

Microfluidic-Based Ultra-Wide Tuning Technique for TM_{010} Mode Dielectric Resonators and Filters

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Abstract—This paper introduces a new technique of designing widely frequency tunable TM_{010} mode dielectric-loaded waveguide resonators and filters. The proposed tuning method is based on using liquid metals to tune the resonant frequency by altering the liquid level inside the resonator hollow-channel. A single-pole bandpass filter is designed, fabricated, and measured for proof-of-concept purposes. The realized filter demonstrated wide frequency tuning from 2.33 GHz to 0.67 GHz maintaining low insertion loss < 1 dB all over the tuning window. The presented results exhibit the great potential of the proposed technique in high-performance widely-tunable next-generation RF systems.

Keywords—dielectric resonator, liquid metal, waveguide filter, tunable filters, wide tuning.

I. INTRODUCTION

The massive evolution in the various multi-standard and multi-band communication technologies has emerged a vital demand for more efficient and flexible RF front-end components and filters to manage the increasingly crowded spectrum more effectively. High-performance frequency-agile filters are key and fundamental component of many current and next-generation communication services, including future flexible satellite payload systems. Dielectric resonators have been introduced since the early '60s and employed widely in various microwave applications due to their compact structures and good spurious-free performance in comparison with the other waveguide configurations, in addition to the high unloaded Q and the ability to operate at high power levels. Accordingly, a couple of tunable bandpass filters have been introduced based on dielectric resonators in different hybrid electric-magnetic modes (e.g. HEH, HEM, TME), using various tuning methods as in [1]–[4].

Generally, the tuning methods for dielectric resonator filters presented in previous literature are distributed into two main techniques: mechanical tuning and electrical tuning. In the mechanical tuning method, the frequency is tuned using movable tuning elements (e.g. screws, discs, sidewalls) as presented in [1] and [2]. Despite the straight-forward tuning and high power handling capability, these designs are burdened by the bulky size, high complexity, high cost, and low-speed of tuning. All above is in addition to the very small and limited tuning range. On the other hand, electrical tuning elements (e.g. varactors, RF MEMS) were utilized in [3] and [4] to bring the advantages of higher tuning speed, reduced size and cost. However, such filters suffer from major limitations in terms of linearity, quality factor, and high-power handling capability.

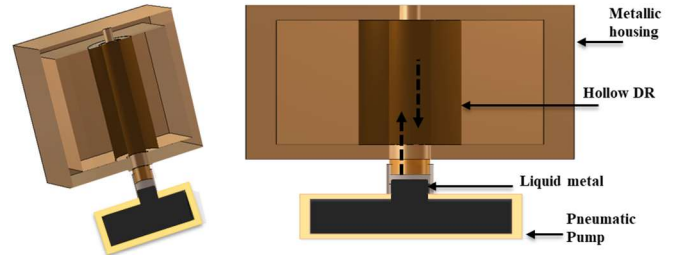


Fig. 1. Illustration drawing (cut-away view) of the proposed widely tunable TM mode dielectric-loaded waveguide resonator using liquid metal actuation.

Besides, the challenging integration of semiconductor and MEMS tuning circuits on the 3D resonator structure incorporates more losses and increases the filters' complexity. All of these drawbacks limit the capability of attaining low-loss over wide tuning ranges. [5] presented a hybrid tuning method combining both mechanical and electrical tuning techniques, proposing an electrically switchable tuning rod to improve the speed of tuning. However, it also shares the same limitations of bulky, complex structure, and small tuning range.

TM_{010} mode dielectric resonators and filters were firstly presented in [6], a few decades ago. In recent years, they have received increasing attention and employed successfully in many major high-performance applications (e.g. mobile base-stations, satellite payloads) due to their strongly desirable features in comparison with the other dielectric resonators. They offer high volume-saving structures and also better spurious-free stopbands, besides the improved stability against vibrations and more feasibility for tuning. All of these advantages promote the use of TM_{010} mode dielectric resonators in the implementation of high-performance tunable bandpass filters, which according to the authors' knowledge, has never been reported in the previous literature.

Liquid metal (LM) microfluidics have recently been explored as a promising switching and reconfiguration candidate [7]–[10], mainly because of their linear properties, low-loss, and compatibility with high-power applications. A couple of planar and hybrid reconfigurable/tunable filters were introduced using liquid microfluidic-based concepts [7]–[9]. However, the performance of such PCB-based structures is always limited by the low power handling, low Q factor, and loss increasing, which subsequently affects the tuning capabilities. Also, a microfluidically reconfigurable TE_{01} mode rectangular waveguide (RWG) filter was presented in [10]. Despite the advantage of high power performance of the WG

structure, the proposed filter has shown a very small frequency reconfiguration and relatively high insertion loss.

