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Novel designs of high-temperature superconducting bandpass filters for future digital communication services

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Abstract

The design and experimental results of a 5-, 10- and 23-pole lumped-element HTS bandpass filters for the applications in digital terrestrial television and other digital communication services is reported here. These filters are designed around 800 MHz centre frequency, 7.6 MHz bandwidth using end-coupled lumped element resonators on yttrium-barium-copper-oxide (YBCO) or thallium-barium-calcium-copper-oxide (TBCCO) thin films in a 2 inches lanthanum aluminate ($LaAlO_3$) substrate. A new layout profile of a complex 23-pole filter for 70 dB out-of-band rejection 0.4 MHz away from the passband edges is designed, fabricated and tested in an integrated RF-cryocooler measurement system. The design of 23-pole filter was very compact and a significant amount of computer time was elapsed to electromagnetically simulate the structure-which was finally done by parts. These lumped element filters were tuned in liquid nitrogen using small pieces of lanthanum aluminate substrates and PTFE rods. The measured frequency responses of 5- and 10-pole filter are quite encouraging. In this investigation, a very useful conclusion is drawn that a compact lumped element design in twinned substrates like lanthanum aluminate is highly susceptible to the local variations in the film parameters and this effect becomes more and more severe as we increase the order of the lumped element filters.

Keywords: Electromagnetic simulations, method of moments, high-temperature superconductivity, microstrip filters.

1. Introduction

Highly selective, minimum insertion loss, narrowband high-temperature superconducting (HTS) microstrip filters have huge potential for future wireless communications. As an example, for the application of digital terrestrial television, there is a requirement of HTS filters at around 800 MHz with 7.6 MHz bandwidth, 70 dB rejection loss at 0.4 MHz away from the band edges. In order to achieve that requirement it was calculated that such a filter should be of Chebychev type of 23rd order. This performance is impossible to achieve in conventional conductor technology.

Based on this example requirement, a number of design strategies such as the use of lumped element end-coupled bandpass filters, open-square loop-elliptic filters, spiral meander filters were investigated and assessed [1–15]. For realizing such a filter in microstrip form, the starting point was to identify a simple structure, which has narrow bandwidth and

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*Present address: Department of Electronics and Computer Engineering, Indian Institute of Technology (IIT)-Roorkee, Roorkee 247 667, India; Ph: 91-1332-285591, Fax: 91-1332-285368 can be easily transformed into its equivalent lumped element form, as the lumped element version gives modest miniaturization. An end-coupled bandpass filter is chosen as the optimum design structure [1] because of its inherent narrowband response. In this structure, coupling between any two resonators is weak which produces a narrow bandwidth in comparison to other basic bandpass structures such as, parallel-coupled, hairpin-line and interdigital bandpass filters where the amount of coupling is higher because of the presence of long overlapped region between any two resonators.

In this paper, the design and experimental results of 5-, 10- and 23-pole lumped-element end-coupled HTS bandpass filters with 7.6 MHz BW and centre frequency around 800 MHz is reported. The design was carried out using circuit simulator and full-wave electromagnetic (EM) simulator, Momentum, HPADS.

2. Bandpass filter design

Various designs of microstrip bandpass filters have been reported [1–16]. Here the design principle is based on an end-coupled bandpass filter, in which the transmission line sections act as half-wave resonators. The electrical coupling capacitances are implemented by the gaps at the end of each resonator. In the lumped element equivalent of end-coupled bandpass filter [1], each half-wave resonator is replaced by a parallel resonating structure of an interdigital capacitor and a narrow-width transmission line, which acts as an inductor. The gap between any two resonators is replaced by an interdigital capacitor.

The reason behind choosing this type of structure is basically to realise a <1% FBW bandpass filter and also the layout to fit in a 2-inch HTS substrate. Though for a given number of poles, elliptic filter is known to have better selectivity than Chebychev-type filter, it is the difficulty in designing a proper elliptic resonator structure [3] to meet the design specifications and also to satisfy the above criteria, which made us prefer the Chebychev-type design. Generally, elliptic filter works based on parallel-coupled resonators with cross coupling and the layout of an elliptic resonator take significant amount of design space.

2.1. *5-Pole lumped element filter*

The investigation reported here is based on the requirement of filters for digital terrestrial television application with the following specifications.

