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Study on the Effect of the Feedline Inductance in Wideband Tunable Band Pass Combline Filters

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Abstract—This letter proposes a novel analysis and design method of a continuously adjustable bandpass combline filter. It investigates the feedline design specifications and introduces an external quality factor (Q_{ext}) tuning structure to achieve a constant fractional bandwidth over 60% tuning bandwidth. The design approach allows to determine the optimum feedline structure for the filter and is verified by full-wave simulation and measurement. The results show a constant fractional bandwidth of 4.5% over the entire operating frequency range between 225–400 MHz.

1. INTRODUCTION

Tunable bandpass filters (BPFs) play an important role in RF front-ends both in RX and TX chains. They are applied in the RX path to obtain maximum receiving sensitivity and in the TX path to suppress the harmonics of the power amplifiers. Additionally, they are widely used tools in electromagnetics laboratories for various measurements.

Several research activities have been conducted to develop electronically tunable BPFs based on various technologies including varactor diodes [1], MEMS [2], plasma devices [3], liquid crystal structures [4], and ferroelectric thins films [5]. The previously published tunable BPFs offer a compact and high tuning speed; however, they suffer from higher insertion loss, limited power handling capability, intermodulation distortion effects produced by varactor diodes in their structures, and the need for an external bias network. The mechanically tunable cavity filters provide low insertion loss, high-quality factor (Q), high power handling capacity, and good spurious and out-of-band rejection. Both electronically- and mechanically-tunable combline filters need to have an appropriate adjustable mechanism which shifts the center frequency by changing the capacitors that are placed at the end of each resonator [6–9].

There are two main concerns in designing combline tunable filters: The first concern is to design the variable capacitors functioning in the entire operating frequency while maintaining the filter's frequency response. For mechanically tunable filters, this can be addressed by properly designing the profile of the capacitors' rotating arms such that the appropriate capacitor values are achieved at each frequency.

The second concern is to maintain the coupling bandwidths between the resonators within an acceptable range in the entire bandwidth so that the filter shape does not deteriorate. The simulation results demonstrate that in combline filters, the fractional coupling bandwidth between inter-resonators intrinsically remains constant by changing the filter working frequency. However, in such filters, the fractional coupling bandwidth between the input probe and the first resonator (CBW_{S1}) varies significantly with changing the operating frequency. Extensive experimentation and special mechanisms are needed to keep the CBW_{S1} relatively constant over the entire operating frequency. The novel tuning method presented in this paper attempts to address these issues by introducing an external quality factor

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(Q_{ext}) modifier structure to have control over CBW_{S1} frequency behavior. The experimentally verified design of this structure ensures that the fractional CBW_{S1} remains constant at all operating frequencies, as the rational coupling bandwidth between the intermediate resonators does so that the filter shape is maintained when the center frequency is shifted.

To validate the design procedure, a fifth-order variable bandpass filter with tuning bandwidth of about 60% in the frequency range of 225–400 MHz was fabricated and experimentally investigated. The proposed filter features a sharp out-of-band rejection which is applicable to suppress strong out of band signal in the receivers input to increase the receivers' sensitivity. The mechanical cavity structure allows to filter out noise and unwanted signals and limit the high power transmit signal to a pre-specified frequency band in order to prevent interfering with other signals in the vicinity. The proposed filter provides a continuously tuning feature with one parameter (shaft rotation angle). This property is achieved by the correct coupling of the feed line into the filter chain and by the proper design of the cam-shaped, mechanically tuned capacitors. The profile of the capacitors rotating part assures a frequency variation that is linear to the shaft rotation angle.

2. FILTER DESIGN

The coupling topology of the proposed filter (shown in Fig. 1) is considered to be linear and symmetric. The linear topology is due to the weak cross coupling between the non-adjacent resonators in the filter confirming no transmission zeros in the frequency response of the filter [10]. The design process was performed based on the coupling matrix synthesis technique for microwave filters presented in [10] and [11]. The ideal coupling coefficients were derived using small frequency steps in the 225–400 MHz band to have control over the frequency behavior. The coupling values were calculated for a fifth-order equiripple filter with Chebyshev approximation having 4.5% rational bandwidth and 0.05 dB passband ripple. Data are tabulated for the center and two extreme frequencies in Table 1. Due to symmetry, CBW_{34}, CBW_{45}, and CBW_{5L} are assumed to be known. As it is expected, if the fractional bandwidths of different coupling parameters are the same at different center frequencies, the shape of the frequency response would maintain over the tuning range.

