IEICE TRANS. ELECTRON., VOL.E92–C, NO.3 MARCH 2009

INVITED PAPER *Special Section on Recent Progress in Superconducting Analog Devices and Their Applications*

Automatic Trimming Technique for Superconducting Band-Pass Filters Using a Trimming Library

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SUMMARY The superconducting band-pass filter has small insertion loss and excellent out-of-band rejection properties. It has been put to practical use in a number of applications. However, in order to expand its range of application, a tuning technique that can restore the filter characteristics is needed. We propose an automatic tuning system using a trimming library and checked the feasibility of the system by tuning a forward-coupled filter with three resonators. The results show that the trimming library method is an effective way of automatically improving the filter characteristics.

key words: *HTS band-pass filter, automatic tuning, trimming library microwave device*

1. Introduction

The superconducting band-pass filter has low loss, sharp frequency selection, and excellent noise removal characteristics [1]–[5]. A receiving band-pass filter system for the base station of wireless communications is in practical use in the United States and China [6], [7]. However, superconducting band-pass filters have gaps between their designed and measured characteristics. The existence of such gaps makes the use of such filters problematic. Gaps between design and measurement occur because of inaccurate parameters used to design the coupling coefficient between resonators, the dielectric constant, and thickness of the substrate, and resonators with different lengths [8]. In order to make such filters practical, we should restore the filter characteristics by using a trimming technique. Of the several reported trimming techniques [9]–[12], the trimming rod method is the most general [13], [14]. In this technique, a trimming rod is moved while measuring a filter characteristic. The drawback of this method is that it takes time to make an adjustment. Hence, we decided to examine the feasibility of an automatic trimming technique.

It is important to know which resonator shifts the characteristics so as to restore the filter characteristics in a short time. We previously reported on a measuring technique to determine the resonance frequency and Q value of each resonator [13], and we found that this technique could be used to restore the filter characteristics. However, it is not suitable for automatic trimming because it took a long time to measure the resonance frequency and Q value of each resonator. Hence, we examined the feasibility of an automatic trimming method using a trimming library and special equipment. In this paper, we describe this method briefly and discuss its effectiveness.

Manuscript received June 30, 2008.
Manuscript revised October 30, 2008.

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DOI: 10.1587/transele.E92.C.302

2. Automatic Trimming Process Using a Trimming Library

Figure 1 shows the flowchart of automatic trimming using a trimming library. First, the filter characteristic is measured, and then the date is normalized. The normalized technique is described in Sect. 2.1. Next, the normalized value is compared with data in the trimming library, and the trimming library data that corresponds best to the measured data is selected. The trimming library is described in Sect. 2.2. The automatic trimming system using trimming rods is described in Sect. 2.3. The trimming rod is set on the resonator, and it can be moved by a stepping motor. The process is also described in Sect. 2.3. If the restored filter characteristic after trimming meets the specifications of the filter, the trimming process stops. If the restored data do not meet the specifications, the trimming process is repeated.

2.1 Normalization of Measured and Library Data

To compare the characteristics of the filter against the data in the library in a short time, the data have to be normalized. Figure 2(a) shows the raw experimental data and those of an S-NAP simulation using the equivalent circuit shown in Fig. 3(b). As shown in Fig. 2(a), we found that the insertion loss and ripple have to be normalized when the library data is compared with the experimental data. We normalized the insertion loss of S_{21} and the maximum ripple to 0 and 1 dB, respectively. The reason for normalizing the maximum ripple by 1 dB is to clarify the difference between the experi-

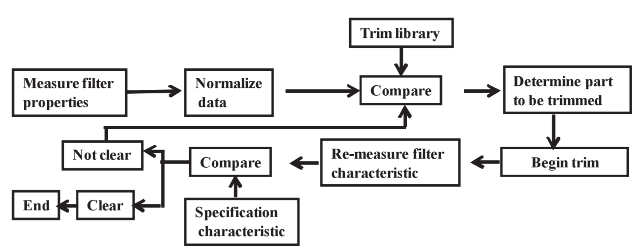
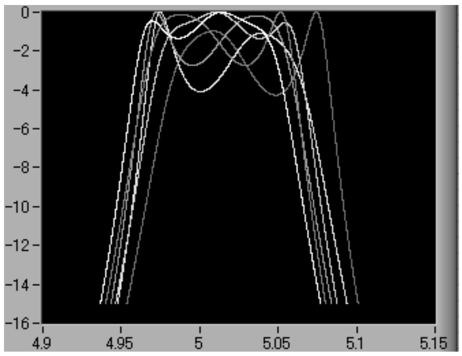
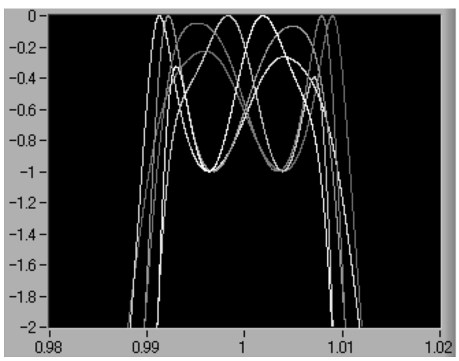


