Tuning Fork Filter Design for Hand Scribe Tuning

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***Abstract* — This paper proposes a design technique for high-performance planar filters. The technique provides tuning elements that enable filter tuning by hand scribing, and a parameter extraction based technique to determine what should be scribed. Each resonator has a tuning element, the tuning fork that provides shunt capacitance to ground and is coupled to the resonator by means of a series capacitor. The resonator is tuned by physically disconnecting part of the shunt capacitor. The series capacitor reduces the tuning sensitivity to approximately 10% of what would be seen if the tuning fork was directly connected to the resonator. This reduced sensitivity enables tuning by hand, e.g. with a diamond scribe. A parameter extraction based technique was developed to diagnose the filter couplings and resonant frequencies, and to provide a recipe for scribing the tuning forks. As an example a 10-pole high temperature superconducting filter was designed, fabricated, and scribed. The predicted and measured results agree very well for this filter.**

***Index Terms* — Tuning, parameter extraction, laser trimming, coupling matrix, hand scribing, superconductor filter.**

I. INTRODUCTION

Several tuning techniques for high performance planar filters, such as superconductor filters, have been developed. Such filters are usually patterned on high dielectric constant substrates and designed to be very compact in size. Maintaining high-performance in the filter design stage or in manufacturing requires a stable tuning process. Unlike cavity filters, planar filters do not generally require tuning of the couplings as the filter response is less sensitive to coupling variations than resonant frequency variations. Using the precise lithography techniques developed for semiconductor processing, couplings that are well repeatable within in acceptable range can be produced. However, substrate thickness variations and/or process variations such as etching conditions are likely to cause unacceptable resonant frequency variations and thus require tuning.

There are two main approaches to filter tuning. The first approach, mechanical tuning, is widely used in the industry. Filters are tuned mechanically by moving elements such as dielectric rods or conductive tips over resonators up and down. For superconductor filters, sapphire rods or superconductor-coated tips are used. Sapphire rods are placed at high electric filed area over resonators and tune resonant frequency by changing shunt capacitance to ground. Superconductive tips can be used both magnetic and electric filed tuning but usually they are applied to magnetic field, because it can tune more effectively. The tip changes magnetic field surround resonators and varies inductance of resonator. A big advantage of these mechanical approaches is reversibility. Filters are tuned through a trial and error process by moving the elements up and down. Later on, tuning still can be adjusted if it is necessary. One disadvantage of mechanical tuning is that the tuning elements can potentially impact the resonant frequencies of other resonators or inter-resonator couplings when they are applied, especially when they are placed close to the circuit. In reality, that happens often. The variation in coupling ultimately limits the filter's tuning range. This effect can be minimized by taking it into account during filter design. Designers may arrange resonators tuning locations away each other and away from the couplings to avoid that impact. Of course this matter limits freedom of design. There are other issues that may be caused by having mechanical part. Metallic flakes may drop from mechanical screw part during and after tuning. These flakes may affect Q-factor and also change tuning as they are free to move around on the circuit. The tuning elements also need to be fixed after the tuning is finished to keep the filter's performance constant.

The second approach does not need mechanical parts and is done by processing. A couple of methods, such as laser trimming [1] or thin dielectric layer deposition [2] have been reported. Tuning by this approach will be permanent, and should not change once it is set. However, there is also no more chance to retune or readjust. Hence, tuning must be done very carefully. In general, this second approach is preferable to the first one even though the first approach is predominantly used. The advantages are, simpler structure and less cost because of no mechanical part, reliable because being permanent tuning and more freedom for design because of no interference from the tuning elements. Two major issues have to be resolved in order to realize the second approach. First, a reproducible tuning process must be developed. Second, a robust method that provides a tuning recipe is necessary. Both must be very accurate since the tuning is not reversible.

In this paper, we propose a novel filter design that realizes very accurate tuning without requiring any expensive tools such as laser trimming machine. We intended to tune high performance filters by hand using a diamond scribe. The tuning process is described in the next section. The tuning recipe is obtained by analyzing the filter data using a parameter extraction technique [3-5]. Then, based on the analysis we optimized the filter response and predicted the tuned result before scribing. Excellent agreement between the prediction and tuned result will be shown in the later section.

