URSI AP-RASC, Sydney, Australia, 17 – 22 August 2025

Tunable Bandpass Filter Design Using Paraelectric Oxide Single Crystal Substrates

Yinyi Zhao(1), Pulugurtha Markondeyaraj(1), Arjuna Madanayake(1), and Satheesh Bojja Venkatakrishnan(1)
(1) Florida International University, Miami, FL, 33185

Abstract

The fixed response frequency of conventional bandpass filters poses challenges in emerging ultra-wideband (UWB) communication systems, where universal radios capable of spanning extremely wide frequency ranges are anticipated. A pivotal enabler for such systems is the development of reconfigurable filters, particularly ultra-fast tunable bandpass filters. Among the promising approaches, integrating high-K dielectric crystals offers a means of achieving frequency agility by altering the effective dielectric properties of the propagation medium by changing their position, resulting in a shift in the operational band. In this study, we demonstrate a tunable bandpass filter (BPF) employing a paraelectric oxide single-crystal substrate with ultra-low loss within a passive microstrip filter architecture. Preliminary analysis reveals a resonance band shift from 11.8 to 12.2 GHz, exhibiting high-Q, thus highlighting the efficacy of this approach for frequency reconfigurability in next-generation communication systems.

1. Introduction

As wireless technologies evolve toward reconfigurable systems, there is an urgent demand for ultra-fast tunable filters to support applications such as RIS and ISAC for 6G and beyond [1]. These filters play a pivotal role in enhancing spectral efficiency, enabling seamless multi-band operations, and addressing dynamic spectrum requirements. Developing such advanced filters will significantly impact the realization of adaptive, high-performance wireless communication networks and next-generation applications. Various material-based tunable filter structures exist, including mechanical tunable filters, which are among the earliest designs [2]. Semiconductor technology such as gallium arsenide is used as varactors in tunable filter design, where capacitance is controlled by the applied DC voltage. The introduction of ferroelectric varactors such as Barium Strontium Titanate (BST), especially the BaxSr1−xTiO3, are also widely used for tunable filters but facing challenges like poor linearity and high losses at microwave frequencies, and that limits their performance above 10 GHz [3-4]. Recently, hafnia-zirconia (HZO) alloy-based tunable bandpass filters have been explored by using them as varactor in the circuit to achieve the tunability by changing the applied voltage [5-6]. The multicomponent oxide material-based bandpass filter is able to operate above 10 GHz [7]; however, they remain constrained by the inherent limitations of varactor-based designs.

In this work, we present a new approach of tunable bandpass filter using the zirconia, where instead of changing the applied DC voltage, we modify the relative position of zirconia crystals with respect to the microstrip traces. Using this approach, we overcome the limitations exhibited by varactor-based design. In comparison, authors of [5] demonstrated a S11 Q-factor of 10 – 20 at 65 GHz, with an average insertion loss (IL) of 3 dB. Other notable comparison involves [6] demonstrating tunability between 36 – 39 GHz with the Q-factor of 4, and IL of around -4 dB.

On the other hand, our proposed tunable BPF at X-band (12 GHz) exhibiting a very high Q-factor of 100 – 120, which shows significant improvement over [5] and [6]. The insertion loss for our design is below 4 dB and our proposed design has a better return loss performance compared with others. By changing the position of Zirconia crystal, compared with other techniques like varactor based tunable BPF. It is the first of its kind reported in the literature, featuring a significantly simpler circuit design without requiring additional lumped elements or external DC biasing. Notably, the proposed BPF achieves a tunable range from 11.8 to 12.14 GHz with an average operational bandwidth of 150 MHz.

The work presented in this manuscript marks a significant advancement in tunable bandpass filter design, contributing to the development of next-generation communication systems. The traditional varactor-based tunable filters have reached their limits in terms of performance, particularly at higher microwave frequencies. Our novel approach addresses these limitations by leveraging the unique properties of zirconia crystals. The motivation behind this research lies in the pressing need for more efficient and adaptable filters to support the dynamic

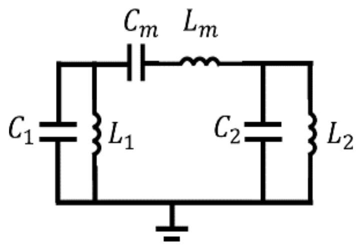

Fig. 1. Figure 1. Equivalent capacitance network for microstrip coupled line filter [8]

demands of modern wireless communication networks. The enhanced tunability, simplified circuit design, and improved performance metrics of our proposed filter make it a promising candidate for future applications.

2. MICROSTRIP BANDPASS FILTER STRUCTURE DESIGN

A. Coupled line filter model

The equivalent network circuit for one N section coupled line microstrip line filter is shown in Fig. 1 [8]. The coupling capacitor between the adjacent microstrip lines is modeled as Cm, C1 and C2 refer to the capacitance between the microstrip lines and the substrate per unit, respectively.

