

# Continuously Tunable 3-D Printed Helical Resonators and Bandpass Filters Using Actuated Liquid Metals

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**Abstract**—This letter reports on a new class of agile helical resonators and bandpass filters (BPFs) with continuously-tunable center frequency. RF tuning is achieved by altering the liquid metal (LM) volume within an additively-manufactured plastic tube that has the shape of a helix and forms the inner conductor of the helical resonator. A low-cost and versatile integration scheme using 3-D printing and pneumatically-actuated Galinstan is proposed. For proof-of-concept validation purposes, a helical resonator with center frequency tuning between 1 and 1.5 GHz, and unloaded quality factor between 131 and 145 was manufactured and measured. Two BPF prototypes namely: 1) two-pole BPF with center frequency tuning between 1.16 and 1.49 GHz and insertion loss (IL) < 2 dB and 2) three-pole BPF with center frequency tuning between 1.18 and 1.49 GHz, and IL < 2.1 dB, were manufactured and tested at  $L$ -band.

**Index Terms**—Bandpass filter (BPF), cavity filter, helical filter, helical resonator, tunable filter.

## I. INTRODUCTION

**F**REQUENCY-AGILE RF filters are important counterparts of almost every emerging wireless communication, radar and instrumentation system. They are used to suppress interference and to facilitate dynamic spectrum access. Furthermore, they have the potential to reduce the overall size of multistandard radios as opposed to conventional RF-switched filter banks [1], [2]. Various tuning mechanisms have been explored to date for 3-D bandpass filters (BPFs). These include p-i-n diodes, RF switches, varactors, stepper motors and RF microelectromechanical systems (MEMS) [3]–[8]. While diodes and switches enable discrete tuning, varactors result in high passband insertion loss (IL) for frequencies  $> \sim 0.5$  GHz [5]. Mechanical tuning schemes such as those using MEMS [5], or stepper motors [4] are slow (e.g., 100–1000 s of  $\mu$ s) and RF MEMS suffer from long-term reliability issues.

Actuated fluidics such as liquid dielectrics (LDs) and liquid metals (LMs) [9]–[21] are becoming a popular tuning

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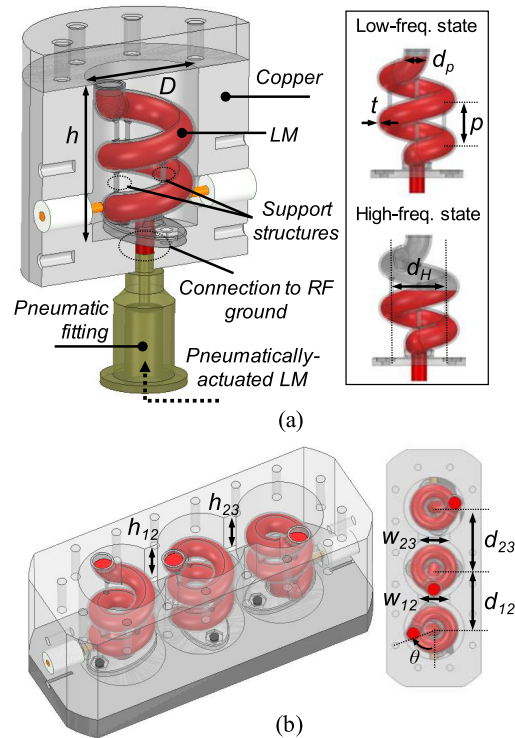


Fig. 1. Conceptual drawing of the LM tunable helical resonator concept and its application to a third-order BPF. Center frequency tuning is achieved by altering the volume of the LM (red) within a 3-D printed SLA/PP-based dielectric tube (gray). (a) Resonator with  $h = 21.2$  mm,  $D = 16$  mm,  $d_H = 8.8$  mm,  $d_p = 3.48$  mm,  $p = 7$  mm,  $t = 0.4$  mm, and turns = 1.89. (b) Third order BPF comprising of three iris coupled resonators.

