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Compact superconducting dual-log spiral resonator with high Q-factor and low power dependence

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Abstract

A new dual-log spiral geometry is proposed for microstrip resonators, offering substantial advantages in performance and size reduction at subgigahertz frequencies when realized in superconducting materials. The spiral is logarithmic in line spacing and width such that the width of the spiral line increases smoothly with the increase of the current density, reaching its maximum where the current density is maximum (in its center for 2 resonators). Preliminary results of such a logarithmic ten-turn (2 5 turns) spiral, realized with double-sided YBCO thin film, showed a -factor seven times higher than that of a single ten-turn uniform spiral made of YBCO thin film and 64 times higher than a copper counterpart. The insertion loss of the YBCO dual log-spiral has a high degree of independence of the input power in comparison with a uniform Archimedian spiral, increasing by only 2.5% for a 30-dBm increase of the input power, compared with nearly 31% for the uniform spiral. A simple approximate method, developed for prediction of the resonant frequency of the new resonators, shows a good agreement with the test results.

Keywords

HTS microwave devices, HTS resonators, logarithmic spiral, spiral inductors, YBCO thin films.

Disciplines

Computer Engineering | Computer Sciences

Compact Superconducting Dual-Log Spiral Resonator With High Q-Factor and Low Power Dependence

Zuhair M. Hejazi, *Member, IEEE,* and Peter S. Excell, *Senior Member, IEEE*

***Abstract*—A new dual-log spiral geometry is proposed for microstrip resonators, offering substantial advantages in performance and size reduction at subgigahertz frequencies when realized in superconducting materials. The spiral is logarithmic in line spacing and width such that the width of the spiral line increases smoothly with the increase of the current density, reaching its maximum where the current density is maximum (in its center for $\lambda/2$ resonators). Preliminary results of such a logarithmic ten-turn (2×5 turns) spiral, realized with double-sided YBCO thin film, showed a Q_o-factor seven times higher than that of a single ten-turn uniform spiral made of YBCO thin film and 64 times higher than a copper counterpart. The insertion loss of the YBCO dual log-spiral has a high degree of independence of the input power in comparison with a uniform Archimedian spiral, increasing by only 2.5% for a 30-dBm increase of the input power, compared with nearly 31% for the uniform spiral. A simple approximate method, developed for prediction of the resonant frequency of the new resonators, shows a good agreement with the test results.**

***Index Terms*—HTS microwave devices, HTS resonators, logarithmic spiral, spiral inductors, YBCO thin films.**

I. Introduction

APPLICATIONS of high-temperature superconductors (HTS) in resonators are crucially dependent on the reliable achievement of high-quality factors and power handling ability, avoiding nonlinear effects. At the same time, the size, weight, and cost should be minimized if they are to be commercially viable. It is known that HTS materials have the property of losing their superconductivity in any region of the conductor where the current density exceeds the critical value. Therefore, the geometry of the resonator/filter is a crucial factor in this issue [1], [2]. To increase the power-handling capability of a planar filter, widening the lines and reducing the peak surface current density has been discussed [3]. Increasing the line width provides more conductor area for carrying the current. This, however, decreases the line characteristic impedance Z_o (inversely proportional to the peak current at standing wave peaks along the length of the resonator) and the overall size of the resonator such as uniform spiral structures in particular.

Although Z_o can be increased by using thicker dielectric or lower ε_r, this may lead to higher dielectric losses and incompatibility of the dielectric material with HTS films.

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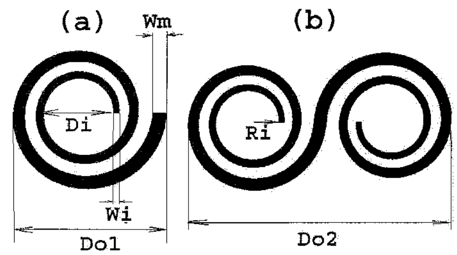

Fig. 1. Geometrical parameters of log-spiral resonators: (a) ($\lambda/4$) single log-spiral and (b) ($\lambda/2$) dual log-spiral. (The wide end of the single log-spiral has to be grounded.)

