Superconducting Microstrip Filters Using Compact Resonators with Double-Spiral Inductors and Interdigital Capacitors

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Abstract — **Novel resonators composed of double-spiral inductors and interdigital capacitors are developed, which not only are compact in size but also have no harmonics up to three times of the fundamental frequency. The center frequency is insensitive to the thickness of the substrate. A miniature seven-pole narrow-band HTS bandpass microstrip filter has been designed, fabricated and tested for an astronomy observation application, which requires a center frequency at 610 MHz and 0.82% fractional bandwidth. The computed and measured results are found in excellent agreement.**

I. Introduction

High-Temperature Superconductor (HTS) filters are having wider and wider applications in the wireless communications industry because of the desirable small insertion loss, steep skirt and high out-of-band rejection. Recently the Jodrell Bank Observatory, UK has been looking at using HTS filters for the observation of pulsars. The pulsars radiate a lot of energy at the UHF band. The problem for radio astronomy is the interference from the ever-increasing number of transmitters using adjacent bands, such as television channels. High performance narrow-band filters with very sharp responses are required to maximize the receiver bandwidth, whilst removing the adjacent interferers without adding significant noise. The receivers at the observatory work at a temperature of around 20K, so the cooling is already available.

In many applications, including the above, keeping the filter structure to a small size is very important. This makes the required weak coupling a challenge in the case of narrow-band microstrip filter design; this is due to the slow decay of the electromagnetic fields between traditional resonators [1]. The parasitic cross coupling among non-adjacent resonators can also be quite severe in this situation. Keeping the resonators far apart will enlarge the circuit unattractively.

In this paper, novel resonators composed of double-spiral inductors and interdigital capacitors are proposed. They are not only small, but also have a spurious passband shifted to very high frequency. The resonators hold most electric and magnetic energy near the surface of the substrate. This makes the coupling between non-neighboring resonators very weak. The design and measurement of a seven-pole filter using these resonators is described.

II. Realization of the Resonator

In traditional half-wavelength straight resonators, at resonance, the current is stronger in the middle of the resonator, whereas positive charge mainly exists at one end, and negative at the other, as shown in Fig. 1(a). In other words, the maximum electric field exists at both ends of the resonators, whilst the maximum magnetic field in the middle. It is possible to dramatically miniaturize the size of devices by bending the traditional half-wavelength straight resonators into two or more sections and loading with interdigital capacitors [2]-[6]. However, there are many drawbacks in using conventional meander lines, when many more turns are needed to realize low frequency filters at the UHF band. For example, in the traditional zigzag resonator, as shown in Fig. 1(b), the currents in neighboring legs in the middle of the resonator are very strong. But they are of opposite directions, partly canceling the inductance. Thus less magnetic energy is stored compared to the straight resonator. Also, at both ends of the zigzag resonator neighboring legs have charges of same polarity, reducing the capacitance.

The proposed resonators are shown is Fig. 2. They are symmetrical double-spiral (spiral-in-spiral-out) inductive lines loaded with interdigital capacitors. The proportion of the inductive spiral section, relative to the capacitor is optimized by simulation [7] so as to produce the smallest size resonator. It is demonstrated in the Fig. 2 that the middle of the resonator, where the current is strongest, is at the outmost of the structure. Hence the negative mutual inductance will not deteriorate the size of the structure too much. The advantage of these resonators is that the capacitance between the ends is very strong and most electric energy is stored between the interdigital lines and

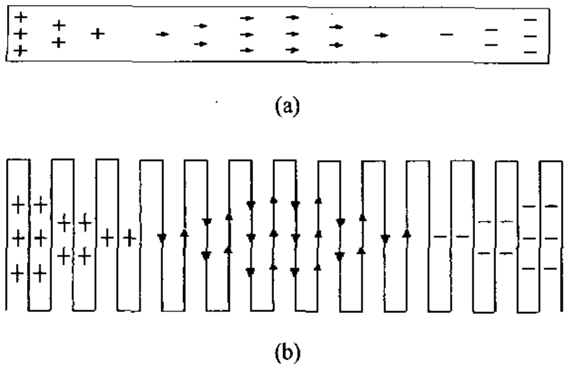


Fig. 1. Current and charge distribution when (a) conventional straight resonator and (b) zigzag meander line resonator are resonant.

