DIRECT SYNTHESIS OF TUBULAR BANDPASS FILTERS WITH FREQUENCY-DEPENDENT INDUCTORS

Qiang Huang, Ji-Fuh Liang, Dawei Zhang and Guo-Chun Liang
Conductus Inc.
969 West Maude Ave.
Sunnyvale, CA. 94086

ABSTRACT

A method for direct synthesis of a tubular filter with thin-film frequency-dependent lumped element resonators is presented. The synthesis procedure is developed with frequency-dependent inductors to accommodate large parameter aspect ratio in compact configurations. The explicit design equations are derived from required coupling coefficients among resonators, which provide a great flexibility in choosing design parameters. A design example of a 4th order bandpass filter using high-temperature superconductor (HTS) thin-film material is shown which has a 0.6% fractional bandwidth, a less than 0.2-dB insertion loss and a 20-dB return loss. Experimental data shows a good agreement with simulation performance. The technique is especially useful for designing ultra-narrowband filters where the proper coupling is difficult to achieve.

INTRODUCTION

Superconductor filters have found wide applications in the wireless communications industry. The very small insertion loss and sharp filter response in a compact package are basic market differentiators compared to the conventional filter products. However the design of narrowband filters with a small size is difficult due to the parasitic cross coupling among non-adjacent resonators.

Significant effort has been made to develop compact narrowband filters with HTS thin-film technology. A HTS tubular bandpass filter with spiral inductors was demonstrated in 1992 [1] and a filter frequency transformation technique has been introduced for the tubular bandpass filter circuit in 1995 [2]. The later method used a frequency-dependent inductor, which significantly reduced the inductor size without sacrificing the resonator unloaded Qs and provided great flexibility in choosing design parameters.

This paper presents a more generalized designing method and synthesis procedure for tubular filters with frequency-dependent planar inductors to accommodate large parameter aspect ratio in compact configurations. The explicit design equations are derived from required coupling coefficients among resonators, which provide a great flexibility in design parameters. As an example, a 4th order tubular narrowband filter has been made with a fractional bandwidth of 0.6%. The small resonator size and reduced parasitic cross coupling results in a 90-dB out-of-band rejection, a 0.2-dB insertion loss and a 20-dB return loss.

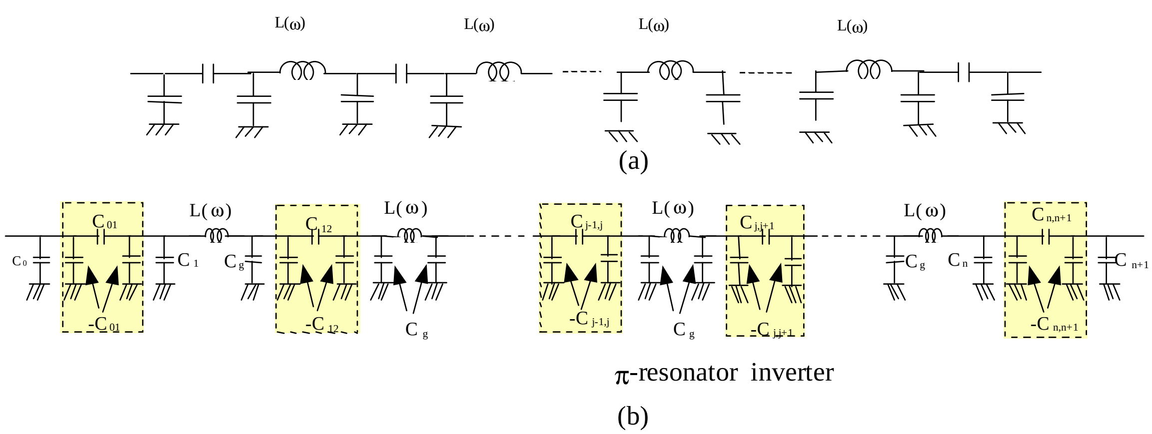

Figure 1 (a) A typical tubular lumped element filter. (b) The tubular lumped element filter with inverters and π-resonators.