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II. TUNING FORK RESONATOR

Figure 1 shows "Tuning Fork Resonator" designed for hand scribe tuning. Original resonator forms spiral-in and spiral-out (SISO) [6] shape half-wavelength structure. A "Tuning Fork" tuning element is connected to the resonator through a series inter-digital capacitor C_g at one end of the resonator. The element is electrically floating from the resonator. Frequency tuning of the resonator is implemented by scribing away portions of that floating part. This has the effect of reducing the shunt capacitance C_s of the floating part as shown in equivalent circuit in Fig. 1. Total capacitance of a resonator can be described as

$$C_0 \rightarrow C = C_0 + H \qquad (1)$$

$$H \equiv \frac{C_g C_s}{C_g + C_s} \qquad (2)$$

Original frequency f_0 changes to f by having the tuning fork structure.

$$f_0 \rightarrow f = \frac{1}{2\pi\sqrt{L(C_0+H)}} \cong f_0\left(1-\frac{1}{2}\frac{H}{C_0}\right) = f_0 + \Delta f \qquad (3)$$

Sensitivity of frequency shift can be evaluated by derivative of Δf by C_s

$$\frac{d\Delta f}{dC_s} = -\frac{f_0}{2C_0}\frac{dH}{dC_s} \qquad (4)$$

The sensitivity factor

$$\frac{dH}{dC_s} = \frac{C_g{}^2}{\left(C_g + C_s\right)^2} \qquad (5)$$

represents sensitivity ratio to the case when the fork is directly connected to resonator and a part of resonator is scribed without the decoupling structure. Figure 2 shows frequency shift and the sensitivity factor to scribed length L calculated for this particular example. The calculation is done using momentum provided by Agilent Technology. This tuning fork is designed to be able to tune 1 MHz as maximum when the fork is scribed 2 mm, which is almost full length of the fork. The sensitivity factor varies from 0.05 to 0.3 over the range in Fig. 2. It is 12 kHz/50 μm at L = 0 and 46 kHz/50 μm at L = 20 mm. If the fork was directly connected to the resonator, shift amount is 9.2 MHz when the fork is scribed 2 mm. The sensitivity is about 230 kHz/50 μm and that is constant over the range unlike decoupled case. Practically, hand scribing within 50 (+/- 25) μm precision with a diamond pen under a microscope is realizable even for inexperienced tuners so that this single tuning fork can tune the resonator within 50 kHz precision over 1 MHz range.

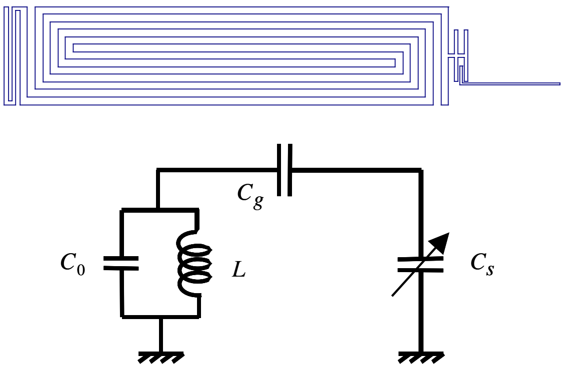

Fig. 1. Tuning Fork resonator and its equivalent circuit. The Tuning Fork is hung at one end of resonator (right side) through the gap capacitor C_g . The resonator is tuned by changing shunt capacitor to ground C_s .

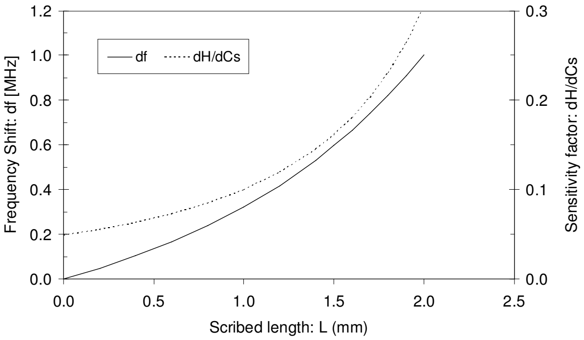

Fig. 2. Tuning range given by the Tuning Fork in Fig. 1. This single Tuning Fork gives up to 1 MHz frequency shift when the Fork is fully scribed (2 mm length). The maximum sensitivity factor H in this tuning range is still less than 30 % of the case where the tuning element is connected directly to the resonator.

