltage. Therefor a smooth surface is required. To achieve this, the fabrication has to fulfil requirements in substrate polishing and cantilever assembly. The minimum frequency at zero bias will otherwise be shifted up, thus reducing the tuning range.

III. Fabrication Process

The assembly and interconnect technology between LTCC microstrip structures and piezoceramic element is important for the device performance. Control over the thin film air-gap capacitor on the thick film LTCC substrate requires the integration of a polishing step into the processing sequence. The fabrication employs regular thick film LTCC processing of DuPont 951 tape with a permittivity of 7.8, a loss tangent of 0.002 and a sintered tape thickness of 100 μm. Filled vias provide bottom surface device contacts for second-level assembly, and a stepped 1×1 mm^2 cavity with ground metallization on the step is punched to accept conductive epoxy adhesive in the final assembly process of the piezoceramic part. The fixed lower electrode of the tunable capacitor is printed on top of the 1.2 mm thick substrate (Fig. 4a). Proprietary high-K tape is used to provide the high dielectric layer between the capacitor electrodes (Fig. 4b). To balance shrinkage and thermal stress during sintering, a symmetric stack of tapes is added on top, which also provides sacrificial material for the polishing step (Fig. 4c). Subsequently the bottom surface is slightly polished for the planarity of the top surface. The sacrificial material at the top is removed completely, and the polishing process is proceeded until the desired thickness of the high-K tape (8 μm, permittivity 65, loss tangent 0.002) and a smooth flat surface is reached (Fig. 4d). The microstrip coupled lines 1 & 3 (w = 0.5 mm, s = 0.25 mm, L = 11 mm) and the ground metallization are screen printed on both top and bottom surfaces. The movable part of the center line (RF1) is identical with the cantilever bottom metal (w = 1 mm, L = 7 mm). It overlaps with the thick-film section (RF2) on the LTCC substrate to form a capacitor area of 1×1 mm^2 (Fig. 4e). Finally, the cantilever is fixed in its position by conductive epoxy [14] (Fig. 4f). Fig. 5 shows a photograph of the final device. Its size is 12×7 mm^2.

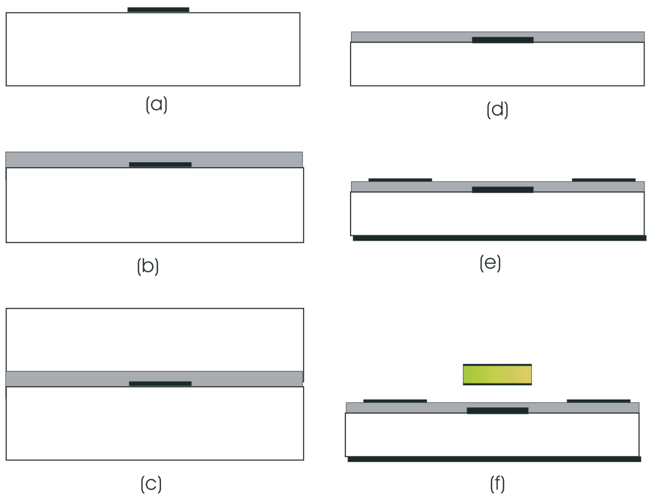

Fig. 4. Fabrication process.

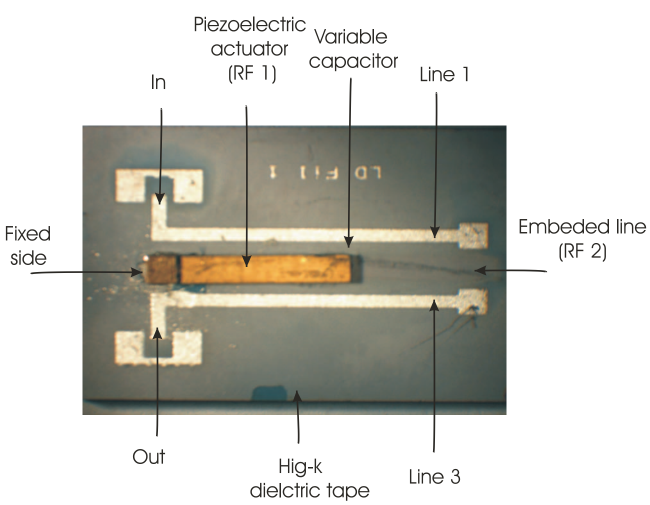

Fig. 5. Photograph of tunable bandpass filter, the fixed part of the center line is embedded, it is invisible.

