Electrical Tuning of Dielectric Resonators with LIGA-MEMS

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***Abstract*—A novel dielectric resonator (DR) resonant frequency tuning concept implemented, for the first time, in a micro-electro-mechanical-systems (MEMS) "Lithography, Electroplating and Molding" (LIGA) process, is presented. The complete system, except for the DR, is manufactured in the LIGA process. A description of the structure, consisting of a transmission line-DR system, coupled with a metallic Mach-Zenhder-Interferometer (MZI), is given. Simulation results, which show the resonance frequency tuning, the low Q-factor-reduction and first measurements with manufactured samples, as proof of concept, are included.**

I. INTRODUCTION

Today, it is more and more usual to communicate via satellites, orbiting the earth for military, commercial and scientific applications. Sound, data and images of high quality can be offered using these communication channels [1]. In many modern spacecrafts, resonator systems are used for changing the communication frequencies and highly precise oscillators for filtering or mixing the signal are required to reach the desired data rates. Therefore, systems for tuning the resonance frequency of a dielectric resonator (DR) electronically, while maintaining a high quality factor (Q-factor), are useful to balance non-ideal properties of the DRs due to manufacturing tolerances and geometrical inaccuracies. Among the technical aspects, a simple implementation of the frequency tuning system is necessary for many applications to be applicable in small transceivers combined with RF-MMICs [2]. Compared to waveguide resonators, DRs are smaller, lighter, and enable adequate circuit performance. Especially, the fact that a direct coupling to the transmission line without waveguide adapter is possible, is an important advantage of the dielectric resonator [3].

Many methods (mechanical, magnetic, optical and electrical) for changing the resonance frequency of a dielectric resonator have been published. The mechanical frequency tuning method [4], [5], [6], e.g., with a tuning screw, is the one traditionally employed. For high resonance frequencies this principle places high demands on the manufacturing and the mechanical adjusting process. In particular, if the resonance is higher than 20 GHz, the requirements for the tuning accuracy are so high that it is not suitable for inexpensive production. Other possibilities for tuning the resonance are systems with magnetic [6], [7] or optical [8] principles. Unfortunately, the implementation is cumbersome and expensive. All these disadvantages suggest the adoption of systems with electrical tuning. For example, semiconductor varactor-based electrical tuning systems with dielectric resonators are used for many modern applications in spacecraft communications.

This paper presents a novel DR tuning structure based on exploiting the capacitive loading of a Mach-Zehnder interferometer (MZI) to tune its interference properties and, in turn, tune the resonance frequency of a DR coupled to it. The overall structure consists of an electrostatically actuated, laterally-moving MEMS beam, capacitively loading the MZI, which, in turn, is coupled to a DR-microstrip system. The novelty of the work hereby presented is that the system (except for the DR) is, for the first time, implemented via a LIGA-MEMS process. Due to this DR resonance frequency tuning architecture, the reduction in quality (Q)-factor, characteristic of semiconductor varactor tuning-based tuning approaches, is lower.

After a description of the fabricated structure and its tuning concept, the manufacturing and design properties of the "Lithography, Electroplating and Molding" (LIGA)-MEMS process [9], [10] are given in detail in Section III. The simulated performance and first measurements, which provided proof of the LIGA-MEMS implementation of the concept are given in Section IV-A and IV-B.

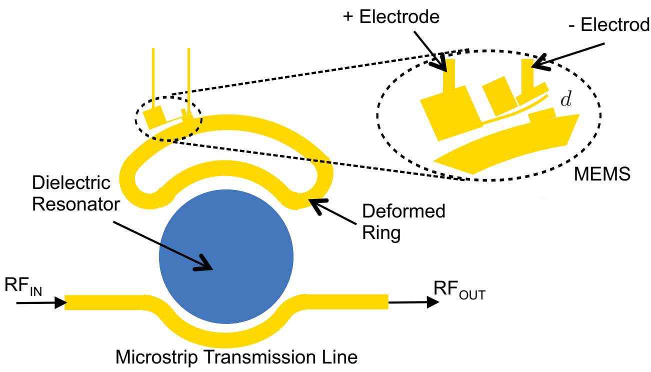

Fig. 1. Structure layout of the electronically tunable dielectric resonator with MZI ring and RF transmission line.