Fig. 1 Flowchart of automatic trimming method using a trimming library.



(a)



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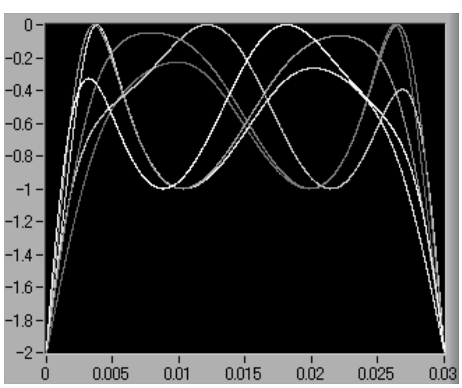


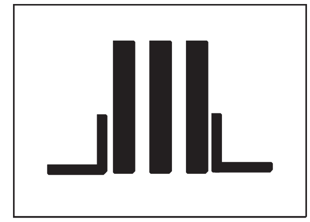
(c)

Fig. 2 Experimental and S- NAP simulation data.

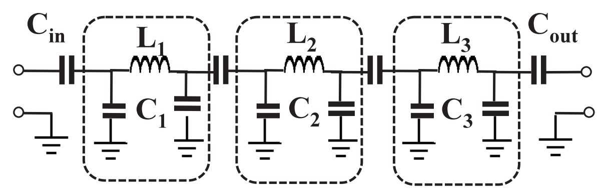
mental data and library data, however the value of 1 dB is not important. The data after this processing is shown in Fig. 2(b). Next, we normalize the frequency, and since we use the Lab-View software, we have to express it numerically. The frequency range was covered by 3000 points, and it is displayed from 0 by 0.03 in figure. Moreover, the maximum value of S_{21} was assumed to be 2 dB to facilitate comparison between the library and the experimental values.

2.2 Trimming Library

Figures 3(a) and (b) show a three-pole forward-coupled filter configuration and its equivalent circuit. We used a conventional π-type equivalent circuit. First, we determined the optimum values of C_{in}, C_{out}, C_1, C_2, C_3, L_1, L_2, and L_3 to



(a)



(b)

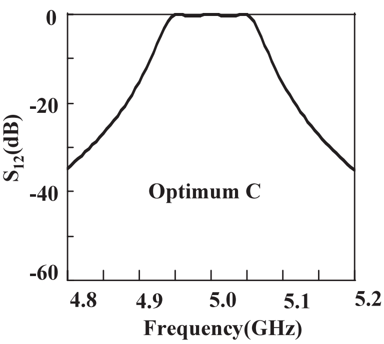
Fig. 3 Configuration of comb-type filter with three resonators and its equivalent circuit.

meet the specifications of the filter by using the S-NAP circuit simulator. Next, we calculated the filter characteristics by changing the values of C_1, C_2, and C_3. The changes in C_1, C_2, and C_3 were assumed to be 1% or 2%. Figure 4 shows results for (a) the optimum C, (b) a 1% reduction in C_1, and (c) a 1% reduction in C_1 and a 2% reduction in C_2. The filter characteristics changed greatly as C changed. We normalized the simulation data by using the same process described in 2.1. We entered these data in the trimming library. Here, L does not change. The reason is as follows. We used a sapphire trimming rod to restore the filter characteristics. Since the L element shown in the equivalent circuit in Fig. 3(b) cannot be changed, we made the trimming library in which the C element changes.