A variety of investigations has been carried out with conventional and HTS uniform Archimedian spirals, having different number of turns, line spacings, line widths, and configurations (microstrip and suspended substrate). The quality factors of the best investigated devices did not exceed 1200 at 77 K [4]–[6].

In this paper, a novel spiral geometry is proposed so that the spiral is logarithmic in line spacing and width. The width of the spiral increases smoothly to reach its maximum only where the current density is maximum. In a half-wave loose-coupled spiral resonator, a dual-log spiral (DLS) would allow a maximum width at the central part, where the current density reaches a maximum, the width decreasing logarithmically in both directions toward its ends. If the resonator has to be a quarter wavelength in length, then a single log-spiral may suffice, but the half-wavelength type has the advantage that it may avoid any electrical connection to the case or feed lines. Thus, such a DLS was investigated with the objective of increasing both the Q-factor and the power handling capability.

II. Geometry and Design Considerations

A sample layout illustrating the geometrical parameters of the proposed log-spiral resonator in single ($\lambda/4$) and dual ($\lambda/2$) options is shown in Fig. 1.

The equation for a single log-spiral in polar coordinates can be presented as

$$R = R_i q^{\Phi/2\pi} \tag{1}$$

where R is the local expansion radius, R_i is the initial inner radius, $q > 1$ is the expansion rate or incremental factor between turns ($q > 1$ for a spiral expanding in a counterclockwise direction, and *vice versa*), Φ is the rotational angle of the spiral, i.e., $0 \leq \Phi \leq 2\pi N$, and N is the number of turns. Equation (1) can also be written as

$$R = R_i e^{K\Phi} \tag{2}$$

where $K = \ln q/2\pi$. In Cartesian coordinates, (1) can be written as

$$x = R_i q^{\Phi/2\pi} \cos\Phi$$
$$y = R_i q^{\Phi/2\pi} \sin\Phi. \tag{3}$$

The total length of a single log-spiral curve is given by

$$l_{t1} = \frac{R_m - R_i}{\cos\alpha} \tag{4}$$

where R_m is the maximum outermost local radius and α is the angle subtended between the local radius at any point of the spiral line and the tangent at that point. However, since the microstrip track has a definite width, the length of the spiral conductor is the length of the central line between the bounding spiral curves. In this case, the local outermost radius of the inner curve is $R_m + W_m/2$ where W_m is the maximum outermost conductor width given by $W_m = W_i q^N$ where W_i is the initial inner width (usually given as input data together with q and N). The local initial radius is $R_i + W_i/2$. Equation (4) will then take the form

$$l_{t1} = \frac{R_m - R_i + \frac{W_i}{2}\left(q^N - 1\right)}{\cos\alpha}. \tag{5}$$

The total length of the dual spiral is thus $2l_{t1}$. The relationship between the parameters K and α is

$$K = \cot\alpha = \frac{\ln q}{2\pi}. \tag{6}$$

So, α can be found from given input data as

$$\alpha = \tan^{-1}\frac{2\pi}{\ln q}. \tag{7}$$

The inner and outer diameter of a single spiral are found to be, respectively,

$$D_i = R_i\left(\sqrt{q} + 1\right) \tag{8}$$
$$D_{o1} = (R_i + W_i)(q^{N-0.5} + q^N). \tag{9}$$

The overall outer diameter of the dual log-spiral (DLS) will be (see Fig. 1)

$$D_{o2} = 2D_{o1} - W_m. \tag{10}$$

To investigate the properties of such a shape for use as a resonator realized with HTS material, a ten-turn microstrip DLS resonator operating in the UHF band was fabricated with YBCO thin film. An identical version was also constructed with copper on "Duroid" substrate. The dimensions of the resonators were (all in millimeters): $R_i = 0.5$, $D_i = 1.112$, $D_{o1} = 8.276$, $D_{o2} = 15.779$, $W_i = S_i = 0.1$, $W_m = S_m = 0.76$, $q = 1.5$, where S_i and S_m are the initial and maximum spacing between turns, respectively. The overall dimensions of the resonator were 10×20 mm. The layout of the test resonators is shown in Fig. 2.

