Ultra-Compact Superconducting Narrow-Band Filters Using Single- and Twin-Spiral Resonators

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***Abstract*—Superconducting filters using spiral resonators have been demonstrated. Compared with meander lines, errors in track width have a smaller effect on the total inductance; fabrication tolerance, simulation accuracy, power handling, and quality factor are consequently improved. The coils do not require air bridges, which are difficult to produce in superconductors. The devices can be designed using a standard procedure based on the coupling coefficients between resonators and coupling to source and load. Fourth- and sixth-order Chebyshev filters employing single and twin spirals are demonstrated for 0.86% bandwidth filters with center frequency of approximately 1750 MHz. A new coupling structure has been introduced for the single-spiral resonators. Despite the very small size of approximately 1.7 × 1.7 mm, the resonators have a quality factor of approximately 30 000 at 77 K and the filters can handle approximately 20 mW.**

***Index Terms*—Filter, low loss, miniature, narrow-band, superconductor.**

I. INTRODUCTION

MICROWAVE lumped-element filters have become competitive with the advent of superconductors, which have permitted devices to be miniaturized to much less than a wavelength without introducing prohibitive attenuation. A spiral inductor usually requires a bridge so designs have often resorted to meander lines [1] and single-turn inductors, which can have a reasonable effective inductance (i.e., reactance slope $dX/d\omega$) [2] when in combination with parallel capacitors. Self-resonant spirals have a similar size to lumped elements, but do not necessarily require a bridge, and have been proposed [3] and implemented [4], but without a systematic design procedure. In [5], a filter was modeled using lumped elements, but the model does not appear to have been actively used for filter synthesis. Other miniaturized filters are reported in [6]–[8].

This paper considers two microstrip spiral filters with geometries illustrated in Figs. 1 and 2. (Stripline or coplanar lines may also be possible.) In the first layout, each resonator consists of a narrow half-wavelength line bent into a twin spiral, with the two ends of the line in the center of each spiral, but the center of the line available for input and output taps via T-branches. This was proposed in [4] to provide the small coupling coefficient required. A new coupling mechanism is provided in Fig. 2: apart from the four isolated resonators (single spirals), there are two additional quarter-wavelength spirals whose main purpose is external coupling via the magnetic fields.

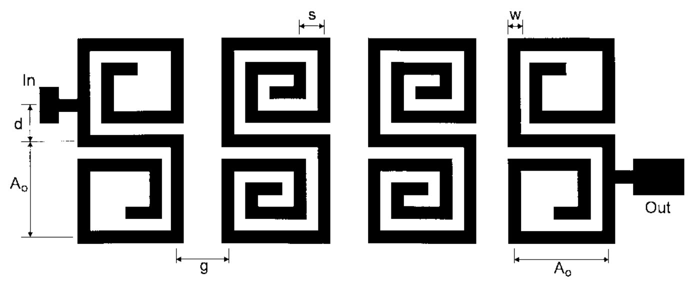

Fig. 1. Twin-spiral filter layout. For simplicity, only a fourth-order filter is illustrated. Dimensions A_0, s, and g are measured between track center lines. (Not to scale; each spiral actually has approximately seven turns).

The field patterns of straight microstrip and microstrip spirals are compared in Fig. 3. As the width of microstrip is miniaturized, the electric and magnetic fields become more concentrated near the microstrip. The region where energy is stored, therefore, decreases in two dimensions, i.e., *disproportionately*. In contrast, the fields under the spiral have a significant magnitude all the way down to the ground plane because of the mutual inductance between tracks and their combined electric field. Meander lines are even worse than straight microstrip in this respect because adjacent lengths of the track have currents traveling in opposite directions, which confines magnetic fields even more. Consequent advantages of spirals are as follows.

- Over-etch of the tracks only affects the fields near the surface; the significant fields deeper in the substrate are not affected so that filter parameters are not greatly changed.
- In simulations, using only one cell in the whole width of the track still gives quite accurate results for the same reason.
- Larger energy storage for the same maximum RF magnetic field improves the power-handling capability of the devices.
- The greater energy storage for the same current densities improves the quality factor.
- Fields are also larger at a greater distance above the spirals, permitting easier tuning. The accompanying increase in loss due to induced currents in the normal-metal housing is very small in the filters considered here.