alternative for planar and 3-D RF components due to their shape versatility and reversibility, and their potential for continuous RF tuning [9]. Particularly, Galinstan has been used in different types of reconfigurable RF components [9]–[21], from switches and phase shifters to antennas and filters with wide tuning, low loss, and relatively high-power handling. However, LM-based tuning concepts are in an early stage of research and have yet to improve their tuning speed and reliability. In terms of 3-D filters [14]–[21], actuated LMs have been reconfiguring the height or the presence of vias in substrate-integrated waveguides (SIWs) that in turn enable frequency tuning [15], [16] and band switching [14]. Furthermore, they have been altering the capacitance of coaxial [19], [20] and waveguide BPFs [21] either through pneumatic actuation [19]–[21] or electrowetting [10], [11]. Similar concepts have been shown for LD-based tuning schemes in [17] and [18].

This letter explores for the first time the potential of actuated LMs and 3-D printing for the realization of highly-miniaturized and widely-reconfigurable 3-D helical resonators and resonator-based BPFs. Whereas helical filters have been demonstrated before, the majority of them are frequency static. There exist only two tunable helical BPF topologies using piezoelectric actuators and varactors. However, they have been implemented for low frequencies (up to 320 MHz in [7] and 365 MHz in [8]) due the manufacturing complexity of the helix, the difficulty to realize small capacitive gaps ( $\sim 2\text{--}10\ \mu\text{m}$  in [8]) and the high varactor loss [7]. Contrary to these approaches, this letter proposes a low-cost and versatile tuning scheme using pneumatically actuated LMs. The organization of this letter is organized as follows. In Section II, the tunable helical resonator concept is presented. Its applicability to complex BPFs is explored in Section III through the design and testing of a two-pole and a three-pole prototype. Last, Section IV outlines the contributions of this work.

## II. TUNABLE LM-BASED RESONATOR CONCEPT

The LM-based tuning concept is depicted in Fig. 1 for the example case of a tunable helical resonator and a third-order BPF. The resonator dimensions were chosen using the operating principles and design method in [8] for a tunable center frequency between 1 and 1.5 GHz. The proposed resonator configuration behaves as a capacitively-loaded quarter-wave resonator and can be modeled using the circuit model in [8]. It is shaped by a metalized plastic cylindrical cavity and a LM-based helix that is formed by a plastic helical-shaped tube and filled with a highly conductive LM. The helix connection to the RF ground is performed through the LM that flows within a metallic channel in the bottom wall of the cavity [see Fig. 1(a)]. Galinstan is used as a LM due to being highly conductive ( $\sigma: 3.46 \times 10^6\ \text{S/m}$ , [14], [20]) and nontoxic. The frequency of the resonator is tuned by varying the amount of Galinstan within the tube which resembles a helix with reconfigurable number of turns. As shown in Fig. 1(a), a larger number of turns (or more LM within the tube) leads to a lower frequency of operation.

To facilitate low-cost and versatile integration, all of the resonator parts are additively manufactured (AM). In particular, the cavity was manufactured by a stereolithography apparatus (SLA)-based desktop printer and was Cu-plated with a commercially-available process that creates a  $50\text{-}\mu\text{m}$ -thick Cu layer. Two alternative materials and AM processes were considered for the realization of the helix. These include: 1) SLA manufactured tube using a clear resin [22] with a  $50\text{-}\mu\text{m}$  layer resolution and 2) polypropylene (PP) based tube using a commercially-available multijet fusion process with a  $80\text{-}\mu\text{m}$  layer resolution. Since the tube is exposed to the electromagnetic (EM) fields in the cavity, its walls need to be as thin as possible. Considering the limitations of each process a thickness  $t$  of 0.25 and 0.4 mm were, respectively, chosen for the SLA and the PP helix. Furthermore, support structures were added between the turns to increase the mechanical stability. A fitting tube was added at the bottom wall to facilitate insertion of the LM through syringes.