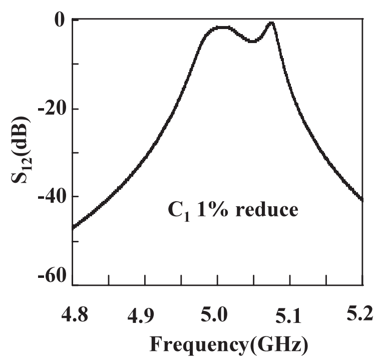
2.3 Trimming Procedure

We have already reported on the trimming technique for a forward-coupled filter using a sapphire rod [13]. The following is clear from our previous experiments: (1) The best sapphire rod position to change the resonance frequency of the resonator is the point that the maximum voltage is generated in the resonator. (2) The best sapphire rod position to change the coupling coefficient between resonators is the center of the gap between the resonators. The positions of the sapphire rod are shown as circles in Fig. 5(a). Figure 5(b) shows a schematic drawing of the trimming rod. The upper sapphire rod is connected to the shaft of the stepping motor, and it can be moved up and down smoothly. We developed an automatic tuning system.

Figures 6(a) and (b) show the model figure and a photograph of the system. The system consists of six modules that move the sapphire rods. The interval between the rod and the filter can be controlled by the stepping motors. The resolution of each stepping motor is 1 μm/ pulse. The cavity for the filter is cooled by a cryocooler. The operating temperature of the filter is 70 K.



(a)



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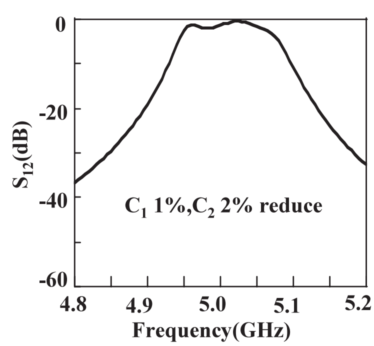
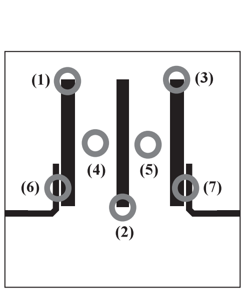
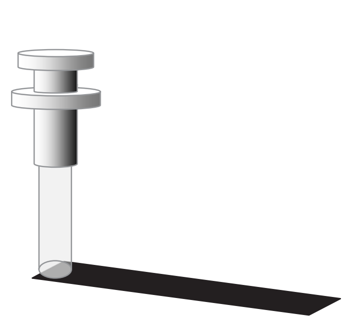


(c)

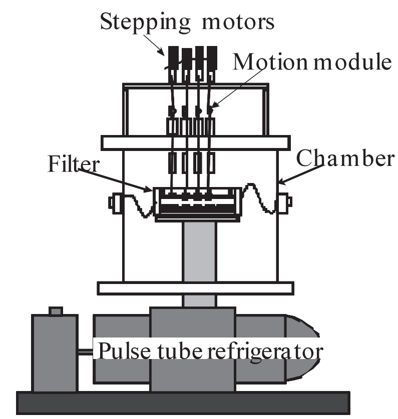
Fig. 4 Results of simulation with S-NAP circuit software: (a) optimum C, (b) 1% reduction in C_1, and (c) 1% and 2% reductions in C_1 and C_2, respectively.



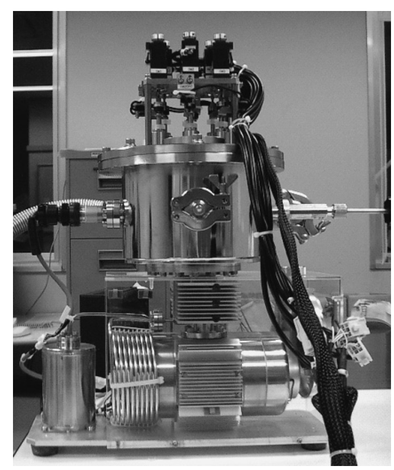


(a) (b)

Fig. 5 Schematic drawing of filter configuration of a forward-coupled filter (a) and sapphire trimming rod (b): The circles in (a) indicate the positions of the rod trimmer.



(a)



(b)

Fig. 6 Schematic drawing and picture of automatic tuning system.

3. Experimental Results and Discussion

Figure 7 shows the experimental and library data. The figure shows two trimming library data, one for which C_1 is reduced by 1% and the other for which C_1 and C_2 are reduced by 1% and 2%, respectively. We judge which library data are more suitable by referring to the following equation. The best library number was the one that gave the smallest S.

$$S = \sum_{i=1}^{3000} \sqrt{\left| \underset{i}{S}(21)mea^2 - \underset{i}{S}(21)lib^2 \right|}$$

where S(21) mea and S(21)lib are the measurement data and library data, respectively.