In this paper, a new microfluidic-based, frequency tuning mechanism for the design of widely tunable TM_{010} mode dielectric resonators and filters is presented. The proposed tuning method is based on the actuation of liquid metals inside TM_{010} mode hollow ceramic resonators, where the inner hole of the resonators is used as a channel for the liquid metals [11]. This mechanism provides the advantage of getting the highest possible achievable frequency tuning with minimal losses and high-quality factors. Furthermore, the presented tuning technique is applied in a simple, low-cost, and efficient configuration.

II. CONCEPT AND DESIGN

An illustration drawing of the proposed liquid metal tunable TM_{010} mode resonator configuration is shown in Fig. 1. The proposed embodiment comprises a hollow cylindrical TM_{010} mode dielectric resonator, a metallic housing, a liquid metal, and a pump. The operation concept is based on LM actuation inside a containing hollow resonator to tune the resonant frequency. The ceramic resonator is metalized and connected with the bottom and top walls of the metallic housing operating at TM_{010} mode. The inner hole of the dielectric hollow resonator is utilized as a containing channel for the intrusion of the liquid metal from the bottom of the metallic housing. Then, the ingoing LM functionalizes as a tuning post to change the resonant frequency of the resonator. As LM level increases inside the channel, the EM field is perturbed resulting in a decrease of the resonant frequency. A microfluidic eutectic alloy of gallium, indium, and tin — commercially known as “Galinstan” — is chosen here due to its advantages of high electrical conductivity ($\sigma = 3.46 \times 10^6 \text{ S/m}$) and non-toxic characteristics. The pump is used to pneumatically control the movement of the liquid metal inside the resonator channel.

In addition to its advantages stated in the previous section, the TM_{010} mode resonator structure is particularly chosen because of two key reasons. Firstly, its configuration is ideally suitable for the proposed mechanism as the LM can be actuated simply and effectively through a direct, single path with no need for any further modifications or elements. Secondly, since the electric field of the TM_{010} mode dielectric resonator is confined and focused at the center of the resonator where the LM is being actuated, the proposed mechanism can be applied efficiently to provide a very wide frequency tuning window.

To verify and evaluate the proposed concept of widely tunable TM_{010} mode resonator filters, a one-pole bandpass filter is designed and investigated in terms of its performance and tuning capabilities. Fig. 2. demonstrates the 3D EM model of the proposed structure. It includes a metallic box surrounding a dielectric resonator with a relative dielectric constant of 44 and an unloaded quality factor equals to 20000. The filter is designed to operate at 2.33 GHz which represents the initial frequency of the tuning window. Since it's a TM mode structure, the height of the dielectric resonator does not affect the resonant frequency, but just on the unloaded quality factor. Then, the outer and inner diameters of the resonator are adjusted to obtain

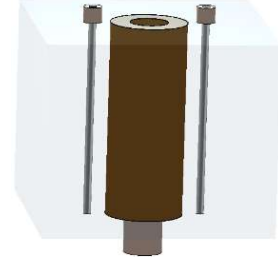


Fig. 2. EM-based 3D model of the proposed widely tunable 1-pole BPF.

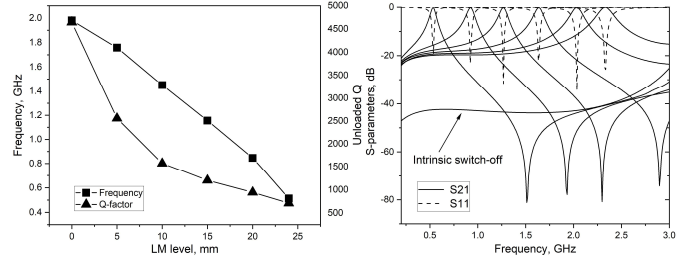


Fig. 3. Simulated filter responses: (a) Simulated frequency and unloaded Q-factor as a function of the LM level inside the resonator channel; (b) Simulated S-parameter responses with different tuning states.

the desired resonant frequency. The used resonator height is 25 mm to offer a relatively high Q, while the outer and inner diameters are chosen here as 10 mm and 5 mm, respectively. $30 \times 30 \times 25$ mm metallic cavity is adjusted properly to attain a high Q factor and a good spurious-free stopband.