A crude calculation using a parallel set of lines carrying equal currents indicates that a spiral size of $A_0 = 8h$ is required for over-etch insensitivity and energy density to reach about half the value of a very large spiral. The resonators to be described here are smaller, but nevertheless achieve an estimated factor of

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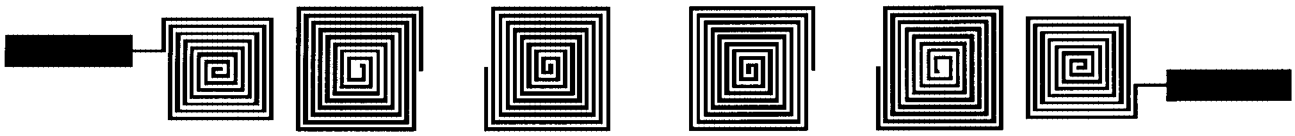

Fig. 2. Single-spiral filter layout. Input and output are on the extreme left-hand side and right-hand side (approximately to scale).

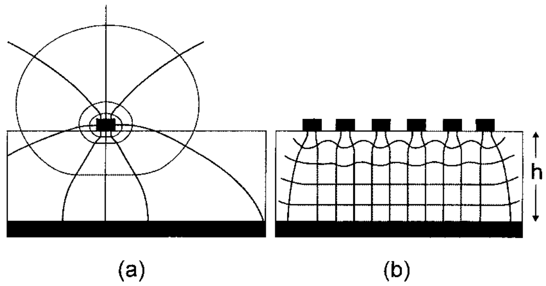

Fig. 3. Field patterns in: (a) a narrow microstrip and (b) part of a spiral, where all currents are in the same direction.

two improvement over microstrip in the first four of the above features.

II. Simulations for Coupling Coefficients

Using full-wave simulation by commercial software ("SONNET-LITE"), coupling coefficients k [9] and external coupling k_e were evaluated. ($1/k_e$ is the external quality factor Q_e [9].) Kinetic inductance was ignored. Initially, the lossless case was considered. The values were later used to build up larger multiresonator filters; design equations are given in [9]. First, a suitable resonator size was found by trial and error. Taking a cell width equal to w, and for a substrate thickness $h = 0.5$ mm, relative permittivity 9.65, linewidth $w = 0.05$ mm, and center-to-center separation $s = 0.1$ mm, a twin-spiral resonator with resonance $f_0 = 1755$ MHz was found with $A_0 = 1.4$ mm, while for the single spiral, $f_0 = 1751$ MHz when $A_0 = 1.7$ mm. Varying the cell widths and then extrapolating to zero, f_0 becomes 1760 and 1740 MHz, respectively; these values could have been readjusted by changing the lengths of the spiral.

To find k, a typical layout consisted of two resonators, one capacitively connected to an input line and the other to an output similar to [6]. With very low external loading, the frequency response $|s_{21}|$ had two very sharp peaks separated by Δf and mean frequency f_0; in the narrow-band limit, $k = \Delta f / f_0$ [9]. Using a cell width equal to w in simulations, several runs could be done rapidly so that k was found as a function of resonator separation g (Fig. 4). Values of k for larger gaps are also required to confirm that unwanted coupling between nonadjacent resonators is small enough. For typical gaps (>3 mm for twin spirals and >4 mm for singles), k is less than 0.2×10^{-3}. Investigating this unwanted coupling using a lumped-element model confirms that the effect on filter performance is small for the filters considered here.

There is more than one way of finding k_e. Using a structure similar to Fig. 1, but with only two well-separated resonators, the simulated $|s_{21}|$ showed a resonance whose peak value and