Filter specifications

Centre frequency : 800.0 MHz
Lower passband cutoff : 796.2 MHz
Upper passband cutoff : 803.8 MHz
Lower stopband cutoff : 795.8 MHz
Upper stopband cutoff : 804.2 MHz
Passband ripple : 0.25 dB p-p
Passband group delay variation : 1 *m* sec p-p
Stopband attenuation : 70 dB

For the required passband ripple, L_{Ar} dB, the minimum stopband attenuation, L_{As} dB, at $\Omega = \Omega_{\mathrm{S}}$ (angular frequency at stopband edge), the degree of a Chebyshev lowpass prototype, which will meet this specification, can be calculated by [1]

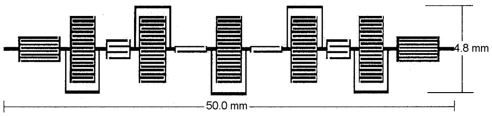

FIG. 1. Layout of 5-pole filter in a 2-inch substrate.

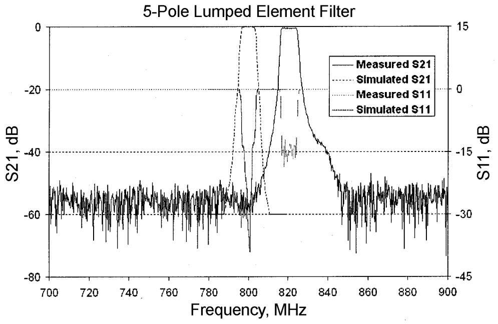

FIG. 2. Simulated and measured transmission (S21, left Y axis) and reflection (S11, right Y axis) responses of the 5-pole filter.

$$n \geq \frac{\cosh^{-1}\sqrt{\dfrac{10^{0.1L_{Ar}}-1}{10^{0.1L_{As}}-1}}}{\cosh \Omega_s}. \tag{1}$$

Using (1), it is calculated that Chebychev type of 23rd order filter will meet the specifications. From a lowpass prototype response, a bandpass response is transformed [1].

For the HTS microstrip realization, YBCO or TBCCO films with lanthanum aluminate ($LaAlO_3$) as substrate were chosen. A $LaAlO_3$ substrate with relative dielectric constant $e_r \sim 24.0$ and thickness $h = 0.5$ mm and loss tangent 0.0003 was preferred among other commonly used HTS substrates (such as sapphire, MgO) because of its high dielectric constant, which helps in realising a filter in smaller substrate area. The high-temperature superconducting film is assumed to have a thickness of 0.0007 mm.

Initially, a 5-pole lumped element filter was designed as a confidence building first step towards the designing of 23-pole filter. The specification of the 5-pole filter is derived from the closest possible simulated response of the specification of the 23-pole filter.

The design of 5-pole lumped-element capacitively coupled bandpass filter is based on circuit optimisation method using the HPEEs of circuit simulator. This simulator optimises all the variable dimensions of both interdigital capacitors and interdigital resonators in the 5-pole filter.

Once circuit optimisation is complete, the layout of the circuit is generated using design synchronization in that software. Full-wave simulations [17] are done using electromagnetic simulator momentum on the generated layout. To simulate the structure process size of 89 MB and 3 hours of computer time was required. The final layout of the 5-pole filter was obtained after running iterative optimisation on momentum simulation till the simulated response closely matches the required specifications. The passband of the 5-pole filter is simulated same as that of the 23-pole filter and the roll off the 5-pole filter was simulated as best can be optimised from the specifications of 23-pole filter (Fig. 1). Full-wave electromagnetic simulation response and the measured transmission and reflection response of the 5-pole filter are shown in Fig. 2.

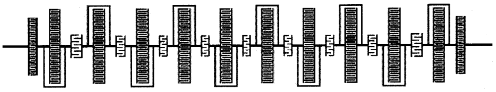

FIG. 3. Layout of 10-pole filter (fabricated in 2-inch circular film).

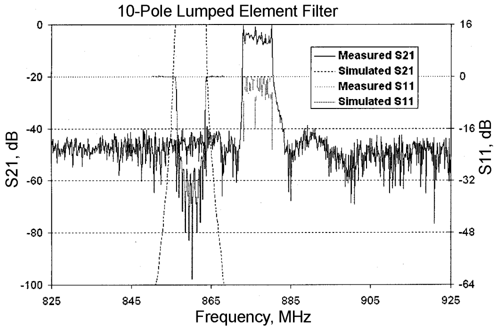

FIG. 4. Simulated and measured transmission (S21, left Y-axis) and reflection responses (S11, right Y-axis) of the 10-pole filter.