ANALYSIS OF A TUBULAR FILTER

Figure 1 (a) shows a typical tubular lumped element filter circuit. The major step in designing this filter is to design

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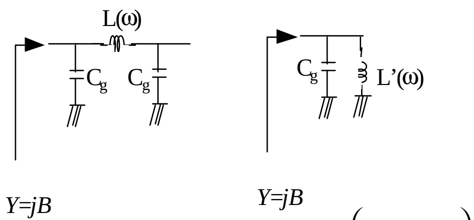
individual resonators and choose proper coupling among them, specifically two parameters need to be identified--resonant frequency and susceptance slope parameter of the resonators. In this process, the filter was re-arranged by π-resonators, each of which consists of a series inductor with shunted capacitors at both ends, as shown in Figure 1 (b). Those resonators are in turn coupled through impedance inverters made of a π-capacitor network with negative shunted capacitance. The series inductors L(ω) in the π resonator could be either a fixed-value inductor or a frequency-dependent one.



$$L'(\omega)=L\left(1-\frac{1}{\omega^2 LC_g}\right)$$

$$jB = j\omega C_g + \frac{1}{j\omega L'(\omega)}$$

$$= j\omega C_g + \frac{1}{j\omega L\left(1-1/\omega^2 LC_g\right)}$$

Figure 2. A π-resonator which can be seen as a parallel resonator

As shown in Figure 2, the π-resonator can be seen as a special type of parallel resonator with resonant frequency and susceptance slope parameter as follows:

$$\omega_0 = \sqrt{\frac{2}{LC_g}} \qquad (1)$$

$$b = \frac{\omega_0}{2}\frac{dB}{d\omega}\bigg|_{\omega=\omega_0} = 2\omega_0 C_g(1+k_L) \qquad (2)$$

$$k_L = \frac{\omega_o}{2L}\frac{\partial L}{\partial \omega}\bigg|_{\omega=\omega_o} \qquad (3)$$

where the shunted capacitors on both sides of the inductor are assumed to be equal. The k_L is the slope parameter of the inductor defined in [2].

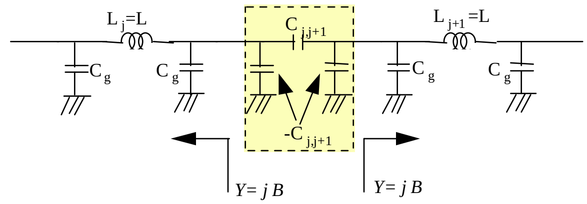


Figure 3. Inter-resonator coupling

Assume all the resonators are the same, the inter-resonator coupling shown in Figure 3 can then be expressed as [3]:

$$k_{j,j+1} = \frac{J_{j,j+1}}{\sqrt{b_j b_{j+1}}} = \frac{\omega_0 C_{j,j+1}}{b} \qquad (4)$$

It can be seen based on equations (2)-(4), that the coupling coefficient $k_{j,j+1}$ can be varied by the resonator slop parameter b which is directly resulted in the inductor slop parameters k_L (Equation 3). Compared the discussion in reference 2, the above discussion provides an alternative understanding of the relationships between filter bandwidth and the inductor slope parameter (the different inductor slop parameter will affect the coupling among resonators and in turn will affect filter bandwidth).

To ensure a realizable capacitor at the filter input an additional shunt capacitor C_0 must be added in front of the input inverter as shown in Figure 4.

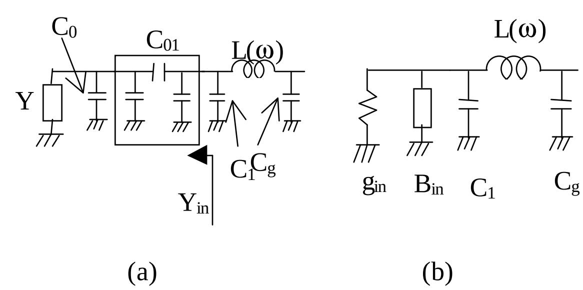


Figure 4. (a) The input coupling circuit. (b) The equivalent input circuit.

The equivalent admittance looking from the first resonator can be found from Figure 4 (a) and (b),

$$Y_{in} = g_{in} + jB_{in} \qquad (5)$$

$$g_{in} = \frac{(\omega C_{0,1})^2 Y_0}{Y_0^2 + (\omega C_0)^2} \quad (6)$$

$$B_{in} = \frac{-(\omega C_{0,1})^2 \omega C_0}{Y_0^2 + (\omega C_0)^2} \quad (7)$$

where, C_0 is coupled with the C_1 to make the first resonator resonant at the desired frequency, while C_{01} provides proper coupling.