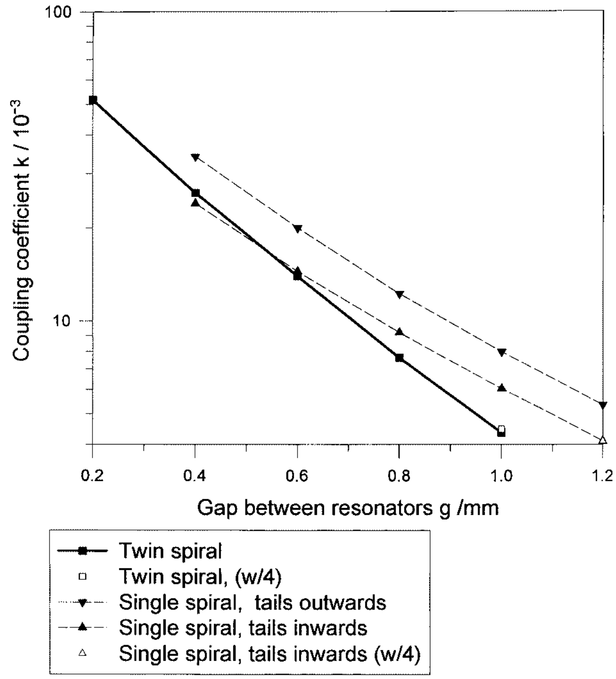

Fig. 4. Coupling coefficient as a function of resonator separation. "Tail" refers to the end of the track on the outside of the spiral. Cell width = w, except as specified in the key. There is an extra filled triangle obscured by the white one.

3-dB bandwidth were used to find k_e with the help of graphs prepared from a simple lumped-element model. (These simulations could also have yielded k). To find k_e for single spirals, the structure simulated consisted of an input coupler and only one resonator separated by gap g, similar to the left-hand-side portion of Fig. 2, and a weakly coupled output line. As the output did contribute to the resonator loading, k_e was evaluated by comparing the peak $|s_{21}|$ and 3-dB bandwidth with a lumped model. The results are given in Fig. 5. For the twin spiral, larger values of k_e, up to 79×10^{-3} (not shown) can be obtained by tapping it from the top or the lower left-hand side (left-most resonator in Fig. 1). Values smaller than 11×10^{-3} are not possible, as the center of the resonator is not accessible to a tap; an asymmetrical arrangement would be required.

The portion of a twin-spiral resonator between one inner end and the tap point forms a quarter-wavelength resonator, introducing a spurious response at a frequency slightly higher than the main resonance, while the portion between the tap point and the other end gives a lower frequency resonance. This was the reason for opting for the more complicated two-resonator arrangement in the first case, the structure having been found from simulations to give reasonable results. These spurious resonances are also believed to be responsible for fortuitous stopband zeros in the simulated response of one of the filters to be described (Fig. 6).

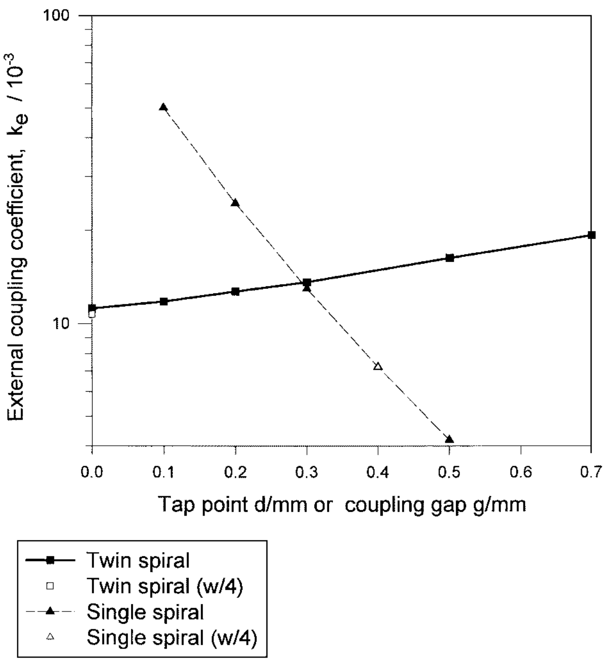

Fig. 5. External coupling coefficient k_e. For the twin spiral, it is a function of tap point d, while for the single spiral, it depends on spacing g.