Figure 2 shows very encouraging measured results with sharp transition from passband to stopband (roll off). The filter worked with 820 MHz centre frequency, 8.0 MHz passband, 0.29 dB insertion loss and ripple level of 0.3 dB. Return loss in the passband is greater than 15.0 dB. The difference between the measured and the simulated response in transmission characteristic is seen to be in the smoothness of the filter and in the shift of the response curve with respect to frequency. In order to smoothen the passbad response, the 5-pole lumped element filter was tuned using small pieces of lanthanum aluminate substrates and PTFE rods [4, 5].

The shift in the response curve with respect to frequency might be due to the filter response's sensitivity with the parametric variations of filter constituents, such as the dielectric constant of the substrate, and the thickness of the substrate, and of the film. If the practical values of those parameters are different from their simulated ones, the responses might differ. Sensitivity analysis of these filters is conducted and reported [2, 16].

2.2. *10-Pole lumped element filter*

The design methodology of 10-pole lumped element filter is the same as that of 5-pole filter. Emphasis was laid on laying it out straight, to minimize nonadjacent elements coupling problems. It is also fitted within a 2-inch substrate.

The layout of the 10-pole design is shown in Fig. 3. In order to accommodate more poles within the same area as that of the 5-pole filter, the number of finger pairs in all interdigital resonators and interdigital capacitors is increased (Fig. 3).

Initially, EM simulation [17] of the 10-pole design was carried out, dividing the entire layout configuration into two halves. A total process size of 532.85 MB RAM and over 14.00 h of computational time was required to simulate the first part and 566.59 MB RAM and more than 22.27 h of computational time for the second part. An attempt was made to run an EM simulation on the entire design of 10-pole filter. It took more than 104.30 h to simulate the process size of 895.61 MB. Simulated and measured frequency responses of the 10-pole filter is shown in Fig. 4. The filter is simulated for 860 MHz center frequency, 7.6 MHz BW, 0.2 dB insertion loss and refection loss of more than 20 dB. Here, it is

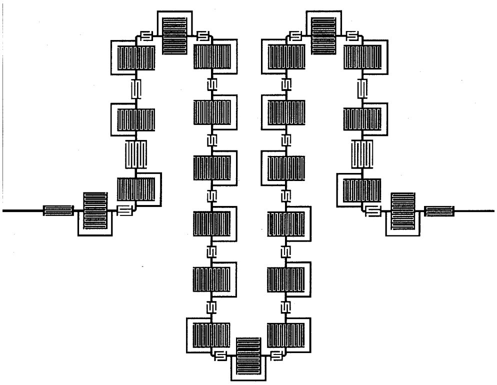

FIG. 5. Layout of 23-pole filter in a 2-inch substrate.

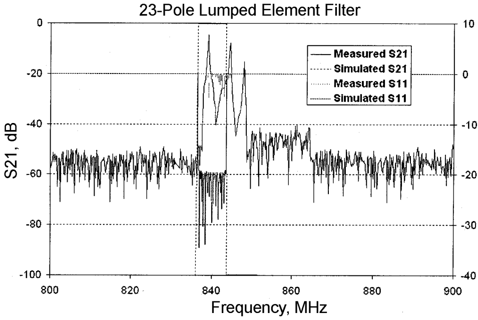

FIG. 6. Simulated and measured transmission (S21, left Y-axis) and reflection (S11, right Y-axis) responses of the 23-pole filter.

observed that with increase in the number of resonators with such thin and short the transmission line sections in a filter, the requirement of computer memory and speed to simulate the structure increases exponentially, which poses a real problem for the development of such filters.

The measured response of the 10-pole filter is shown in Fig. 4. The filter had worked and had shown quite a sharp transition but the passband shape was not perfectly smooth. Ripples in the passband may be mainly due to the nonsuperconducting inclusions in the film which absorb EM energy and also due to impedance mismatch as the conductivity gradient present at the interface between silver paint over superconductor and connector pins. Port positions which are at the extreme ends of 2-inch film, where film quality is hardly the same as that in the middle of the film, could also be a reason for this impedance mismatch. Moreover, dielectric profile of $LaAlO_3$ substrate is not uniform across the substrate surface area because of its inherent twinned regions [2].

2.3. *Novel 23-pole lumped element filter*

After successful design and testing of a 5-pole and 10 filters, an attempt was made to design and fabricate one 23-pole filter within a 2-inch substrate. The specifications of the 23-pole filter are given in Section 2.1. Using the design methodology as explained in 5- and 10-pole filers, the 23-pole design circuit was simulated and optimised to the required specifications. The layout profile of the 23-pole filter is shown in Fig. 5.