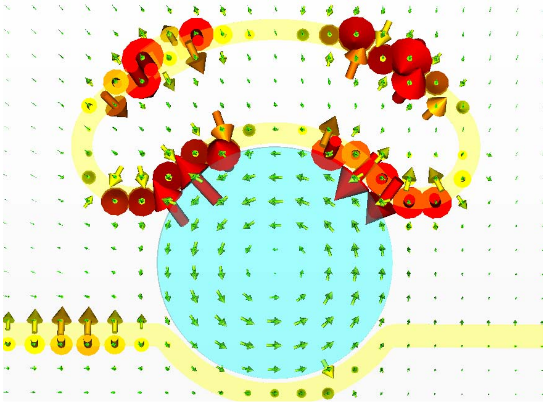

Fig. 2. Absolute electric field lines at resonance frequency with second resonant mode of MZI ring.

II. The Tuning Concept

The structure used for tuning the resonance frequency of the DR is shown in Fig.1. The resonator from Trans-Tech with $\epsilon_r = 36$ and a diameter of 5.85 mm is positioned in between a microstrip line (MS) and a deformed metallic ring working as Mach-Zehnder interferometer (MZI). At resonance frequency of the system the RF signal transmitted through the microstrip transmission line is filtered. Part of the energy is coupled to the DR, whereas most part of the energy is reflected and results in a high S_{11} at resonance frequency and therefore the structure works as bandstop filter. In the following subsections the coupling between the single devices and their functionality are described.

A. MS-DR Coupling

In this paper, only resonances with fundamental mode TE_{01} of the dielectric resonator are considered, which are commonly utilized in filters and oscillators. The resonant frequency f_{DR} in GHz of mode TE_{011} in free space can be approximately computed as [11]

$$f_{DR} = \frac{68}{D_R\sqrt{\epsilon_r}}\left(\frac{D_R}{2H} + 3.45\right) \quad (1)$$

In this formula D_R and H represent the DRs diameter and height in millimeters, whereas ϵ_r is the relative permittivity. To get a spurious mode-free operation, the optimum ratio of $\frac{H}{D_R}$ should be about 0.4 [12]. The DR is coupled to a microstrip line using fringing magnetic fields. The deformation of the microstrip line increases the coupling factor between the two devices [13]. The complete structure from Fig.1 is enclosed by a metal box. The metal enclosure is required to enhance the functionality of the dielectric resonator and avoid radiation loss. It is also found that the resonance of a DR does not only depend on the properties of the ceramic and its geometry, but also on the size of the metal cavity, especially the distance to the top. The resonance frequency of the DR, considering the microstrip line coupling and the metal shields, can mathematically be calculated [14].

B. DR-MZI Coupling

At the top of the structure a deformed ring is coupled to the DR. In order to get a high coupling between the devices the resonance frequency of the deformed ring f_r should be similar to that of the DR. Also the special form is chosen to increase the coupling between MZI ring and DR. Furthermore, a study of the radiation efficiency (RE) of the MZI, which is defined as the ratio of the radiated power to the total input power, as a function of its line length showed a high radiation for the first resonant mode [15]. By increasing the mode number the radiation could be decreased and therefore a higher Q-factor of the filter was reached. A good ratio between ring size and low radiation suggested that the second resonant mode be used. The deformed ring circumference was chosen accordingly to adjust its second resonance frequency to f_0 of the DR. The simulated E-field distribution for the coupling between MS, DR and deformed ring with second resonant mode is shown in Fig. 2.

C. Horizontal Moving MEMS

To tune the resonance frequency of the structure, e.g., for compensating manufacturing tolerances of the DR, an adjustable capacitive loading at the top of the deformed ring is used (see inset in Fig. 1). The position of the loading affects the tuning range and Q-factor level of the structure as presented in a previous study [15]. The field lines in Fig. 2 show a maximum of the E-field for the second resonance at the position of the loading. By changing the capacitance, the propagation constant of the electromagnetic waves flowing through the MZI ring can be influenced. Due to the coupling between MS-DR-MZI the changing of the propagation constant directly influences the DR resonance frequency and therefore the frequency of the bandstop filter.

The capacitance is built by a thin metallic beam opposed to a protuberance at the top side of the deformed ring. The beam is connected to one electrode (+) whereas the second electrode (-) is above. By applying a voltage between the electrodes, the beam can be moved away from the deformed ring, towards the (-)-electrode, and the capacitive loading changes, due to increasing the distance d. A metallic stopper in-between the two electrodes prevents the device from short circuiting.