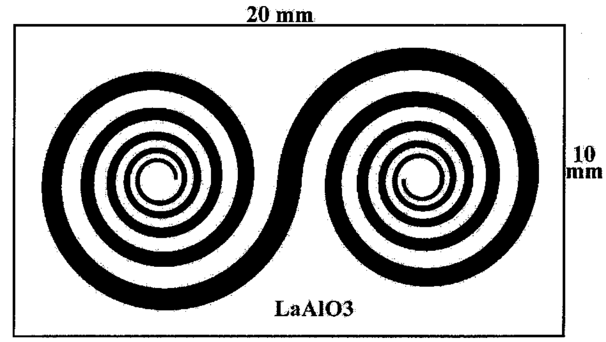

Fig. 2. Final layout of the ten-turn dual log-spiral resonators.

III. Calculations and Experimental Results

A. Resonant Frequency F_o and Unloaded Q_o-Factor

An analytical prediction of the resonant frequency of such a spiral resonator was not available to apply in the methods (described in [6]) for a uniform Archimedian spiral.

In the present case, the nonuniformity of the line width and spacing makes it impossible to apply the formulas for mutual inductance effects between spiral segments. The resonant frequency may also be predicted using electromagnetic simulation software, but standard methods are only viable if the spiral configuration is rectangular and uniform. The circular and nonuniform shape requires a high degree of grid resolution to maintain the spiral geometrical parameters in their original shape, requiring excessive computational resources. Thus, an approximate method was developed and found to give adequate practical results.

The resonant frequency of a half-wavelength microstrip line can be given as [7]

$$F_o = \frac{c}{2l_t\sqrt{\varepsilon_{\text{eff}}}} \tag{11}$$

where $c = 3 \times 10^8$ m/s and l_t is the total length of the microstrip resonator. Equation (11) can only be applied with sufficient accuracy if the correct effective permittivity is calculated. This also is a problem due to the complexity of the log-spiral shape since ε_{eff} is dependent on the total equivalent capacitance of the microstrip line and hence is very sensitive to its nonuniform width and spacing. However, a good approximation for ε_{eff} can be found using the following procedure.

For a very wide microstrip line, most of the electric field is confined to substrate dielectric [7] and, thus

$$\varepsilon_{\text{eff}} \approx \varepsilon_r. \tag{12}$$

For a very narrow microstrip line, the field is almost equally shared by the air ($\varepsilon_r = 1$) and the substrate so that

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2}. \tag{13}$$

The dual log-spiral shares both cases (very thin line at the center and very wide line on the outside of the spiral), so an average of both cases can be taken, to obtain a good approximation for ε_{eff} as

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + \frac{\varepsilon_r + 1}{2}}{2} = \frac{3\varepsilon_r + 1}{4}. \tag{14}$$

However, mutual effects due to nonuniformity of the line width and spacing may affect the effective length of the spiral and hence it becomes uncertain. Therefore, a geometric factor accounting for the nonuniformity of the spiral should be included to compensate for the variation when the line width and spacing of the dual log-spiral are nearly uniform.

This can be accomplished by averaging the width of the DLS as $W = (W_i + W_m)/2$ and its spacing as $S = (S_i + S_m)/2$. The new uniform width W and spacing S are used to create a new dual uniform Archimedian spiral with the same number of turns N and initial inner radius R_i as those of the DLS. The total length of the dual uniform-spiral is then normalized to the total length of the DLS to extract the geometric factor G, where W_m, W_i, R_i, S_i, and S_m were defined previously. Equation (11) can be rewritten as

$$F_o = \frac{c}{2 l_t G \sqrt{\varepsilon_{\text{eff}}}}. \tag{15}$$

The Q_o-factor can be calculated from the measured Q_L and insertion loss IL using the expression [8]

$$Q_o = \frac{Q_L}{1 - 10^{(IL/20)}} \tag{16}$$

where $Q_L = F_o/BW$ is the measured loaded Q-factor, F_o is the center frequency, and BW is the 3-dB bandwidth. IL is the measured insertion loss at resonance in decibels.