Momentum simulation [17] of the entire 23-pole design layout was not possible with the available computer work stations as it demanded several Giga bytes of computer RAM and several GHz clock speed of the processors. This is because as the number of poles within a given area is increased and also the more thin and short the transmission line sections of the constituent element become, meshing grids for such structure need to be more dense to reach a converging simulation result. Instead, an alternative simulation approach, dividing the layout into five parts, was carried out to simulate the design layout. Each individual part is then run for momentum simulations and subsequently adding those respective S parameter data files in a schematic window an overall estimate of the response is obtained. Even an iteration of the simulation of these parts took several days to complete. So, in order to fine-tune the EM simulated response to match the required specifications in an iterative manner will therefore be an enormously huge time-consuming affair. The predicted method of moments (MoM) [17] response after an iteration thus obtained is not close to the circuit simulation response.

A 23-pole filter was fabricated using the dimensions of the constituent elements that were obtained after the circuit simulation. Circuit simulation response and the measured frequency response of the 23-pole filter is shown in Fig. 6. The filter is simulated for 840-MHz centre frequency, 7.6-MHz BW, 0.2-dB insertion loss and refection loss around 20 dB.

Figure 6 shows very sharp passband-to-stopband transitions, but the passband profile is not good. The reasons for this kind of response can be manifold: Firstly, as the layout covers almost entire surface of the film, the film quality needs to be accurately uniform over the entire surface, otherwise one single nonsuperconducting inclusions or any form of defects will either break the current path or may cause severe impedance mismatch to kill the response altogether.

The etching process [2, 4, 5, 16] needed to be checked thoroughly, as nonuniform etching rate was observed across the filter surface from different etchants. Nonuniform etching may cause over etching or undercutting of the dimensions of the filter. Sometimes, it is observed that because of over etching some dimensions of the filter are corrupted with various forms, which severely affect its performance. Dry etching could be a better proposition for these kind of delicate designs.

Secondly, the design of a 23-pole lumped element filter demands uniform dielectric constant, substrate height and film thickness across the entire surface. Any form of deviations of these film and substrate parameters would have nonuniform impacts in the elements; as a result, the filter response may be severely affected. Another interesting point to be noted is the substrate used here, that is, lanthanum aluminate, which has twinned regions [2] with dielectric constant different from its nontwinned regions across the substrate surface. This non-uniformity of the dielectric profile of the lanthanum aluminate substrate may be large enough for the thin and small transmission line sections of this compact design to perform differently.

Thirdly, the filter is very compact; unwanted interelement parasitic coupling from the non-adjacent elements could be sufficiently large to cause far enough impedance mismatch among the constituent elements. This problem could not be solved even running EM simulation on individual parts, unless the entire design layout is run on simulation. It was considered too demanding for the present-generation computers.

3. Fabrication and testing

The lumped element bandpass filters (5, 10, 23 pole) were fabricated using YBCO thin film with a thickness of 700 nm over a 2-inch diameter and 0.5-mm thick $LaAlO_3$ substrate. These filters were patterned using conventional wet photolithography and each one of them was then mounted within an aluminium box with SMA input and output connectors and silver paint to make the contacts. Each of these filters is tested in liquid nitrogen at 77 K using an HP8510c vector network analyser with an input power of 0 dBm. Prior to the measurement of the filter, a full two-port calibration was performed at room temperature. The filters were tuned in liquid nitrogen placing pieces of lanthanum aluminate substrate and sapphire rods over the resonators and capacitors sections of the filter layout. These filters were also tested in an automated RF-cryocooler measurement system at 65 K.

4. Conclusions

A 5-, 10-, 23-pole lumped-element filters around 800 MHz, 8.0 MHz BW bandpass HTS filter on a 2-inch lanthanum aluminate substrate were designed, fabricated, tested and tuned.

From the measured responses, it was observed that the 5-pole filter performed best in terms filter response shape, followed by 10 and 23 poles. This is because the constituent elements of a lower-order filter are less closely spaced and also occupy less surface area than that of a higher-order filter; therefore, are less demanding for uniform substrate and film parameters to perform efficiently. With increase in the number of poles in a filter, the selectivity of the filter increases as observed from the measured responses of 5-, 10- and 23-pole filters. In order to avoid the sensitivity with the substrate and film parameters in lumped element filter designs, resonators with relatively bigger dimensions will be helpful.

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