III. Manufacturing the LIGA-MEMS

The complete structure in Fig. 1 is manufactured by the LIGA process at the Institute of Microstructure Technology (IMT) of the Karlsruhe Institute of Technology (KIT). The ceramic carrier has a thickness of 1 mm and a permittivity of $\epsilon_r = 10.2$. The used metal is nickel with a thickness of 0.1 mm and there is a thin Titanium layer between carrier and metallization.

By etching the Titanium layer below the small structures as the thin beam (see inlet of Fig. 1) these parts become movable, as shown in Fig. 3. A voltage between the two electrodes will create a force of attraction and move the beam and therefore increase the distance d between MZI and beam. This motion was simulated via the IntelliSense software module

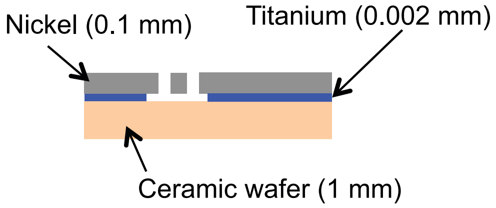

Fig. 3. Layer stackup of processed structure with LIGA technology.

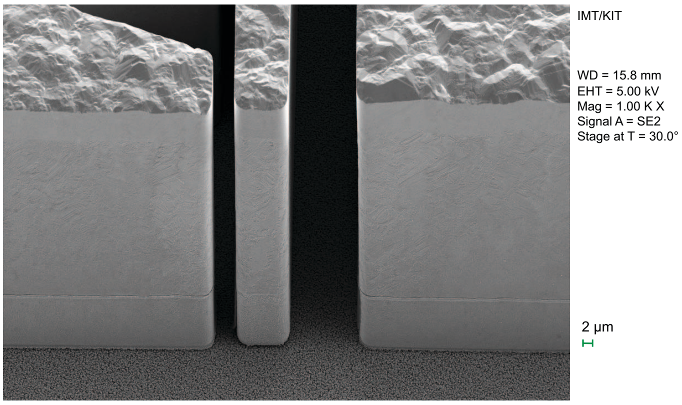

Fig. 4. SEM picture of the movable beam for tuning the capacitive loading of the MZI-ring.

SYNPLE [16]. A great advantage of these technology is the possibility to manufacture structures with very high aspect ratios. This allows a relative high (0.1 mm), but very thin (0.01 mm) movable beam with high capacitive loading effect to the MZI. In state of rest the distance between beam and MZI is around 5 μm and between beam and (-)-electrode 15 μm. The SEM picture in Fig. 4 show this movable beam with its very accurate geometry and the extremely smooth metallic walls in detail.

IV. PERFORMANCE

A. Simulation Results

To simulate the distortion of the MEMS beam in CST Microwave Studio the distance d was changed from 0 μm to 5 μm. The results in Fig. 5 show that the resonance frequency increases for higher values of d. The Q-factor for the structure with capacitive loading and d=0 μm is 1104 with center frequency f_c=10.094 GHz and decreases at d=5 μm to 644.5 with f_c=10.234 GHz. The relative Q-factor decreasing of 41.6% for a relative frequency tuning range of 140 MHz at a working frequency around 10 GHz is a good result compared to other tuning systems based on varactors or mechanical adjustment [3], [17]. The relative low tuning range could be increased by improving the MEMS structure. Simulation studies have shown that a vertical moving MEMS above the MZI cause a larger tuning range due to increasing the values of the capacitive loading.

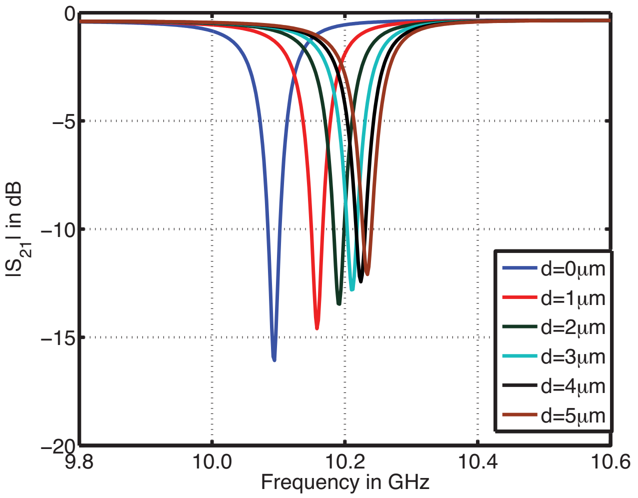

Fig. 5. Simulated S_{21} curves for variation of distance d between movable beam and MZI ring.