S was calculated for all data in the trimming library, and there were 12 library data for the forward-coupled filter with three resonators. From the calculation of S, we determined the best fit library, in which C_1 is a 1% reduction and C_2 is a 2% reduction.

Figure 8 shows the filter characteristics before and after trimming. The sapphire rods on resonators 1 and 2 (positions (1) and (2) in Fig. 4(a)) were shifted down to the prescribed height by using the stepping motor as shown in

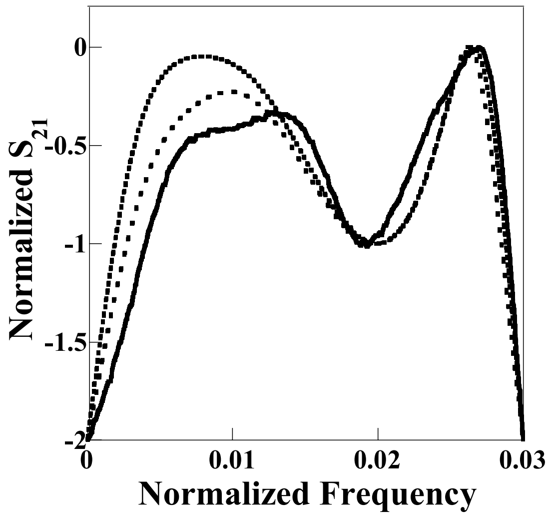


Fig. 7 Experimental and library data.

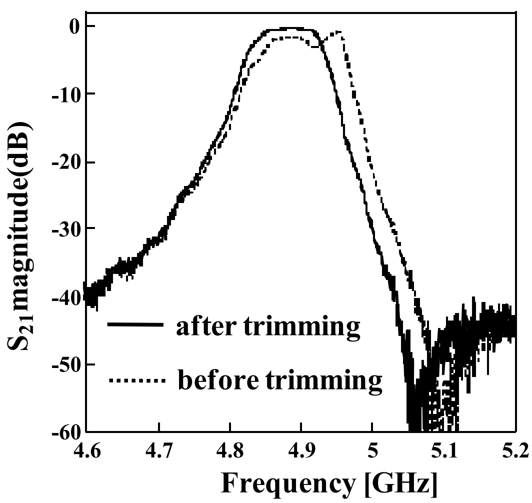


Fig. 8 S_{21} filter characteristic before and after trimming.

Fig. 6(b). As shown in Fig. 8 the trimming reduced the ripple; however, the filter characteristics are not complete. We can see that there is a limit in completing the filter characteristic only by correcting C. The adjustment of the coupling strength between the feed line (positions (6) and (7) in Fig. 4(a)) and the coupling coefficient between resonators (positions (4) and (5)) is also very important for trimming. The sapphire rod can be used to make these adjustments; however, it is necessary to correct the equivalent circuit in Fig. 3(b) for that. We are now examining this adjustment.

4. Conclusion

We examined the effectiveness of a trimming library technique for automatically trimming a forward-coupled filter with three resonators and obtained the following results.
(1) The sapphire rod trimmers were able to correct the ripple of the filter. The correction rods were set on the resonator edge and between the resonators.
(2) The effectiveness of the trimming library method was confirmed.
(3) The trimming rod should be set on the resonator edge and moved up and down.
(4) The heat inflow from the stepping motor shaft did not heat up the cavity. The operating temperature was kept below 70 K by using small cryocooler. (The refrigerating capacity at 70 K is 2 W.)

We need more resonators for an actual filter. Automatic tuning of such a filter is difficult with rod trimming. We are studying another trimming method for such filters and will report on it in the near future.

Acknowledgement

The authors would like to thanks Y. Takano and M. Yokoo of Tohoku Seiki industrial Ltd. for their technical support and K. Aizawa of Yamagata University for his helpful technical support in system fabrication. This work was supported in part by the "Research and development of fundamental technologies for advanced radio frequency spectrum sharing in mobile communication systems" fund of the Ministry of Internal Affairs and Communications of Japan, and also partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C) 18560325, 2006–2008, supported by Hoso-Bunka foundation.

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