Sensitivity and tuning range can be adjusted by changing series capacitance C_g between resonator and the element. Tuning becomes less sensitive by decreasing the series capacitance but instead it needs more shunt capacitance to ground to keep the same amount of tuning range, which results longer tuning fork. Those design parameters should be determined for needed tuning range, acceptable sensitivity and realizable physical size of the tuning fork.

III. DESIGN EXAMPLE: 800 MHz CELLULAR B-BAND FILTER

A. Filter Design

Figure 3 shows filter layout of a 10-pole AMPS-B filter. Filter chip dimension is 34 mm by 18 mm so that two filters can be fabricated on a 2-inch MgO wafer. Design pass band is from 834.8 MHz to 849.7 MHz and return loss is 22 dB. This filter include three quadruplet cross couplings that produce three transmission zeros at each rejection side. Those values

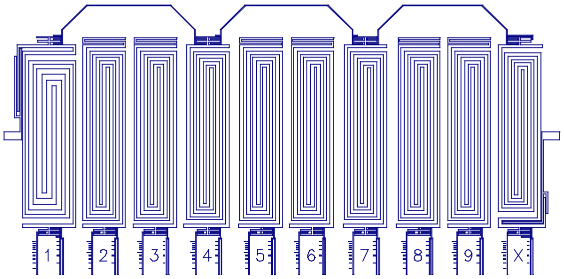

Fig. 3. A layout of 10-pole AMPS-B band filter. Two tuning Forks, those give different tuning ranges, are hung at the bottom of each resonator. Numbers and scales beside tuning forks allows hand scribing easier.

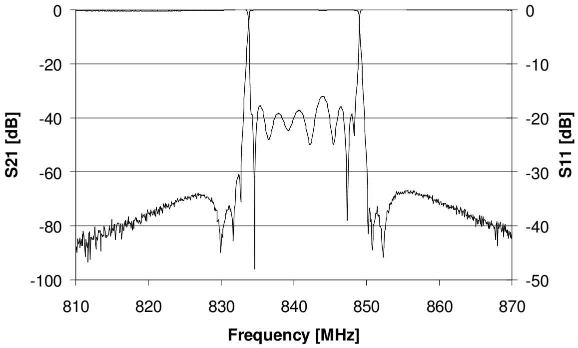

Fig. 4. Initial measurement data before the tuning process.

are designed such that three bounce back peak levels are at 70 dB. The cross couplings are implemented at one side of the resonators array by additional transmission lines those ends are capacitively coupled to resonators. Tuning forks are hung at the other side of resonators array. Cross couplings part and tuning forks part are physically separated from main coupling stream that is carried out through center part along the direction from input to output. Furthermore main couplings are inductive in contrast with cross couplings and couplings to tuning forks are capacitively loaded to resonators. The filter is designed to minimize interference between those different kinds of couplings.

A second tuning fork which provides 2.5 MHz of tuning is added to this filter in order to expand the total tuning range to 3.5 MHz. The sensitivity of the second fork is not as good as the first fork because of its wider tuning range. If 2.0 MHz of tuning was adequate, we could have used two of the the same original forks preserving the tuning sensitivity. Scales and numbers are marked along the forks to assist hand scribing easily.

B. Filter tuning

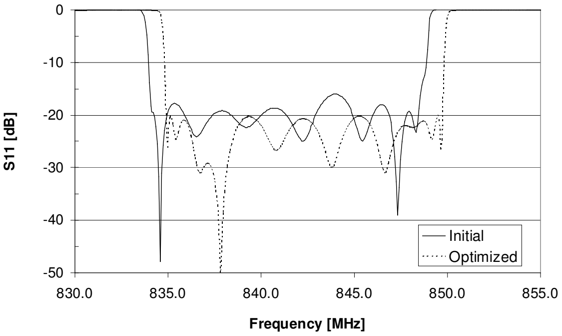

Fig. 5. Initial measured and optimized return loss.

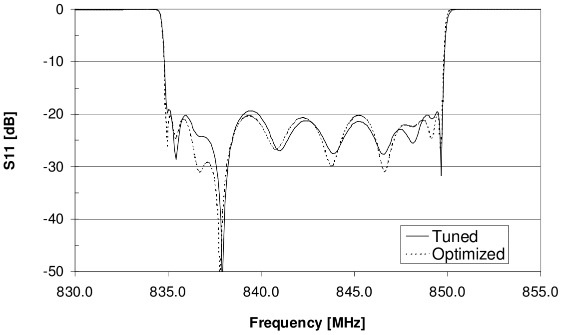

Fig. 6. Tuned and Optimized return loss.