most magnetic energy is held in the area of the double-spiral lines. Thus most energy at the resonant frequency is concentrated near the vicinity of the resonator. This weakens the coupling between resonators, thus enabling the design of narrow-band filters. Another merit of the resonators is that their first spurious passband is at up to triple the fundamental resonant frequency. This is because at its second harmonic frequency, the ends of the resonators have charges of the same polarity, so the capacitance in the interdigital fingers has little effect. Due to the energy distribution discussed above, the resonators are also not sensitive to the thickness of the substrate, whereas this is a problem for many other microstrip resonators and filters. For example, the resonator discussed below has a center frequency of 610 MHz. When the thickness of the MgO substrate changes from 500 μm to 490 μm it is confirmed by simulation [7], that the center frequency will shift only 33 KHz, which is small compared with most other resonators.

One such resonator, with a center frequency of 610 MHz, is fabricated on a 10 mm × 10 mm × 0.5 mm MgO substrate using double-sided $YBa_2Cu_3O_7$ HTS thin film on both sides of the substrate. The size of the resonator is 2.35 mm × 5.05 mm, and the line width and gaps are 50 μm. The unloaded Q of the fundamental mode at different temperatures and input powers is illustrated in Fig. 3. The highest value at 30K and an input power –30dBm is 200,000. The second harmonic peak appears at 1.876 GHz, which is more than three times of its center frequency. The critical temperature is about 86K. Input power levels should be regarded to be arbitrary units since the relation between input power and energy stored in the resonator depends on the coupling.

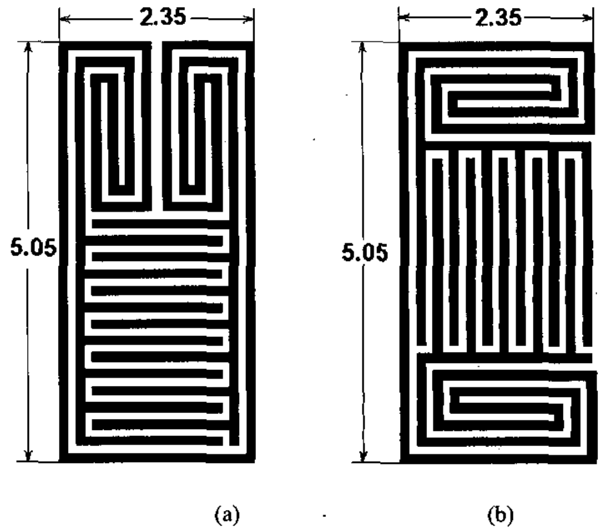


Fig. 2. Layout of two example resonators composed of double-spiral inductors and interdigital capacitors. The dimensions are in millimeters and the diagram is not to scale.

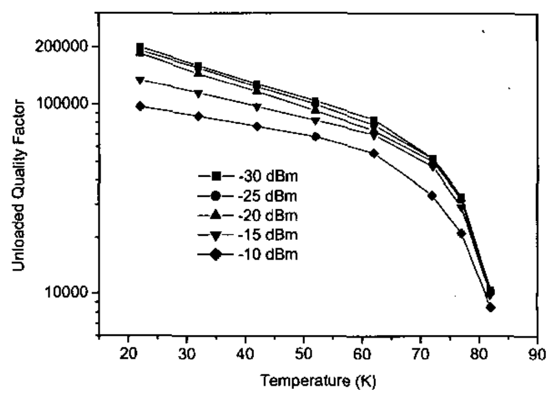


Fig. 3. Measured unloaded quality factor of the resonator over different temperatures and input powers.