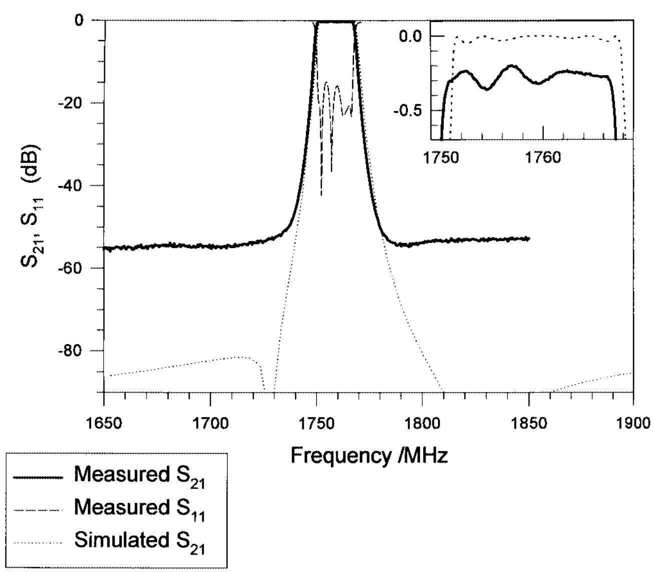

Fig. 6. Measured (77 K) and simulated responses of the twin-spiral six-pole filter designed as a Chebyshev filter with 0.05-dB ripple and 0.86% fractional bandwidth. Inset shows the passband magnified.

When the twin spirals are tapped, the resonant frequency falls. A graph of frequency shift against d (not shown) was generated; it was found that the 5-MHz shift (for $d = 0$) could be corrected by shortening the line, removing a length $7w$ from the center of each spiral.

Some indication of tunability with metal screws can be seen from lowering the roof of the cavity. At a height of 1 mm, resonance increases by 4 and 9 MHz, respectively, for the two types of resonators, while the values of Q associated with the roof resistance (arbitrarily chosen to be room-temperature gold $R_s = 0.0126\ \Omega$/square) are 40 000 and 30 000. Dielectric pucks provide a much more restricted tuning range.

Other miscellaneous simulation results are summarized as follows. A straight half-wave resonator with the same w would have a length of 36 mm, and about half the value of Q, assuming that current crowding is the same in the two cases. A meander line would have three times the area of the single spiral and about a fifth of the Q. Doubling the number of turns (and, consequently, doubling A_0) reduces f_0 by a factor of approximately four.

Further data was obtained from user-written method-of-moments software similar to [10]. The coil is divided into cells, each with an unknown voltage and current. Interactions are modeled by electrostatic and static magnetic equations, and solved by matrix or eigenvalue techniques. By deliberately omitting electric or magnetic coupling, it was found that the latter is usually the dominant mechanism, and that the two effects have the same sign. They can be made to have the opposite sign for the single spirals by making one clockwise and the other anticlockwise (these directions being defined when moving along the track from the outside to the center). This is important for future quasi-elliptic filters. For the twin spiral, an over-etch, which reduces w to 0.048 mm makes f_0 fall by 0.7 MHz, and if h is reduced to 0.48 mm, f_0 shifts down by 7.6 MHz. If ε_r is only 9.6, then f_0 rises by 4.2 MHz. These fabrication sensitivities are expected to be similar for the other spiral.

III. Design of Filters and Measured Results

As a first attempt, three ultra-miniature filters with relatively modest specifications were fabricated, with center frequencies, as above, and 0.86% bandwidth. The simplest one has been reported briefly as a preliminary finding [11] and will be omitted here. Of the other two, the first was a six-pole Chebyshev filter implemented with the twin spirals. Designed maximum passband ripple was 0.05 dB, which is rather small because of the limited range of available k_e. Resonator spacing was found from Figs. 4 and 5; $d = 0$ mm, and the gaps were (Fig. 1, left to right) 0.775, 0.9, 0.925, 0.9, and 0.775 mm. The second filter was made of single spirals with four poles and a maximum ripple of 0.07 dB, as close to equi-ripple as the quantized distances on a 0.025-mm grid allowed. Gaps were 0.375, 0.9, 1.15, 0.9, and 0.375 mm. The whole filter layouts were validated by full-wave simulation ("SONNET") using a finer cell width ($w/2$ and $w/4$, respectively). By curve fitting to a lumped-element model, the parameters of these filters were estimated to find any errors. Only the values of f_0 of the individual resonators required realignment, by less than 1 MHz, which was done by removing a length of up to $3.5w$ from the center of each spiral. Overall dimensions, excluding a margin to avoid interaction with the box walls, were 13 mm × 2.8 mm and 14 mm × 1.7 mm. The substrate was 0.5 mm-thick MGO, with 600 nm of YBCO on each side. Packaging details and measurement techniques are similar to [11] and [12]. Calibration at room temperature used standard short, load, etc. placed in the cryostat, with a 0.45- or 0.48-dB correction added to allow for the temperature (77 and 30 K, respectively), as determined in a separate run. A thru-reflect line (TRL) calibration using a substrate similar to the filters has not yet been done.