B. Measurement Results and Comparisons

The test HTS devices were fabricated using double-sided YBCO thin films on $LaAlO_3$ substrate. Another set of spiral resonators, identical except made of copper, was fabricated on Duroid substrates with the highest available dielectric constant ($\varepsilon_r = 10.2$). However, the resonant frequency of the HTS resonators would be expected to be lower than the copper resonators, by a factor equal to the inverse ratio of the square roots of the respective substrate permittivities.

The resonator components were placed in a metallic shield case, designed according to experimental investigations [9], [10] for optimization of shield cases enclosing spiral resonators.

The resonators were immersed in liquid Nitrogen at 77 K and measured using a vector network analyzer. Full two-port measurements were carried out because of the convenience offered by the resonator shape. The input–output loops were each located above one of the dual spirals. The input–output coupling coefficients were controlled by the height of the loops above the resonators.

A typical plot of the measured frequency responses of the copper resonator at room temperature, with 10-dBm input power, is shown in Fig. 3. The responses of the HTS resonator at 77 K and selected input powers of −10, 10, and 20 dBm, are presented in Figs. 4–6, respectively. From the plots, it can be seen that the measured F_o of the HTS resonator is 0.4225 GHz.

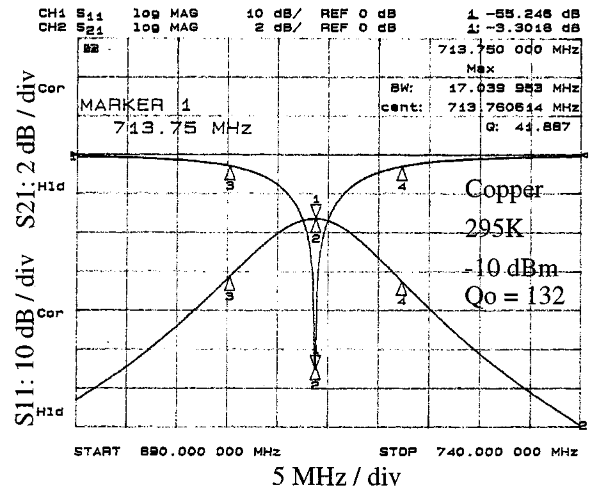

Fig. 3. Measured S_{11} and S_{21} of the copper ten-turn DLS resonator on Duroid substrate at room temperature and −10-dBm input power.

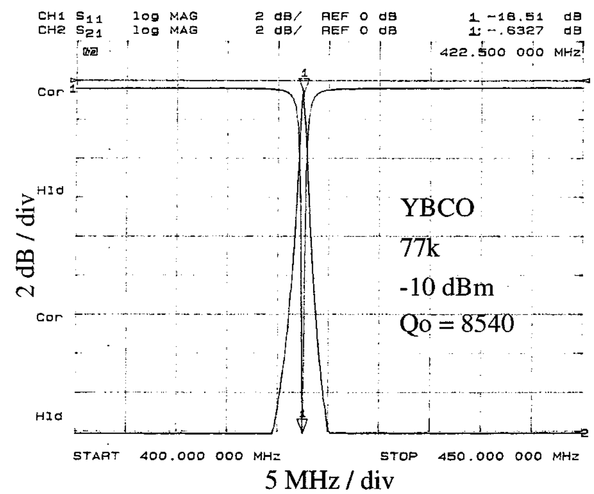

Fig. 4. Measured S_{11} and S_{21} of the YBCO ten-turn DLS resonator on $LaAlO_3$ at 77 K with −10-dBm input power.

Using $\varepsilon_r = 24$ for LaAlO3, and applying this in (14), gives $\varepsilon_{\text{eff}} = 18.25$. The total length of the HTS dual-spiral from (5) is then: $l_t = 73.684$ mm $= \lambda_g/2$. Hence, $\lambda_g = 147.368$ mm and (11) yields

$$F_o = \frac{300}{147.368\sqrt{18.25}} = 0.4765 \quad \text{GHz}.$$

The deviation from the experimental value is expected because of the uncertainty in the effective length of the spiral due to its nonuniformity.