III. Filter Design

The filter is initially developed to meet the following specifications proposed by the Jodrell Bank Observatory:

Center frequency: 610 MHz
Passband: as wide as possible (not precisely specified)
Insertion loss: 0.5 dB max
Return loss: 15 dB min
Out-of-band rejection:
40 dB min at 606 MHz and 614 MHz

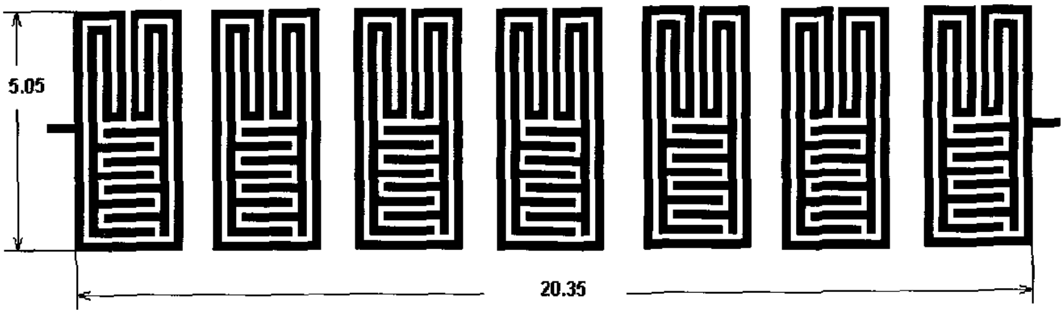


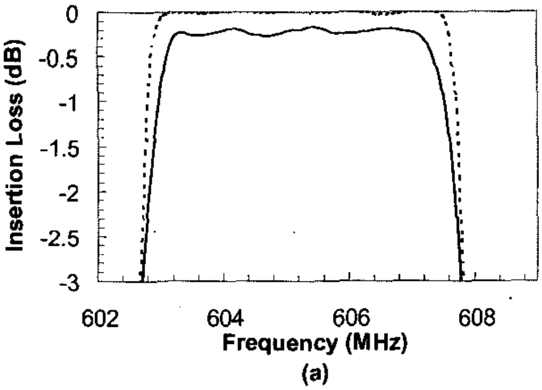
Fig. 4. Layout of a seven-pole microstrip filter using the novel resonators. Dimensions are shown in millimeters and the diagram is not to scale.

A seven-pole filter with 0.82% fractional bandwidth is designed using these resonators. The layout of the filter is shown in Fig. 4. The main circuit of the filter only has an area of about 5.0 mm × 20 mm. The design procedure can be found in [8] and [9].

IV. Experimental Results

The filter is fabricated on a 32 mm × 10 mm × 0.5 mm MgO substrate. The circuit is bonded onto a titanium carrier which is fixed into a titanium housing. Both the carrier and box are plated with 6μm thick gold. The HTS feed-in line of the filter is also covered with gold. Dielectric screws are used for tuning the filter.

The experimental and simulated lossless responses are shown in Fig. 5. The simulated performance shown in Fig. 5 is actually shifted down 4.7 MHz as the measured center frequency is a bit lower than the specification. This shift can be corrected in a second design. The filter is tuned at 26K. In the passband, the ripple is about 0.1 dB, the maximum passband insertion loss is less than 0.3 dB, and the minimum return loss is about 20 dB after tuning.