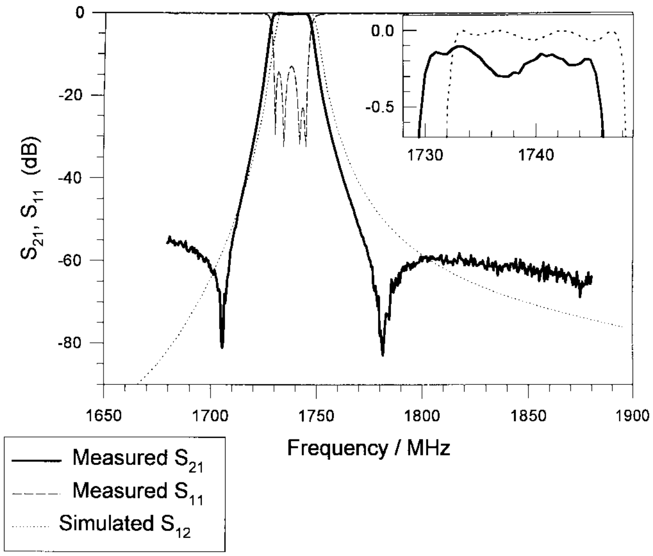

Fig. 7. Measured (77 K) and simulated responses of the single-spiral four-pole filter designed as a Chebyshev filter with 0.07-dB ripple and 0.86% fractional bandwidth. Inset shows the passband magnified.

Responses at 77 K are shown in Figs. 6 and 7. Maximum loss is 0.35 dB, which is comparable to less compact superconducting devices. The simulated results have been shifted to correct for the error in the center frequency, as estimated by extrapolation, as previously described. They assume zero loss. The remaining small frequency offset may be due to kinetic inductance, which was not included in the simulations. Overall the agreement is excellent. Furthermore, the double-spiral device has the same passband as [11] to a small fraction of a megahertz, showing good repeatability at least in the same wafer. The twin-spiral device has a "second" harmonic response at approximately 2600 MHz, as in [11], but below this frequency, the stopband response is below -50 dB. This single-spiral filter's stopband remains below -40 dB up to at least 5500 MHz. The somewhat high stopband response in Fig. 6 and the fortuitous transmission zeros in Fig. 7 may be related to the packaging, which was not accurately simulated. The zeros are not yet under the control of the designer. At 30 K (not shown), the responses shift to the right by approximately 5 MHz, the minimum loss is halved, and the response is flatter (because at 77 K, the small resistive loss affects the band edge more than the center), consistent with [11].

Power capability was estimated by comparing two $|s_{21}|$ measurements in which a filter was cascaded with an amplifier. In one case, the filter came first and, in the other, the amplifier was placed first so that the filter saw a greater power input. At 77 K, the filters experienced a compression of only approximately 0.1 dB at 20-mW input power. This level of loss corresponds to a fall in Q of the order of half. The compression was not measurable at 30 K. It would be expected to get worse as filter order increases. Intermodulation measurements have not yet been performed.

There had been evidence with different filters, which also had narrow tracks [12], that the resonators on the same wafer might have widely varying Q factors so the Q's of individual resonators, or at least small groups of resonators, were of interest. Normally source and load losses dominate so these were replaced by capacitive probes. Even the K connectors had to be disconnected to avoid losses in the dielectric and microwave epoxy joints. With only very weak coupling to input and output, a narrow-band fourth-order filter (for example) shows four close, yet distinct resonant peaks at ω_1, ω_2, ω_3, and ω_4, each with a different value of $q_n = 1/Q_n$, $n = 1, \ldots, 4$. $1/Q$ is approximately (power dissipated)/($\omega \times$ energy stored), and the four values of ω are nearly equal, leading to four equations of the form