The primary structure of the filter is depicted in Fig. 2. The filter consists of five cylindrical metal rods which are separated with four metal bricks which provide coupling windows for each pair of resonators. For a given center frequency, the filter design is a straight forward procedure [11, 12]

Table 1. Desired coupling bandwidths at center and two extreme tuning frequencies for chebyshev approximation.

Frequency (MHz)	CBW_{S1} (MHz)	CBW_{12} (MHz)	CBW_{23} (MHz)
225	10.3	8.6	6.3
300	13.9	11.7	8.6
400	18.5	15.6	11.45
Rational BW	4.6%	3.8%	2.8%

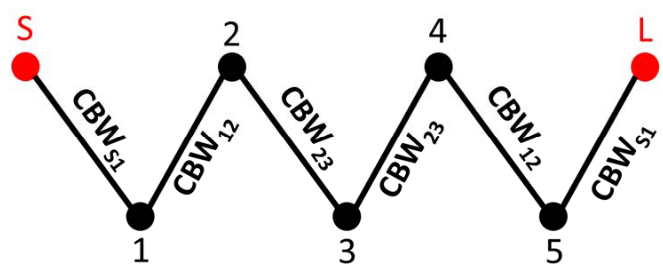

Figure 1. Coupling scheme of a linearly coupled fifth-order filter.

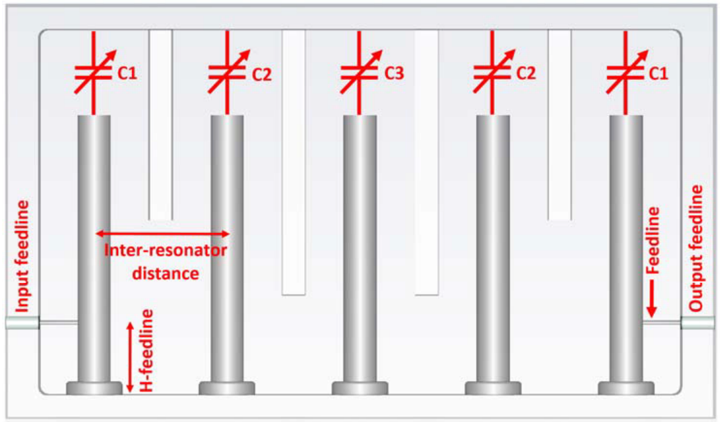

Figure 2. The filter primary structure outline.

often along with optimization of design factors derived from full-wave simulations. The design and optimization process are limited to finding the suitable coupling windows' dimension to obtain the inter-resonator coupling bandwidth and the values of the capacitors so that the filter operates in the desired frequency. The input/output probes can be directly connected to the first/last resonator, and the height of the feedline would determine the CBW_{S1}.

To obtain the CBW_{S1} in simulation, it is needed that all resonators except the first one are shorted at both ends. The simulated structure is depicted in Fig. 3. Using the quality factor extraction method described in [12], the input probe is directly connected to the first resonator, and the probe position and the value of C_1 capacitor are changed until a mound-shaped S_{21} response is obtained at the center frequency having 3 dB bandwidth equal to the desired. It should be noted that, in this simulation, port 2 is a virtual port used only for calculating the CBW_{S1} and is coupled to the first resonator to measure the coupling bandwidth of the input probe to the first resonator. The $|\Delta f_{3\,\mathrm{dB}}|$ parameter shown in Fig. 3 demonstrates CBW_{S1}.

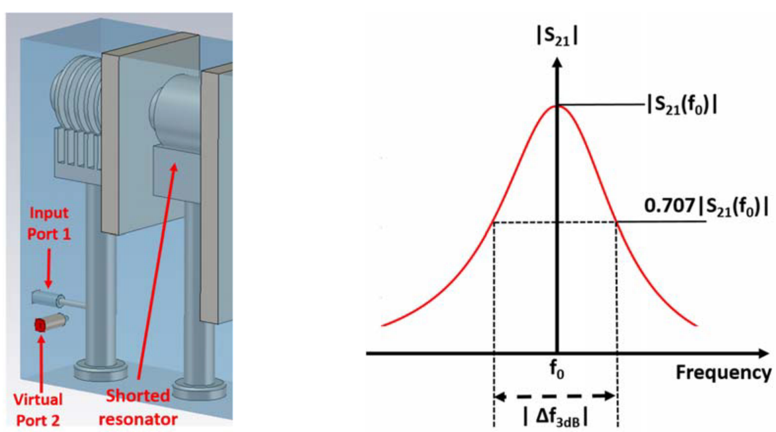

Figure 3. The simulation structure in which CBW_{S1} is calculated using a small virtual probe.