Following the considerations in Section III-A, for the nonuniformity geometric factor, a value of $G = 1.1458$ was found, hence λ_g becomes $\lambda_g \times 1.1458 = 147.368 \times 1.1458 = 168.854\,25$ mm and then (15) yields

$$F_o = \frac{300}{168.854\,25\sqrt{18.25}} = 0.4159 \text{ GHz}$$

which is much closer to the experimental value of 0.4225 GHz. If the predicted value of $F_o = 0.4765$ GHz, for the calculated length of the DLS, is assumed to be true and normalized to the measured value of $F_o = 0.4225$ GHz, an empirical estimation

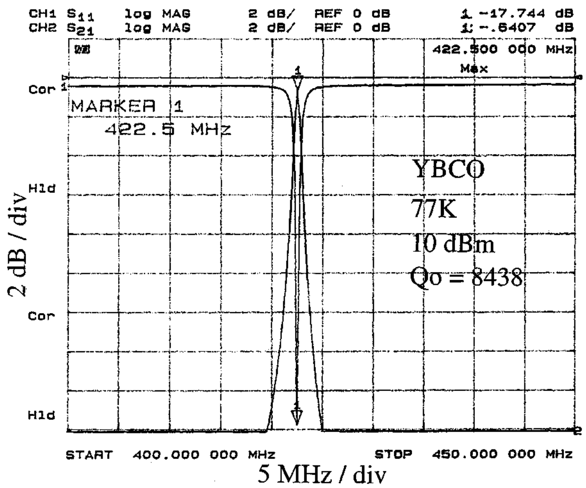

Fig. 5. Measured S_{11} and S_{21} of the YBCO ten-turn DLS resonator on $LaAlO_3$ at 77 K and $+10$-dBm input power.

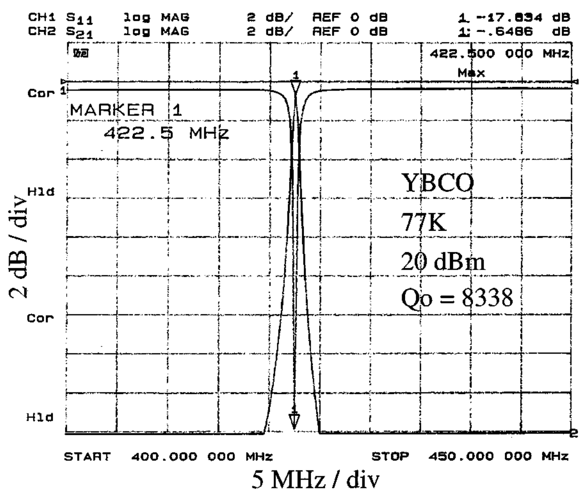

Fig. 6. Measured S_{11} and S_{21} of the YBCO ten-turn DLS resonator on $LaAlO_3$ at 77 K and $+20$-dBm input power.

of G may also be obtained, i.e., $0.4765/0.4225 = 1.1278$ which is close to the calculated $G = 1.1458$.

The Q_o-factor of the spiral is calculated from the measured insertion and loaded Q for this spiral ($IL = -0.6407$ dB and $Q_L = 600$) and substituting in (16)

$$Q_o = \frac{600}{1 - 10^{(-0.6407/20)}} = 8438.$$

The copper counterpart spiral resonator showed a Q_o-factor of 132 at 77 K. The improvement over the copper spiral, demonstrated by the HTS DLS, was thus about 64 times, and nearly seven times over a ten-turn uniform HTS spiral. Also, it was found that the IL of the log-spiral was almost independent of the input power from -10 to 20 dBm, while the power dependence of the uniform spiral was over 1 dB in IL, as shown in Fig. 7. It should be noted here that the uniform spiral was somewhat longer than the DLS and hence its F_o was lower.

The increase in the insertion loss, when the input power was increased by 30 dBm, was only 2.5% for the DLS, while it was nearly 31% for the uniform spiral. The improvements in Q_o and power dependence, provided by a planar spiral structure with microstrip technology, are highly significant for such low operating frequencies and miniature size. This is a very encouraging result for application of such a resonator in high-quality selective filters for mobile and wireless communication systems.