The filter was fabricated using YBCO thin film deposited on a 2-inch MgO wafer and measured at 77K. Return loss at initial measurement was about 17 dB and filter center was about 450 kHz lower than its target center frequency as shown in Fig. 4. Resonators need to be tuned up in frequency to achieve the desired pass band and improve return loss.

The tuning process consists of three steps. The first step is diagnosis of the filter. The measurement data was analyzed by means of parameter extraction technique [3,4]. The extracted coupling matrix is

$$\begin{bmatrix} 0.305 & 0.859 & 0.007 & -0.159 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.859 & 0.144 & 0.686 & 0.007 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.007 & 0.686 & 0.127 & 0.521 & 0.011 & 0 & 0 & 0 & 0 & 0 \\ -0.159 & 0.007 & 0.521 & 0.119 & 0.491 & -0.009 & -0.178 & 0 & 0 & 0 \\ 0 & 0 & 0.011 & 0.491 & 0.138 & 0.686 & 0.010 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.009 & 0.686 & 0.085 & 0.487 & -0.006 & 0 & 0 \\ 0 & 0 & 0 & -0.178 & 0.010 & 0.487 & 0.112 & 0.475 & -0.003 & -0.262 \\ 0 & 0 & 0 & 0 & 0 & -0.006 & 0.475 & 0.126 & 0.744 & 0.012 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.003 & 0.744 & 0.076 & 0.787 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.262 & 0.012 & 0.787 & 0.135 \end{bmatrix}$$

and

$$R_1 = 1.059, R_{10} = 1.063 .$$

The next-neighboring parasitic couplings were taken account into the extraction. Further parasitic couplings can be ignored for this particular design. However, contribution from those

TABLE I

RECIPE FOR THE TUNING FOR RESONATOR NUMBER 1 TO 10 (in kHz).

R1	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***	***R8***	***R9***	***R10***
2322	1184	1024	1017	948	730	742	801	673	913

couplings really depends on each design. Resonator topology, arrangement of resonators, and cross coupling implementation will all impact parasitic coupling values. Further parasitic couplings may have to be included into the coupling matrix as non-zero elements for some cases depending on design. Those undesired coupling matrix elements will generally affect the intended cross coupling structure. These couplings may impact to filter response even though their values are much smaller than main or cross coupling values because they create short-cut paths that don't fit in the desired topology. It may be worth to point out a fact that existence of parasitic couplings makes parameter extraction process difficult, especially when coupling structure is complicated (e.g. multiple cross coupling design) and the resonator Q-factor is high such as superconductor. The reason is that existence of parasitic coupling not only increases the number of optimization parameters but also produces many local minimum solutions of the optimization.

The second step of the tuning process is adjustment of return loss. Return loss was optimized in a computer by adjusting resonant frequencies but keeping the couplings the same with the values that obtained in the first step. Since the real couplings may vary slightly from the ideal design value and parasitic couplings are present, the resonant frequencies need to be intentionally mistuned from their design in order to compensate for these undesired coupling variations and achieve equalized return loss. Practically, filter tuners know this matter and they do intentionally mistune filters even though they may not know quantitatively by how much

The difference between the extracted frequency in the first step and optimized one in the second step becomes a recipe for the physical tuning in the third step. Figure 5 shows optimized return loss response and Table 1 is the recipe targeting the response. By shifting resonant frequencies from 673 kHz to 2322 kHz, filter will be expected to achieve 20 dB return loss at the target center frequency. The filter was tuned based on the recipe by hand scribing with a diamond pen under a microscope. Figure 6 shows the tuned response and the prediction. They agreed very well.

IV. CONCLUSION

We proposed a new design approach for planar filter tuning. The advantage of this technique is not only removing all mechanical tuning parts and allowing easy tuning by hand scribing but it also frees filter designers from the constraints and compromises necessitated by mechanical tuners, potentially enabling new-approaches to high-performance planar filters.

We believe that the tuning technique in this paper will help widely from R&D stage to mass production level. Filters can be tuned without extra mechanical work. In production level, all the mechanical tuning parts can be removed to reduce cost and improve reliability of high-performance planar microwave filters.

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