To obtain the coupling bandwidth between the resonators (not CBW_{S1}), the first two eigenmode frequencies of the two desired resonators must be calculated. As an instance, to calculate the CBW_{12}, it is needed to short the capacitors of the other resonators (third, fourth, and fifth resonators) and calculate the first two eigenmodes of the cavity (f_1 and f_2). In this simulation, $\Delta f = (f_2 - f_1)$ would signify the CBW_{12} at $f_0 = (f_2 + f_1)/2$ frequency which is the mid frequency of the two eigenmodes.

For designing a tunable filter, the starting point is to design a filter at center frequency of the tuning range, e.g., 300 MHz, and then to find appropriate capacitor values to shift the frequency response of the filter leaving all other structural parameters unchanged. In a combline filter, by changing the capacitors properly, the fractional coupling bandwidth of the inter-resonators is preserved. However, the fractional CBW_{S1} and therefore the filter shape deteriorates by changing the capacitors. This effect is demonstrated in Table 2 and is contrasted to the desired CBW_{1S} of Table 1. If the input and output probes are directly connected to the filters (Fig. 2), and the design provides 4.6% CBW_{S1} at the center frequency, then the CBW_{S1} decreases to 3.6% at the lowest frequency and increases to 5.8% at the highest working frequency.

Table 2. CBWS1 at center and two extreme frequencies in the case of directly connecting the input probe to the first resonator.

Frequency (MHz)	225	300	400
CBW_{S1} (MHz)	8.1	13.8	23.2
Rational BW	3.6%	4.6%	5.8%

To address this issue and to have control over frequency behavior of CBW_{1S}, an inductor is added in series between the feedline and the first resonator. The effect of the inductor value on the variation of the fractional CBW_{S1} is simulated in CST studio and is depicted in Fig. 4. It is seen that increasing the feedline inductance increases the ratio of CBW_{S1} at the lower frequency to CBW_{S1} at the higher frequency in the tuning range.

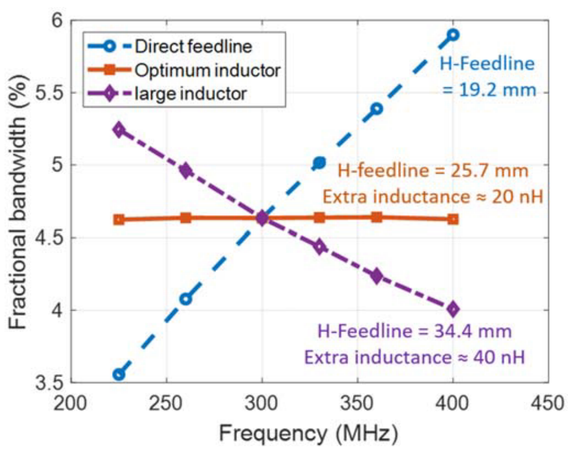

Figure 4. Simulation results of rational CBW_{S1} vs. different values of input series inductor at different center frequencies of the filter.

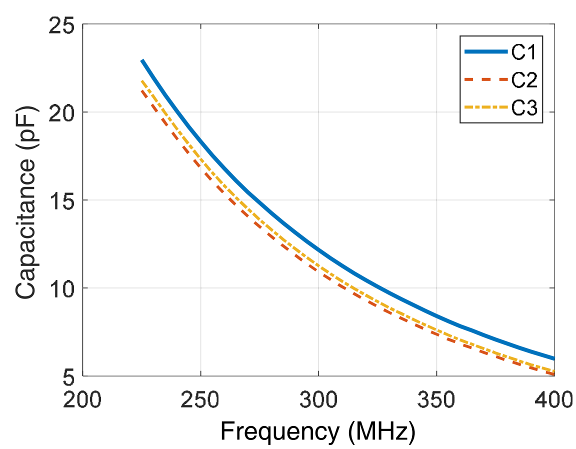

Figure 5. Variation of the capacitor values for different center frequencies of the filter.

Simulation results show that increasing the inductance of the feedline reduces the fractional CBW_{S1} at all frequencies. This can be compensated by increasing the feedline height to obtain the required CBW_{S1}. Indeed, to find a proper value of the series inductance, it is needed to change the inductor value and feedline height until the fractional CBW_{S1} at center and two extreme frequencies are the same and meet the values of Table 1. The values of the extra inductance of the input and output wound inductors shown in Fig. 4 have been obtained by calculating the resonance frequency of a known capacitor in series with this inductor using CST full-wave simulation.