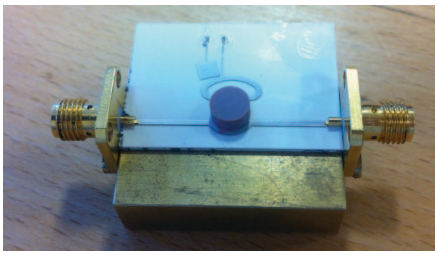

Fig. 6. Sample on a measurement device with SMA connectors at the RF transmission line. For measurements the sample is surrounded by an aluminum box.

B. Measurements

For verifying the functionality test samples on a ceramic carrier have been manufactured. For measurement, the samples were positioned on a metallic ground plane, because the bottom layer of the carriers are not metallized (Fig. 6). Also a metallic box around the complete structure were used to reduce the Q-factor increasing [15] and realize the electric boundaries of the CST simulations. Two SMA connectors are used to feed the RF microstrip line and measure the S-parameters. For connecting the DC-voltage at the electrodes the two lines at the top of the structure are soldered to wires which are accessible from outside the metallic housing.

For the presented structure a frequency tuning from 10.123 GHz to 10.155 GHz was achieved. Very high voltages between 250 V and 265 V were necessary to move the beam and cause the frequency tuning (Fig.7). The microscope picture in Fig. 8 shows that due to the manufacturing process some changes in the layout of the MEMS were necessary. Particularly the shorter beam caused a higher inertia which results in only small variations of distance d at very high voltages. A redesign of the MEMS structure is necessary to improve the tuning range. Nevertheless, the measurements show the proof of concept by a Q-factor reduction of 20.85%

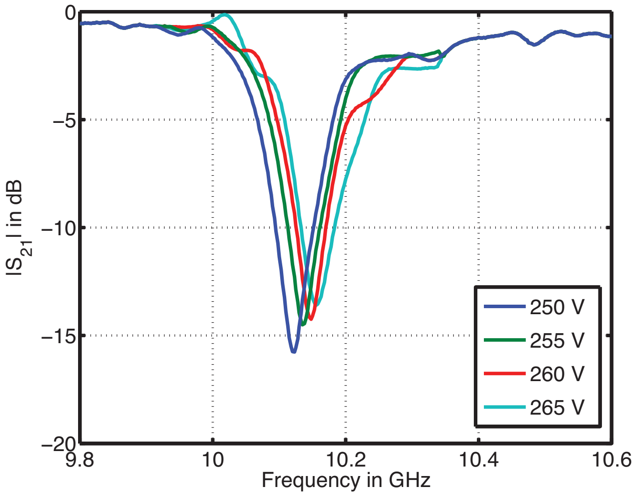

Fig. 7. Measured S_{21} curves for variation of voltage between the two electrodes to move the beam above the MZI ring.

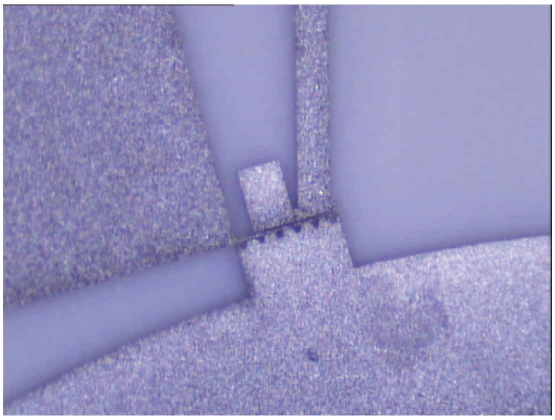

Fig. 8. Microscope picture of manufactured structure with detail view of the MEMS.

for a tuning range of 32 MHz.

V. CONCLUSION

This paper presents an electronic frequency tuning with an implemented MEMS structure for dielectric resonators with low Q-factor reduction. The tuning is done by changing the capacitive loading of a Mach-Zenhder-Interferometer coupled to the dielectric resonator. The system was manufactured with the LIGA process and a horizontal moving MEMS builds the configurable capacitive loading due to the possibility of changing the distance between two opposing metallic plates by electrostatic forces. The high accuracy of the LIGA process combined with a high aspect ratio leads to a large tuning range of the capacitance. The simulations show good results with a relative Q-factor reduction of 41.6% and a tuning range of 140 MHz at 10.16 GHz center frequency.

First measurements with samples manufactured by the LIGA process at the Karlsruhe Institute of Technology show the proof of concept.

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