IV. Measurement And Analysis

The measured and calculated insertion loss ($|S_{21}|$) of the filter is shown in Fig. 6. Simulations are fitted to the measurements by adjusting the capacitance. Differences between measured and simulated characteristics are attributed to a slight angular misalignment of the cantilever in the plane of the LTCC surface. The center frequency of the filter can be tuned from 1.1 GHz (zero-bias) to 2.6 GHz (200 V-bias) (135%), which is slightly larger than demonstrated by current paraelectrically tuned filters [9]. With 2 to 4 dB the insertion loss at center frequency is relatively low due to the absence of lossy paraelectric material. The simulations include resistive and dielectric losses; they particularly reveal resistive losses in the thin cantilever metallization as a major contribution.

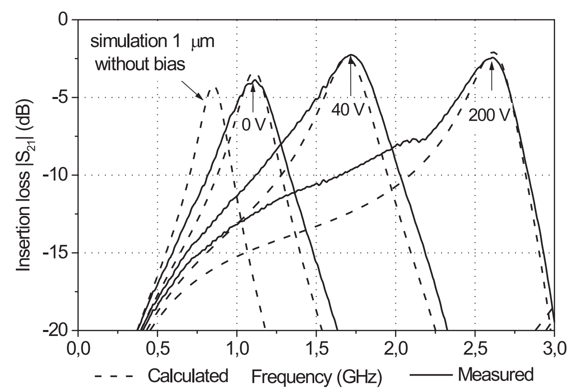

Fig. 6. Tuned bandpass filter with variable capacitor.

The tuning range achievable with the present concept depends on several factors, particularly short and long range surface nonplanarities, i.e. roughness and warpage. As a practical design rule we found a minimum effective air gap of 1 μm to account for residual surface rouhgness effects after polishing. The analysis of the device by electromagnetic simulation reveals a potential for 250% tuning range if roughness and warpage could be eliminated. Fig. 6 shows also that the absolute bandwidth increases over the tuning range in a manner consistent with constant relative bandwidth, as expected. However, side band attenuation deteriorates due to the lower pole of the filter remaining at fixed frequency since it is a zero frequency pole. As with any other filter technology, quality factor and selectivity can be improved at the expense of insertion loss, e.g. by adding further circuit elements or resonators.

With a bias voltage up to 200 V the air gap increases continuously from 2.2 μm to 24 μm. These values were determined by fitting simulated frequency characteristics to measured ones as in Fig. 6. Fig. 7 shows the variation of the measured center frequency and of the corresponding air gap as a function of applied DC bias.Although the current piezoceramic bimorph design with its capability to enforce downwards bending under reversed bias is already useful to compensate for both, the piezoceramic hysteresis and an unintentional air gap due to imperfect assembly, the response to bias voltage may be further improved by using more complex actuators like multilayer piezoceramic versions. Switching speed, dynamic behavior as well as power consumption is currently being evaluated.

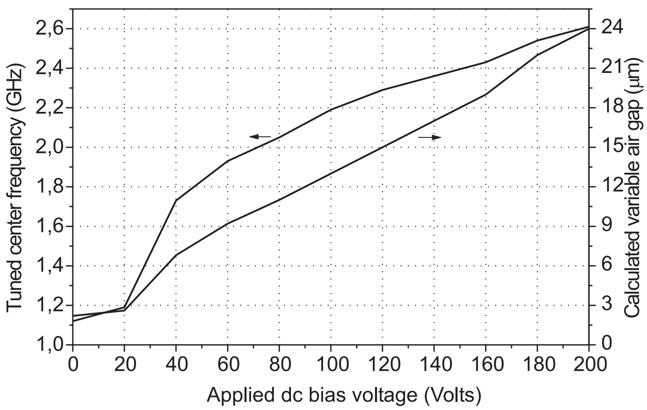

Fig. 7. Measured frequency and the calculated corresponding air gap versus applied DC bias.

V. Conclusion

A piezoelectrically tuned bandpass filter with LTCC coupled microstrip lines and surface-mounted piezoceramic cantilever was presented. One of the microstrip resonators is terminated by a tunable capacitor via variable electrode spacing. This result in a higher achievable quality factor compared with varactor diodes and paraelectric varactor diodes. Compared with MEMS no sticking of electrodes occurs and the continuos tuning properties are improved. A preliminary demonstrator exhibits a wide tuning range from 1.1 to 2.6 GHz with low insertion loss of 3±1 dB throughout the tuning range. These promise further reduced insertion losses by thicker metallizations as well as even wider tuning with tighter control of the surface roughness inside the capacitor. The tuning voltage of up to 200 V may be reduced in future versions by using multilayer actuators. The piezoelectric element replaces one of the coupled resonator lines of a conventional untuned filter so that the tuning function consumes no extra space. Since the cantilever may tune several circuit elements simultaneously, the concept is applicable to higher order filters.

Acknowledgment

The authors wish to acknowledge experienced support in polishing technology by Mr. Eberhard Hoyer and fruitful discussions on piezoceramic device performance with Andreas Wolff. Argillon GmbH contributed useful advice and application-specific modifications of commercial piezoceramic elements.

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