By identifying the value of the capacitance and inductance, the resonant center frequency can then be determined. According to the equivalent circuit shown in Fig.1, changing Cm can change the capacitance of the circuit and therefore change the resonant frequency of the circuit. Authors in [3] applied the varactor between the coupled line to achieve the capacitance changing. Another method is changing the capacitance C1 and C2 where we can directly apply the varactor to the transmission line as shown in the work [9-11]. In this new approach, we are trying to vary the value of C1 and C2 by relatively changing the zirconia's position between the conducting layer and the ground layer so that the response frequency will change.

B. Zirconia material

Paraelectric oxides are ideal for low loss and stable properties because their ionic polarization won't undergo relaxation in microwave frequencies unlike ferroelectric domains that relax at such frequencies based on their domain size and acoustic modes [12-13]. On the other hand, oxides such as zirconia offer moderate permittivity to tune the local fields, feature very low dielectric loss, and can be prefabricated as single crystals that can be embedded in the package. These can be utilized to fabricate innovative tunable filters because the tuning won't be traded-off with the dielectric properties. Therefore, ideal dielectrics with suitable microwave properties can be chosen. By employing super paraelectric oxides with higher permittivity, much higher tuning can be achieved. The zirconia crystal material used in this project is consisted by Y_2O_3 stabilized ZrO_2 with the dielectric constant $\varepsilon_r = 27$.

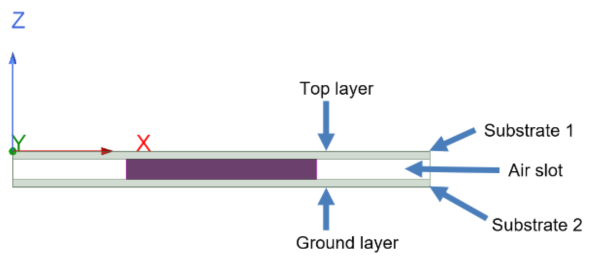

Figure 2. Cross-section of the designed filter structure with Zirconia crystal

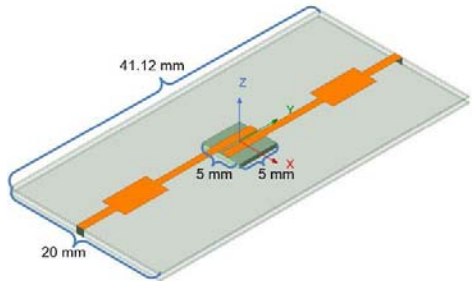

Figure 3. Designed structure in HFSS

C. Tunable bandpass filter design

To achieve optimal performance in our tunable bandpass filter, various optimization techniques were employed during the design and simulation phases. The use of full-wave electromagnetic simulation tools allowed us to fine-tune the filter parameters and ensure that the desired frequency response was achieved. Additionally, impedance matching techniques were applied to ensure minimal signal reflection and maximum power transfer across the frequency band of interest.

The cross-section of the designed microstrip bandpass filter structure is shown in Fig.2 which is consist of three different layers. The zirconia brick is placed between two substrates which are Ro4003c boards with dielectric constant $\varepsilon_r = 3.55$ and thickness $h = 0.203$mm. For substrate 1, only the top layer has the copper conducting layer and the bottom side of substrate 1 has no metal material. Likewise, only the bottom side of substrate 2 has the copper. By varying the position of the Zirconia brick, the capacitance C1 and C2 will change.

The designed 12 GHz tunable bandpass filter is shown in Fig.3 which is consist of two RO4003C substrates and a Zirconia crystal. Fig. 4 shows the corresponding simulated S-parameter for the designed schematic shown in Fig.3.

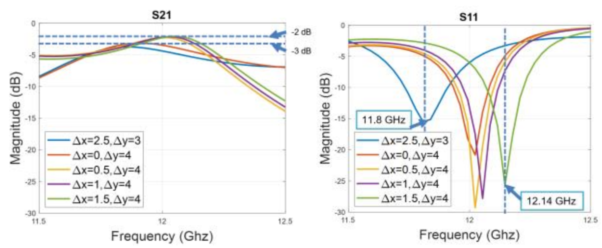

Figure 4. Simulated S-parameters of the proposed tunable BPF in Fig.2

After the optimization, the response frequency of the BPF shifts from 11.8 GHz to 12.14 GHz by varying the position of the Zirconia from the center to 4 mm along the +Y direction and 2.5 mm along the +X direction. The bandwidth of the filter maintains an average of 150 MHz while shifting the center frequency. The insertion loss for the modified filter is around -2 to -3 dB with the return loss reaching as low as around -25 dB.

3. Conclusion

In this work, we explored the possibility of BPF tunability by using the Zirconia crystal. By changing the position of the Zirconia crystal, the resonant frequency of the microstrip BPF shifts from 11.8 to 12.14 GHz with an average bandwidth of 150 MHz Compared with other tunable bandpass filter techniques such as varactor based tunable BPF, our proposed filter structure has less complexity on the microstrip circuit design and no external biasing power is required. Meanwhile, the designed structure maintains low RL and low IL compared with other zirconium based tunable BPF. Picking the 3dB limit bandwidth of S11, the Q factor of the proposed tunable BPF is around 100 to 120 which indicates a very narrowband and high cut-off BPF design is achieved.

4. Acknowledgements

This work was funded by National Science Foundation under the award number # 2321653.

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