Using the proper value of the feedline inductance simplifies the design procedure to the filter structure design at center frequency, which is 300 MHz in our case, and finding the proper profile of the capacitors rotating arm. For achieving a frequency variation that is linear to the capacitor angle, the rotating capacitors' shapes should be designed so that the maximum inter-resonator couplings occur at the center of the desired working frequency for each rotation angle. The capacitance variations of the first, second, and third resonators' capacitors vs. different center frequencies of the filter have been simulated using electrostatic solver of CST and depicted in Fig. 5. The other two capacitances have not been shown due to the symmetric structure of the filter. The results show that the values of different capacitances of each resonator at each frequency are not the same. The results also show that the capacitance variation vs. frequency is a function of $1/f^2$ in which "f" is the center frequency of the filter.

3. MEASUREMENT RESULTS

A prototype of this cavity combline filter was fabricated and experimentally investigated. Fig. 6 shows the outline of the designed filter which is designed for the lowest possible volume. The length of the resonators is less than 0.06λ at the lowest working frequency. Moreover, the resonator spacing was tuned for achieving the desired coupling coefficients over the entire frequency bandwidth. The small length of the resonator was compensated by the interdigital capacitors shown in Fig. 6. The input inductor is implemented using a 1 mm diameter silver plated wire having a 3 mm coil diameter and two turns.

The frequency response of the filter is tuned by rotating a shaft that is shown in Fig. 5. Due to the proper design of the cam-shaped rotating arm of the interdigital capacitors, the filter frequency response changes linearly by shaft rotation, e.g., 1 MHz/deg. Fig. 7 shows the measurement results of the filter vs. different rotation angles. The S-parameter measurements were performed using an HP

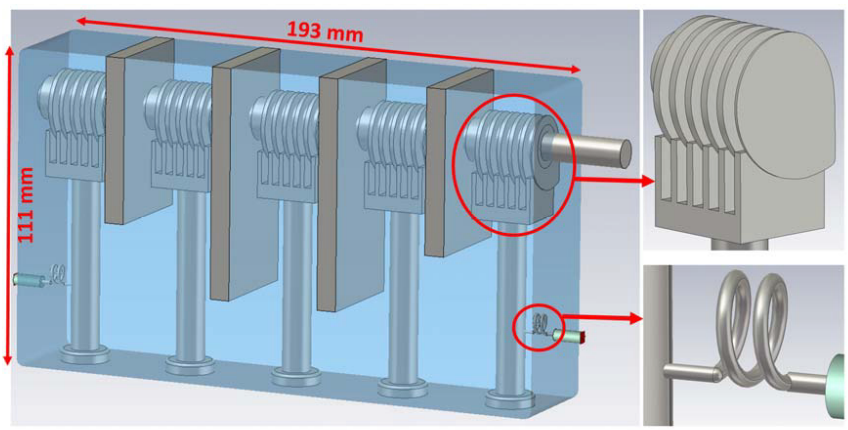

Figure 6. Structure of designed tunable filter.

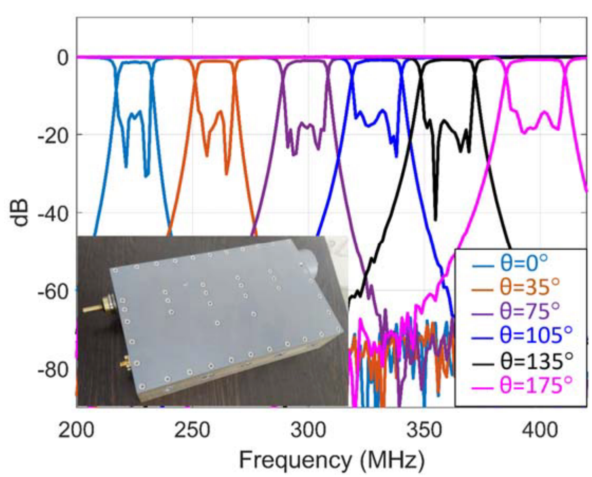

Figure 7. Fabricated filter insertion loss and return loss for different shaft rotation angles (θ).

8753A network analyzer. It is observed that the filter maintains its shape in all tuning states, and the filter return loss is always better than 15 dB which is an excellent result for a tunable filter with about 60% tuning bandwidth. The insertion loss of the filter vs. different working frequencies reduces from 1.4 dB at low end to 0.8 dB at 400 MHz.

4. CONCLUSION

A possible improvement technique for tunable combline filters is discussed in this letter by introducing an inductive feedline structure and external quality factor (Q_{ext}) modifier. The inductance of the feedline controls the frequency variation of CBW_{S1}, and thanks to this property it can be designed in a way to keep the rational CBW_{S1} unchanged in different states of the tunable filter. The filter prototype was designed and characterized in 225–400 MHz frequency range, and the measurement results demonstrated a good tuning feature of the manufactured filter with respect to loss, shape, and reflection coefficient.

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