To validate the LM-based tuning concept two resonator prototypes were manufactured and tested. Fig. 2(a) illustrates

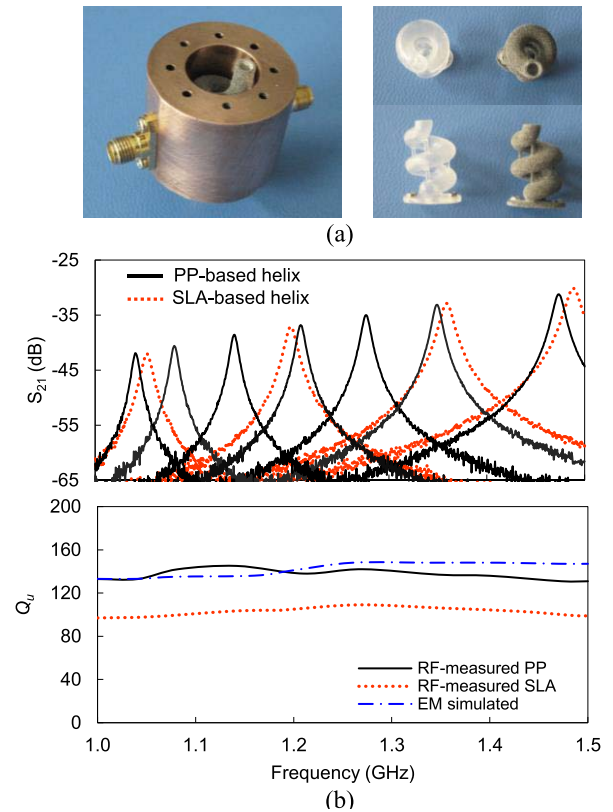


Fig. 2. (a) Manufactured prototype of the LM-tunable helical resonator and detail of the SLA-based (left) and the PP-based (right) helical tube. (b) RF measured power transmission ( $|S_{21}|$ ) and measured and EM simulated  $Q_u$  while altering the volume of Galinstan in the 3-D printed tube.

an assembled resonator (the metallic upper cover and assembly screws have been removed) and the two different helical tubes and Fig. 2(b) depicts its RF measured performance when manually altering the pressure in the syringe which in turn alters the volume of Galinstan. As shown, for a center frequency tuning between  $\sim 1$  and 1.5 GHz the SLA-based helix exhibits an unloaded quality factor ( $Q_u$ ) between 97 and 109 whereas the PP-based helix has a  $Q_u$  between 131 and 145. Since the PP-based approach leads to  $\sim 33\%$  higher  $Q_u$ , it was selected as the most suitable integration approach and its material parameters were extracted by fitting the EM simulated response to the measured one. They are as follows: dielectric constant  $\epsilon_r = 3.1$ , dissipation factor  $\tan\delta = 0.03$ . A comparison of the EM simulated responses is provided in Fig. 2(b) for verification purposes.

## III. LM-TUNABLE BPFs

To validate the applicability of the LM tuning concept to helical BPFs, two filter prototypes namely a two-pole BPF and a three-pole BPFs were designed, manufactured, and tested. They were designed for a Butterworth transfer function, a center frequency of 1.25 GHz and a bandwidth (BW) of 70 and 80 MHz, respectively. The filter design is performed as follows. At first, the coupling coefficients are calculated using the Butterworth low-pass prototype in [21] (two-pole:  $K_{12}$ : 0.04, and  $Q_{\text{ext}}$ : 25.25, three-pole:  $K_{12} = K_{23}$ : 0.045, and  $Q_{\text{ext}}$ : 15.6). Then EM simulations are performed in ANSYS HFSS to correlate the external  $Q_{\text{ext}}$  and interresonator coupling  $K_{12}$  (or  $K_{23}$ ) values to the actual

