Physica C 499 (2014) 57–62

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

An efficient tuning method for narrowband superconducting filters with interdigital capacitor resonators in the time domain

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ARTICLE INFO

Article history:
Received 21 September 2013
Received in revised form 25 December 2013
Accepted 23 January 2014
Available online 1 February 2014

Keywords:
Superconducting filter
Interdigital-capacitor resonator
Time domain
Tuning

ABSTRACT

This article proposes an effective tuning method based on the time domain for improving the performance of high-temperature superconducting (HTS) bandpass filters with interdigital capacitor resonators (ICRs). Analysis of the causes of HTS filter performance deterioration reveal that such deterioration is primarily caused by the resonant frequency deviation of the resonator of the HTS filter; this deviation results from fabrication errors and from the non-uniformity of the thickness and dielectric constant of the substrate. The sensitivity of the filter, which arises from the non-uniformity of the substrate thickness and dielectric constant, is related to the type of the resonator and the group delay characteristic of the filter. A 0.4% fractional bandwidth HTS filter with ICRs at the UHF band is fabricated and tuned using mechanical rods in the time domain. By applying this method, the resonant frequency deviation of each resonator and the coupling coefficient between resonators can be measured and tuned individually. The insertion loss of the HTS filter is improved from 1.06 dB to 0.43 dB, whereas the return loss is improved from 9.57 dB to 15.1 dB.

1. Introduction

High-temperature superconducting (HTS) microwave filters designed for mobile communication systems are characterized by having low insertion loss, high selectivity, and high band edge steepness [1–4]. Filters with interdigital capacitor resonators (ICRs) have been recently developed to realize a wide stopband performance with compact structures [4–6]. The first spurious frequency of ICRs is usually located at approximately $3f_0$ [2], and the fundamental frequency can be reduced by increasing the self-capacitance [4–6]. Thus, ICRs are suitable for designing wide stopband filters at a low frequency. HTS filters with ICRs demonstrate both high in-band and wide stopband performance [4]. However, the non-uniformity of the substrate materials, along with fabrication errors, degrades the filter performance.

Numerous tuning methods have been proposed for improving HTS filter performance [7–14]. Most of these studies have focused either on tuning the center frequency (CF) and the bandwidth or on improving the in-band performance of the filter [7–11]. Although dielectric plate method can effectively adjust the CF of HTS filters [7], waveguides and electric pads have also been used in tuning the CF and the bandwidth [8,9]. Ohshima et al. constructed a trimming library by using a dielectric plate and trimming rods to improve HTS filter performance [10]. Mechanical rods, which have great flexibility and excellent tuning effect, are often used to tune HTS filters [11–13]. However, few studies have analyzed the inconsistency between the initial measured in-band performance of the HTS filter and the simulated results. The majority of reports have used tuning methods based on the frequency domain, which is a trial-and-error process. Few papers have discussed the effect of the resonant frequency deviations of the resonators and the tuning effects of mechanical rods in the time domain.

This paper describes in detail a mechanical tuning method based on the time domain for coupled resonator filters, such as filters with lumped LC resonators, coaxial line resonators, cavity resonators, or microwave waveguide resonators. The tuning effects of the dielectric and metallic rods are calculated and analyzed. The proposed method is more effective and less complex than tuning in the frequency domain. In the time domain, the resonant frequency of each resonator and the coupling coefficients between resonators can be distinguished accurately and adjusted individually. In fact,

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http://dx.doi.org/10.1016/j.physc.2014.01.009
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the tuning mechanism is resonant frequency tuning and coupling coefficients tuning so that this method could be widely used no matter what response type of the coupled resonator filters, which include Chebyshev response, quasi-elliptic response and, Butterworth response and so on. In addition, this study analyzes the resonant frequency deviation of the resonator, which is primarily caused by the non-uniformity of the substrate thickness and dielectric constant. The deterioration of the filter in-band performance caused by the resonant frequency deviation is discussed. The sensitivity of the filter performance is related to the type of the resonator and the group delay characteristic of the filter. Basing on the group delay performance, we can predict the level of consistency between filter design and fabrication. Tuning refers to the effective correction of the resonant frequency deviation. A 0.4% fractional bandwidth HTS filter with the ICRs is tuned to demonstrate the effectiveness of the proposed method, and the in-band performance of this filter is significantly improved after such fine-tuning.