$$q_n = \frac{I_{n,1}^2(R_1 + R_4) + I_{n,2}^2(R_2 + R_3)}{\omega L 2(I_{n,1}^2 + I_{n,2}^2)} \qquad (1)$$

where $R_1, \ldots, R_4$ and $I_{n,1}, \ldots, I_{n,4}$ are the resistances and currents of the individual resonators in the lumped-circuit equivalent, which have equal inductance L and negligible mutual inductance; in a typical symmetrical filter, $I_{n,1} = I_{n,4}$ and $I_{n,2} = I_{n,3}$ so $I_{n,4}$ and $I_{n,3}$ have been eliminated from (1). The currents can be found from simulation; only ratios of currents are required

$$q_n = \frac{I_{n,1}^2}{I_{n,1}^2 + I_{n,2}^2}\left(\frac{r_1 + r_4}{2}\right) + \frac{I_{n,2}^2}{I_{n,1}^2 + I_{n,2}^2}\left(\frac{r_2 + r_3}{2}\right) \qquad (2)$$

where r_1 is the value of $(1/Q)$ of an individual resonator, i.e.,

$$r_1 = \frac{R_1}{\omega L}. \qquad (3)$$

Four equations are available, of which only two are required in a matrix inversion to find $(r_1 + r_4)/2$ and $(r_2 + r_3)/2$, which are the average values of $1/Q$ of pairs of resonators. It is not possible to resolve between r_1 and r_4 because their coefficients in an augmented matrix are equal. This equation is easily generalized to any order filter. It was checked for the two filters by full-wave simulation: the values of q_n were evaluated after including known values of r_1 and r_2, giving coefficients of the matrix without finding the currents.

The matrix is somewhat ill conditioned so the Q values evaluated are approximate (Table I). Q's of isolated resonators, which were fabricated on the same wafer, were found in the usual way from bandwidth and insertion loss, and are included. They confirm that there are no large variations at least within the same wafer so device performance should be predictable as far as resonator losses are concerned. Simulations indicate that the Q of single spirals should, in fact, be slightly higher than twin spirals, as expected because the region of maximum current in the twin spiral is on the outermost turn, where current crowding is asymmetrical. The reason for the discrepancy between simulation and measurement is not known. Wafer-to-wafer reproducibility has not yet been addressed.

The prospect of mechanical tuning was investigated by placing a gold-plated ceiling approximately 0.8 mm above the single-spiral device. This caused a 13-MHz shift (corresponding to the simulated result for 0.9 mm), and a much flatter response, indicating reduced coupling. This demonstrates that tuning is possible in principle. Loss increased by only approximately 0.14 dB. Actual tuning is difficult: to adjust center frequencies and couplings individually, tuning screws

TABLE I
MEASURED Q'S OF RESONATORS IN THE TWO FILTERS

	77K	30K
Twin spirals	30 000 - 40 000	80 000 - 110 000
Single spirals	25 000 - 35 000	45 000 - 65 000

(Seven values of Q taken in each range above)

would be required above each spiral and above each gap, and would have to be under 1.4-mm diameter in order not to touch. Simulations showed that adjusting coupling alone with a reduced number of screws was not viable as the center frequencies were also affected. Tuning the center frequencies alone was attempted using liquid nitrogen rather than a cryostat to allow access to the screws. Adjusting the screws did indeed vary the response, but the 0.2-dB central dip in Fig. 7 could not be reduced significantly; evidently, it is not caused by misalignment in resonant frequency, which had been identified in simulations as one of the possible causes.

IV. CONCLUSION

Two resonator structures have been used to implement narrow-band superconducting filters. Simulations based on pairs of resonators to find the coupling coefficients, together with other simulations for external coupling, were sufficient for the filter design, except for an uncertainty in the resonant frequency of approximately 1 MHz (0.6 parts per 1000). Spirals have significant advantages over straight microstrips and meander lines at 1750 MHz, but these are expected to be even greater at lower frequencies where the spirals can have more turns. The twin spiral has an advantage of a faster decay of k with respect to spacing, but the single spiral is probably the preferable structure because: 1) a wider range of external coupling coefficients can be achieved; 2) the coupling spirals suppress the second harmonic; 3) they are slightly smaller; and 4) the coupling coefficient between two resonators can be positive or negative as required in possible future quasi-elliptic designs.

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