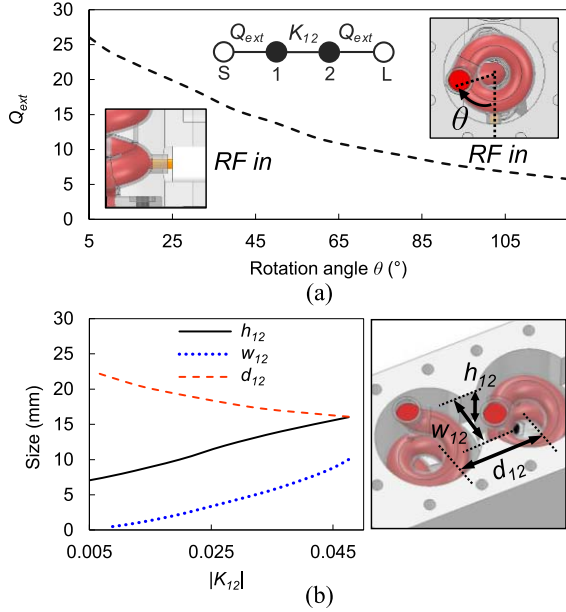


Fig. 3. (a) External coupling  $Q_{ext}$  as a function of  $\theta$  and coupling routing diagram of a two-pole BPF (black circles: resonators, white circles: source and load). (b) Magnitude of the interresonator coupling  $K_{12}$  as a function of  $h_{12}$ ,  $w_{12}$ ,  $d_{12}$ . When not varied  $h_{12} = 16$  mm,  $w_{12} = 10$  mm,  $d_{12} = 16.1$  mm.

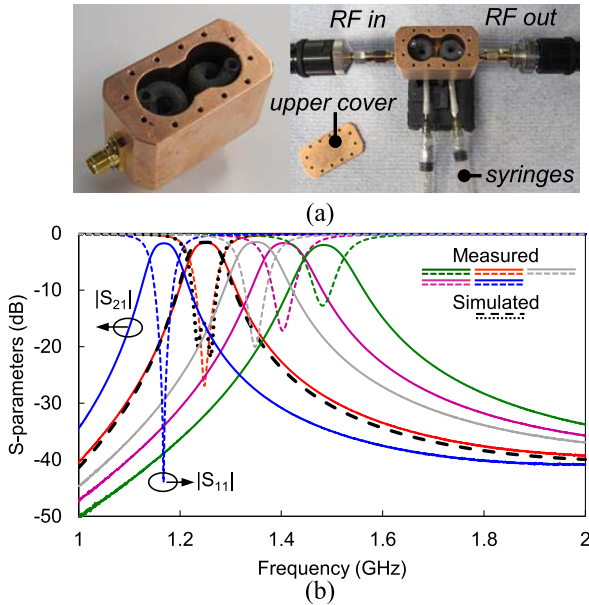


Fig. 4. (a) Manufactured prototype of the continuously-tunable two-pole helical filter. (b) RF measured  $S$ -parameters while altering the volume of Galinstan in the 3-D printed helical tube. An EM simulated state (black trace) is also included.

filter dimensions using the method in [21]. As shown in Fig. 3(a),  $Q_{ext}$  is materialized by tapping the inner conductor of the SMA to the helical tube and its strength is primarily determined by the rotation angle  $\theta$ . The interresonator coupling is dependent on the coupling iris dimensions ( $h_{12}$ ,  $w_{12}$ ) and the resonator distance ( $d_{12}$ ) as depicted in Fig. 3(b). The manufactured prototype of the two-pole BPF ( $h_{12} = 14.9$  mm,  $w_{12} = 11.8$  mm,  $d_{12} = 16.8$  mm) is assembled with screws and its RF measured response while altering the pressure in the syringes is shown in Fig. 4. It exhibits center frequency tuning between 1.16 and 1.49 GHz and  $IL < 2$  dB that corresponds to an effective quality