2. Sensitivity analysis of the filter performance with non-uniform substrate

2.1. Resonant frequency deviation of different types of resonators

The resonant frequency of a resonator can change after fabrication because of fabrication errors and the non-uniformity of the substrate thickness and dielectric constant [11,13]. Three types of resonators, namely, interdigital capacitor, twin spiral, and meander line types, are selected to show the sensitivity of the filter to resonant frequency deviation. The resonators are simulated using Sonnet electromagnetic software to illustrate different resonant frequency deviations. The original resonant frequencies of the three resonators are all 500 MHz, the dielectric constant of the substrate is 9.73, and the substrate thickness is 0.51 mm. The structure layouts of the three types of resonators are shown in Fig. 1. The simulation results of the resonant frequency deviation are shown in Tables 1 and 2, which illustrate that variations in substrate thickness and dielectric constant can cause resonant frequency deviation of the resonators. Results show that the change in resonant frequency deviation ranges from 0.22 MHz to 0.75 MHz and from 0.14 MHz to 10.6 MHz when $\Delta\varepsilon = \pm0.01$, ±0.02, ±0.03 and $\Delta d = \pm0.01, \pm0.02, \pm0.03$, respectively. Among the three types of resonators, ICR has the least sensitivity to resonant frequency deviation because of the changes in substrate thickness and dielectric constant. This finding indicates that substrate uniformity and the type of the resonator are important factors that affect the resonant frequency deviation of the resonator.

Table 1
Simulated resonant frequency deviation of the resonator with the variations of the substrate dielectric constant.

Dielectric constant (ε)	9.7	9.71	9.72	9.73	9.74	9.75	9.76
Deviation of the resonant frequency (MHz)							
Interdigital capacitor	0.7	0.46	0.22	0	−0.24	−0.48	−0.7
Twin spiral	0.74	0.48	0.24	0	−0.24	−0.48	−0.72
Meander line	0.75	0.5	0.25	0	−0.25	−0.5	−0.75

2.2. Degradation of in-band filter performance with different resonant frequency deviations

The resonant frequency deviation of the resonator has a significant effect on the performance of narrowband HTS filters, particularly on the in-band performance. A six-pole Chebyshev prototype filter (CF: 500 MHz; bandwidth: 2 MHz; pass-band ripple: 0.01 dB; and return loss: 26 dB) is designed to illustrate this effect.

Table 3 shows that when the resonant frequency deviation of the first resonator is changed from ±0.2 MHz to ±2 MHz, the corresponding in-band return loss changes from −14 dB to −2 dB, as shown in Fig. 2. The curves of a–f in Fig. 2(A) denote the deterioration of S11 when the resonant frequency of the first resonator

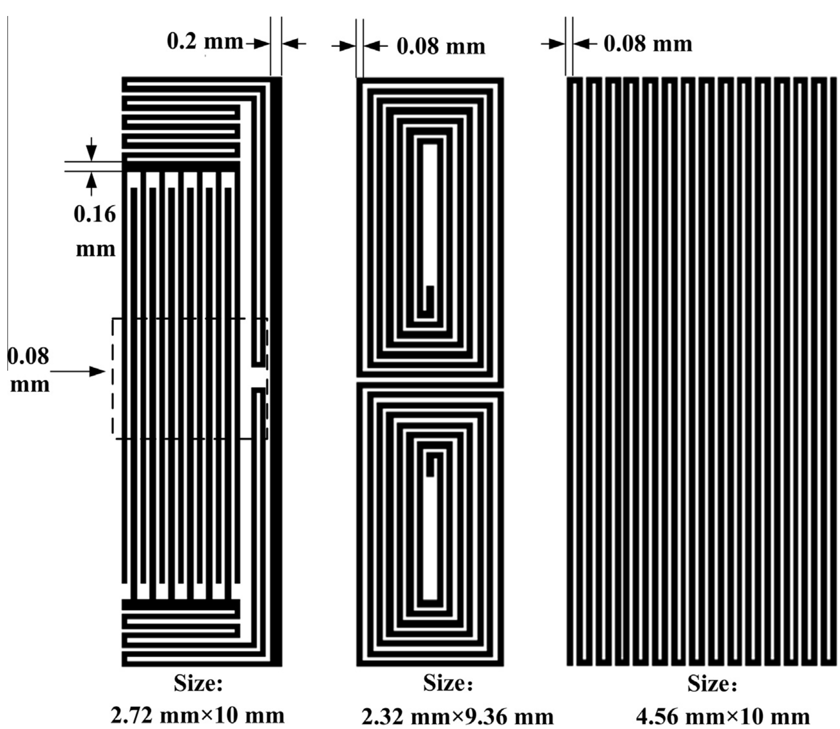

Fig. 1. The structures and sizes of three resonators: interdigital capacitor, twin spiral and meander line.