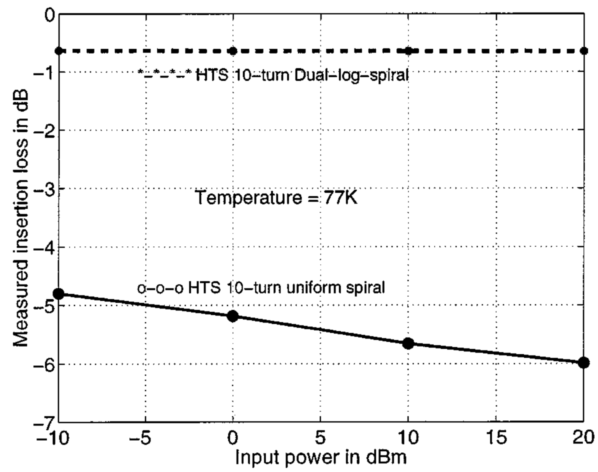

Fig. 7. Measured insertion loss of the YBCO ten-turn dual-log and uniform spiral resonators on $LaAlO_3$ at 77 K as a function of input power.

TABLE I
COMPARISON BETWEEN THE PREDICTED AND MEASURED PARAMETERS OF THE TEN-TURN DLS AND UNIFORM SPIRAL RESONATORS REALIZED WITH COPPER AND YBCO MATERIALS AT 10-dBm INPUT POWER AND 77 K

Spiral type	Spiral material	Q_o Measured	F_o[MHz] Predicted	F_o[MHz] Measured
Uniform	Cu	120	352	348
	YBCO	1120	242	237
Dual-log	Cu	132	632	713.7
	YBCO	8438	415.8	422.5

However, the measured Q_o of the resonator is still limited by several other sources of losses in the device (apart from the YBCO film strip itself) such as: the losses in the copper shield case and the dielectric losses of the standard LaAlO3 substrate and external coupling structures. Suppressing these sources of losses in the device to a minimum, would greatly improve the Q_o and exploit the benefits of extremely low surface resistance of the YBCO conductor strip. For instance, high-quality YBCO 4-GHz disk resonators (ignoring their larger size) on a sapphire and improved LaAlO3 substrates have been reported to achieve Q_o of more than 50 000 at 77 K and sufficiently low nonlinear response up to an oscillating power of 15 kW [11]. These researchers have used the efficient concept of edge current-free disk resonators. On the other hand, if such a disk resonator is used to resonate at the same resonant frequency as our DLS spiral, the disk may have to be about 8 cm in diameter and will have a higher radiation loss. These are the main reasons for limiting their use in filter design at subgigahertz frequencies.

The measured and predicted parameters of the DLS and uniform spiral resonators are compared in Table I. From this, it can be seen that the measured Q_o factor of the DLS YBCO resonator showed a significantly higher value than the uniform YBCO spiral resonator. The resonant frequencies of the copper spirals were much higher than the YBCO spirals due to the significant difference between the permittivities of their substrates.

IV. Conclusion

Compact DLS resonators with a novel geometry were investigated, analyzed, and tested in microstrip configuration. The design had the potential to achieve high Q-factor and substantial independence of input power when realized in an HTS, by matching conductor width to current magnitude. Test results of such a logarithmic ten-turn spiral (i.e., 2 × 5 turns), realized with double-sided YBCO thin film on $LaAlO_3$ substrate, showed a Q_o-factor seven times higher than that of a ten-turn uniform spiral made in the same technology and 64 times higher than a uniform copper counterpart. The insertion loss of the YBCO DLS showed an excellent independence of the input power in comparison with a uniform Archimedian spiral, increasing only 2.5% for a 30-dBm increase of the input power, while the increase was nearly 31% for the uniform spiral over the same range. A simple approximate method for prediction of resonant frequency of the DLS was developed and validated. The DLS is very promising as a building block for filters and multiplexers operating at subgigahertz frequencies.

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