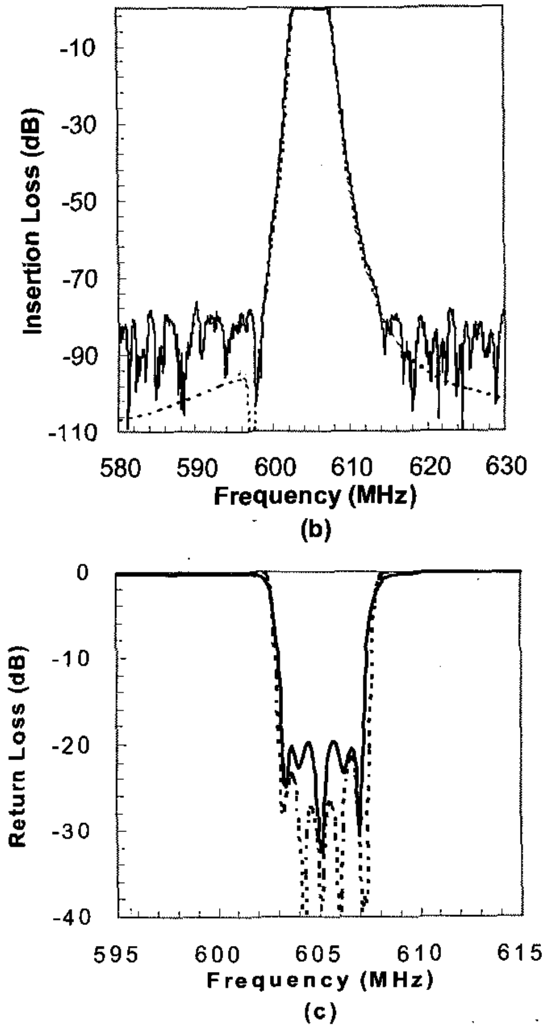


Fig. 5. (a), (b) Measured (solid line) and simulated (dashed line) insertion loss and (c) measured and simulated return loss of the seven-pole filter. The simulation response is lossless and is shifted down 4.7 MHz. The filter is tuned at 26 K for the measured responses.

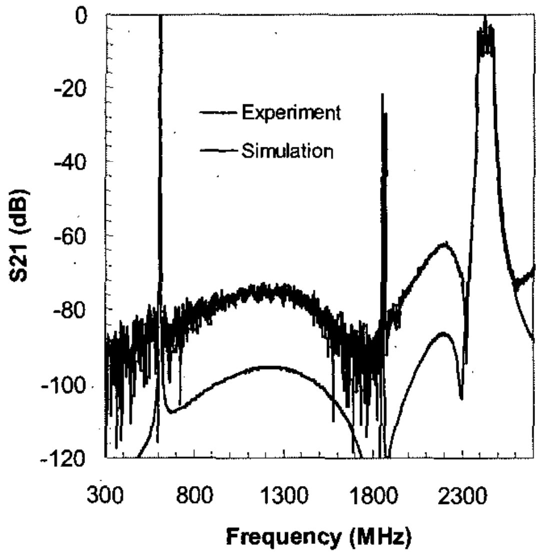


Fig. 6. Wide-range measured and simulated responses of the seven-pole filter.

The 3 dB bandwidth of the passband is about 5 MHz. Before tuning, the maximum insertion loss is about 0.7 dB, and the minimum return loss is about 9.5 dB in the passband. As demonstrated in Fig. 6, the out-of-band rejection is very exceptional at 75 dB, and the first spurious frequency appears at 1.88 GHz, which is three times of the fundamental passband frequency.

Aside from the shift of center frequency, the 40 dB bandwidth of the experimental response is about 8.75 MHz, which is a little wider than expected. The small discrepancy between the simulated and measured responses has not yet been explained. As indicated before, the variations of substrate thickness is ruled out as a major problem. It is also noticed that the center frequency of the filter changes with temperature from 605.3 MHz at 20K to 602.0 MHz at 70K, while the simulator [7] does not distinguish between the two temperatures by ignoring the kinetic inductance effects.

V. Conclusion and Future Work

Novel resonators composed of double-spiral inductors and interdigital capacitors have been introduced. The unloaded quality factor is up to 200,000 at 22K. A very compact seven-pole narrow-band UHF filter using these resonators has been designed, constructed and tested. Measurement shows a 0.25 dB insertion loss, a 20 dB return loss and a very strong out-of-band rejection of 75 dB. The second harmonic passband is moved to triple its center frequency. The overall experimental performance is very good and agrees well with the simulated responses. The outcome of the measured filter proves that the novel resonators hold promise for applications of compact narrow-band filters.

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