The proposed structure is firstly investigated using eigenmode analysis in CST microwave studio without the I/O ports to precisely evaluate to unloaded Q. Simulations considered Copper ($\sigma = 5.8 \times 10^7 \text{ S/m}$) as housing metal, and liquid metal Galinstan with electrical conductivity equals to $3.46 \times 10^6 \text{ S/m}$. The simulated frequency and unloaded Q factor responses are illustrated in Fig. 3(a) in relation to the LM variation inside the resonator channel. As can be seen from the graph, wide frequency tuning is achieved with high Q factor measures. The channel is filled gradually with Galinstan up to 24 mm and the resonant frequency shifted down accordingly, covering a wide span of frequencies ranging from 1.98 GHz to 0.51 GHz providing high tunability of 118%. Also, a high Q factor is maintained all over the tuning window ranging from 4600 to 710. These competitive advantages exhibit the potential of the proposed tuning technique as a promising solution for the design of high-performance and widely tunable waveguide filters.

In tunable filters, proper I/O coupling is essentially required to maintain low-loss responses across the different tuning frequencies. This becomes more challenging in widely tunable filter structures and could cause a significant decrease in the tuning performance. Herein, a 1-pole bandpass filter is implemented to check the feasibility of the proposed wide tuning mechanism in TM_{010} mode tunable filters. The RF feeding configuration is depicted in Fig. 2. The I/O coupling is realized using strongly-coupled capacitive feeding pins to cover the whole wide tuning band effectively with low insertion loss.

The simulated S-parameters of the proposed widely tunable TM_{010} mode filter are shown in Fig. 3(b). The frequency is tuned over a wide range from 2.33 GHz to 0.54 GHz with a high Q factor (>600) and low insertion loss (<0.3 dB). Also, an additional desirable feature of intrinsic-switching is presented, as in which the passband can be easily switched off by just filling the whole resonator channel with LM cutting all field lines of the operating TM_{010} mode.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To validate the proposed concept, a 1-pole liquid metal tunable TM_{010} mode filter is fabricated, assembled, and measured. The filter components and its measurements are depicted in Fig. 4. The dielectric resonator is firstly enclosed and well-soldered with the metallic cavities to ensure against any leakage in the liquid channel. Next, the channel is firstly cleaned with 1% NaOH electrolyte solution to facilitate the movement of LM, and then Galinstan is pneumatically actuated inside the resonator channel using a syringe. The measured S-parameter responses validates the ability to cover a wide frequency span with low losses. The passband frequency is tuned from 2.33 GHz to 0.67 GHz with wide tunability of 110%. Also, low insertion loss is maintained all over the tuning window better than 1 dB, and return loss higher than 18 dB. The filter has a wide spurious-free band up to $5f_0$. Additionally, the desirable intrinsic switching feature of the passband is effectively demonstrated. The extracted effective Q factor varies from 1660 to 120 mainly attributed to the uncertain effective conductivity of Galinstan liquid metal and the lossy effect of NaOH. Therefore, the use of other less dispersive electrolyte solutions (e.g. Teflon solutions) is being considered in further investigations under more robust conditions to enhance the Q factor and reduce the losses. Also, it should be noted that the Q factor can be increased by using better electrically-conductive metals to manufacture the cavities instead of the brass metal used in the proof-of-concept prototype ($\sigma = 1.59 \times 10^7$ S/m). The Galinstan was actuated smoothly inside the ceramic channel without experiencing any absorption or stickiness issues. Nevertheless, an alternative reliable solution of micro Teflon-coating can be applied effectively to the ceramic channel if there are any such worries. The distinctive performance of the introduced technique can be seen in comparison with the similar LM reconfigurable waveguide filter presented in [10]. All of the aforementioned attractive and distinctive features strongly promote the proposed tuning technique in wideband, high power, and low-loss RF applications.

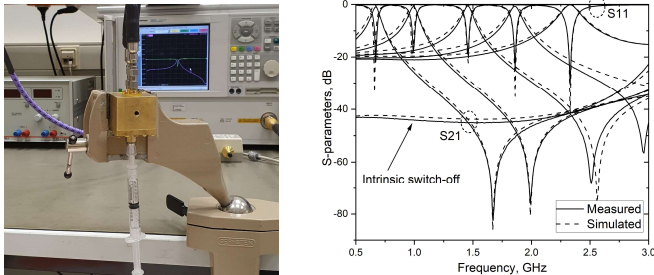


Fig. 4. Photograph of the manufactured prototype and its measurements.

IV. CONCLUSION

A novel microfluidic-based mechanism for the design of widely tunable TM_{010} mode dielectric-loaded waveguide resonators and filters was presented. A single-pole bandpass filter was designed, fabricated and measured for proof-of-concept purposes with good agreement between simulations and measurements. In addition to the wide tuning feature, the proposed method demonstrated many advantages including intrinsic switching, low-loss, simple and low-cost configuration. This new tuning technique is presented as a promising solution in future high-performance wideband frequency-agile systems and technologies.

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