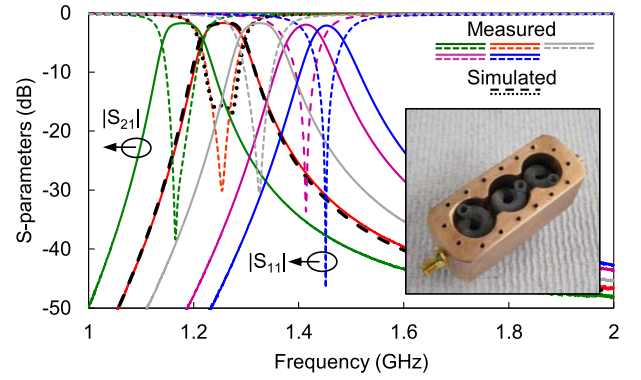


Fig. 5. Manufactured prototype of a continuously-tunable third-order BPF and its RF measured  $S$ -parameters while altering the volume of Galinstan in the 3-D printed helical tube. An EM simulated state (black trace) is also included.

TABLE I

COMPARISON WITH HELICAL AND LIQUID TUNABLE 3-D FILTERS

$f_0$ (GHz)	IL (dB)	$Q_{eff}$	$N$	Type	Vol. (cm <sup>3</sup> )	Ref
0.17-0.23	$\leq 1.3$	192-227	2	3D H/C/var.	21.4	[7]
0.26-0.37	$\leq 3.2$	100-542	2	3D H/C/piezo	21.4	[8]
3.7-4.8	$\leq 7.5$	235-426	2	SIW/C/LM	32.2	[15]
7.96-8.39	$\leq 4.8$	N/A	4	SIW/D/LM	2.7	[16]
2.99-3.03	$\leq 1.1$	N/A	2	3D/D/LD	63	[17]
2.34-2.51	$\leq 4.6$	N/A	3	SIW/D/LD	8.4	[18]
3.4-7.5	$\leq 1$	160-240	2	3D/C/LM	5.7	[20]
18.2-21.1	$\leq 2.8$	N/A	2	3D/C/LM	93.3	[21]
1.16-1.49	$\leq 2$	135-155	2	3D/C/LM	18.13	T.W
1.18-1.46	$\leq 2.1$	179-195	3	3D/C/LM	25.6	T.W

N: order, D: discrete, C: continuous, H: Helical, P: planar, SIW: substrate integrated waveguide, LD: liquid dielectric, var: varactor, T.W: This work.

factor ( $Q_{eff}$ ) of 135–155. A comparison with one EM simulated state is also shown which appears to be in a good agreement and validates the proposed concept. The three-pole BPF prototype ( $h_{12} = h_{23} = 19.8$  mm,  $w_{12} = w_{23} = 8.2$  mm,  $d_{12} = d_{23} = 16.3$  mm), its RF measured and EM simulated response are provided in Fig. 5. It exhibits center frequency tuning between 1.18 and 1.49 GHz, and  $IL < 2.1$  dB ( $Q_{eff}$  between 179 and 195). A comparison of the devised LM-based tunable helical concept with other tunable helical filter concepts ([7], [8]) and LM and LD tuning concepts is provided in Table I. As shown the LM-based helical concept exhibits significantly higher frequency than the rest of the helical BPF concepts. Furthermore, it exhibits significantly higher tuning range than all of the LD-tuning concepts and most of the LM-based 3-D tunable BPFs while it exhibits a comparable  $Q_{eff}$ .

#### IV. CONCLUSION

This letter discussed the design and practical realization of a new class of continuously-tunable helical BPFs. A versatile integration concept using 3-D printing parts and pneumatically-actuated LM is proposed for low-loss and wide center frequency tuning. The operating principles of the LM-based tuning concept were verified through a tunable helical resonator prototype with 1.5:1 center frequency tuning and  $Q_u$  between 131 and 145. Its applicability to continuously tunable helical filters was validated through the manufacturing and testing of a second- and a third-order BPF at L-band.



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