Similar analysis can be applied to the output coupling circuit,

$$g_{out} = \frac{(\omega C_{n,n+1})^2 Y_0}{Y_0^2 + (\omega C_{n+1})^2} \quad (8)$$

$$B_{out} = \frac{-(\omega C_{n,n+1})^2 \omega C_{n+1}}{Y_0^2 + (\omega C_{n+1})^2} \quad (9)$$

FILTER SYNTHESIS PROCEDURES

Based on the above analysis, filter synthesis procedures can be developed as follows:

1. Compute the required coupling (i.e. $k_{j,j+1}$, g_{in}/b and g_{out}/b) for a specific frequency response requirement.
2. Choose a proper inductor $L(\omega)$ which can be frequency dependent
3. Compute C_g and b for the inductor $L(\omega_0)$ using Equation (1), (2) and (3).
4. Calculate the inter-resonator coupling capacitor, $C_{j,j+1}$, using Equation (4).
5. Select C_0 and C_{n+1}.
6. Compute the input and output coupling capacitance C_{01} and $C_{n,n+1}$ using Equation (6) and (8).
7. Calculate B_{in} and B_{out} using the Equation (7) and (9).
8. Compute C_1 and C_n based on $B_{in}+\omega C_1$ and $B_{out}+\omega C_n$ equal to ωC_g.
9. Use above results to construct a tubular filter and compute the filter response.

In procedure step one, the design starts with a set of coupling parameters. Those parameters for the all-pole filters can be derived from a low pass prototype filter [3]:

$$g_{in}/b = \frac{w}{g_o g_1}$$

$$k_{j,j+1} = \frac{w}{\sqrt{g_j g_{j+1}}}; \qquad j = 1, n-1 \quad (10)$$

$$g_{out}/b = \frac{w}{g_n g_{n+1}}$$

where w is the filter fractional bandwidth.

A HTS FILTER DESIGN EXAMPLE

A 4th order Tchebyscheff bandpass filter has been designed based on the above procedures. The filter bandwidth is 0.6%. The required couplings are calculated using the Equation (10). A π-type resonator with a capacitively-loaded inductor is illustrated in Figure 4. The center part of the resonator is a half loop inductor L_0 with a parallel inter-digital capacitor C_0. On each side there are shunt capacitors, C_g [2].

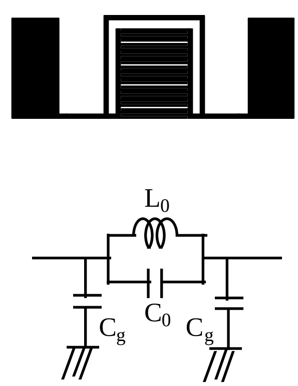


Figure 4. A capacitively-loaded inductor resonator and its equivalent circuit.

Figure 5 is the layout of the filter composed of the resonators discussed above. The filter is made of HTS superconducting thin film YBCO that is deposed on both sides of a 20-mil-thick $LaAlO_3$ substrate.

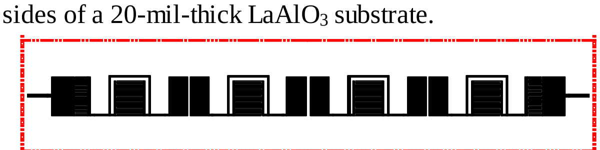


Figure 5. The 4-pole planer HTS Tchebyscheff bandpass filter layout

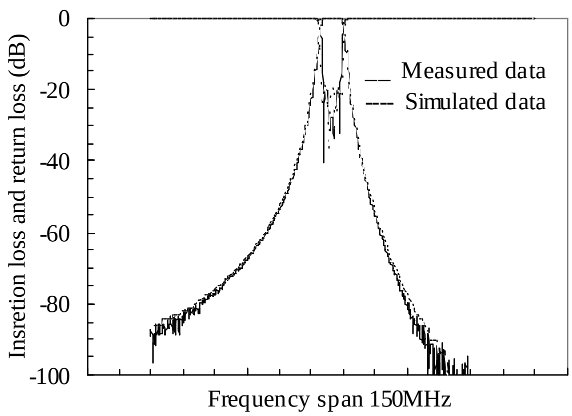


Figure 6. The measured filter response along with the circuit simulation.

Figure 6. is the measured filter response and the simulation data. The measured data matches well with simulation results. The parasitic cross coupling is so small that the filter response is close to an ideal lumped element filter.

CONCLUSION

One practical filter design method using microstrip lumped element circuits has been introduced, the designing and synthesis procedures are presented. A prototype HTS filter with capacitively-loaded inductors has been successfully implemented. Experimental data agrees well with the design. This technique is especially useful in designing narrowband filters.

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