Observation of Bifurcations and Hysteresis in Nonlinear NbN Superconducting Microwave Resonators

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Abstract—In this paper we report some extraordinary nonlinear dynamics measured in the resonance curve of NbN superconducting stripline microwave resonators. Among the nonlinearities observed: abrupt bifurcations in the resonance response at relatively low input powers, asymmetric resonances, multiple jumps within the resonance band, resonance frequency drift, frequency hysteresis, hysteresis loops changing direction and critical coupling phenomenon. Weak links in the NbN grain structure are hypothesized as the source of the nonlinearities.

Index Terms—Bifurcations, nonlinear effects, hysteresis, NbN, microwave resonators.

I. INTRODUCTION

NONLINEAR effects in superconductors in the microwave regime have been the subject of a large number of intensive studies in recent years. Most of the attention is focused on studying one or more of the following issues: investigating the origins of nonlinear effects in superconductors [1],[2], introducing theoretical models that explain nonlinear behavior [3],[4], identifying the dominant factors that manifest these effects [5],[6], find ways to control and minimize nonlinear effects [7],[8] such as, harmonic generation and intermodulation distortions, which degrade the performance of promising superconducting microwave applications mainly in the telecommunication area [9].

Among the nonlinear effects reported in the literature associated with resonance curves, one can find the commonly known Duffing nonlinearity which is characterized by skewed resonance curves above certain power level, appearance of infinite slope in the resonance lineshape, pronounced shift of the resonance frequency and hysteretic behavior [10],[11],[12]. To account for this effect, associated with the rise of kinetic inductance of superconductors, both thermal [13], and weak link [10] explanations have been successfully applied. Other nonlinear effects were reported by Portis et al. [14], where they observed notches that develop on both sides of the frequency response of their HTS microstrip patch antenna, accompanied with hysteresis and frequency shift, as they have driven their antenna into the nonlinear regime. Similar results were reported also by Hedges et al. [15], in their YBCO stripline resonator, and by [16] in their YBCO thin film dielectric cavity. All three studies attributed the observed nonlinear behavior to abrupt changes in the resistive loss of weak links, thermal quenching and weak link switching to normal state.

In this study, being interested in the behavior of nonlinear resonances, we have fabricated different NbN superconducting microwave resonators exhibiting some unusual nonlinear effects, which to the best of our knowledge, have not been reported before in the literature. We study the dependence of these resonators on the injected input power level, and examine the resonance curve behavior under different scan directions showing interesting features. To account for our results, we consider briefly some possible physical mechanisms that may be responsible for the observed effects.

II. RESONATORS DESIGN

A. Resonator Geometries

The resonators were designed in the standard stripline geometry, which consists of five layers as shown in the cross section illustration depicted in Fig. 1. The superconducting resonator was dc-magnetron sputtered on one of the sapphire substrates, whereas the superconducting ground planes were sputtered on the inner covers of a gold plated Oxygen Free High Conductivity (OFHC) Copper Faraday package that was employed to house the resonators. The dimensions of the sapphire substrates were 34mm x 30mm x 1mm. The resonator geometries implemented, which we will refer to them, for simplicity, by the names B1, B2, B3, are presented in the insets of Figs. 3, 4, 5 respectively. The width of the feedlines and the thin part of the resonators was set to 0.4mm to obtain characteristic impedance of 50Ω. The gap between the feedline and the resonators was set to 0.5mm in the B1, B3 cases, and to 0.5mm in B2 case. The

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frequency modes of B1, B2, B3 resonators were theoretically calculated using a simple transmission line model, presented in appendix A, and were also experimentally measured using vector network analyzer (NA). The theoretical calculation was generally found to be in good agreement with the measurement results, as discussed in Appendix A.

III. FABRICATION PROCESS

The sputtering of the NbN films was done using a dc-magnetron sputtering system. All of the resonators reported here were deposited near room temperature [17],[18],[19], where no external heating was applied. The system was usually pumped down prior to sputtering to \( 3 \times 10^{-6} \) torr base pressure (achieved overnight). The sputtering was done in \( \text{Ar}/\text{N}_2 \) atmosphere under current stabilization condition [20]. The relative flow ratio of the two gases into the chamber and the total pressure of the mixture were controlled by mass flow meters. The sputtering usually started with a two minute pre-sputtering in the selected ambient before removal of the shutter and deposition on the substrate. The sputtering parameters of the three resonators are summarized in table 1. Following the NbN deposition, the resonator features were patterned using standard photolithography process, whereas the NbN etching was done using Ar ion-milling.

The fabricated resonators were characterized by relatively low \( T_c \) for NbN and relatively high normal resistivity \( \rho \); that is in good agreement with Ref. [18]. \( T_c \) measured for B1, B2 and B3 was \( 10.7 \), \( 6.3 \), \( 8.9 \) K respectively, whereas measured for B2 and B3 was 348 and 500 [ \( \text{cm}^2/\text{V} \text{s} \) ] respectively.

To obtain resonators with reproducible physical properties we have used the sputtering method discussed in [20], where it was claimed that reproducible parameters of films are assured, by keeping the difference between the discharge voltage in a gas mixture, and in pure argon, constant, for the same discharge current. In Fig. 2 we show one of the characterization measurements applied to our dc-magnetron sputtering system, exhibiting a knee-shape graph of discharge current as a function of discharge voltage. The knee-shape graph was obtained for different \( \text{Ar}/\text{N}_2 \) mixtures at room temperature as shown in the figure. The discharge voltage difference measured in the presence of \( \text{N}_2 \) gas relative to the value measured in pure argon at the same discharge current, is also pointed out in the figure, corresponding to different currents and \( \text{N}_2 \) percentages.

IV. MEASUREMENT RESULTS

All measurements presented in this paper have been conducted at liquid helium temperature.

A. \( S_{11} \) Measurements

The resonance response of the resonators was measured using the reflection parameter \( S_{11} \) of a vector NA. The resonance response obtained for the third mode of B1 resonator \( 8.26 \text{GHz} \) at low input powers, between 23 dBm and 18 dBm in steps of 0.05 dBm, is shown in Fig. 3. A small offset was applied between the sequential graphs, corresponding to different input powers, for clarity, and to emphasize the

| Process parameter | B1 | B2 | B3 |
|-------------------|----|----|----|
| Partial flow ratios (Ar,N2) | \( (87.5\%,25\%) \) | \( (75\%,25\%) \) | \( (70\%,30\%) \) |
| Base temperature | \( 11^\circ C \) | \( 11^\circ C \) | \( 13^\circ C \) |
| Total pressure | \( 6.9 \times 10^3 \) Torr | \( 8.1 \times 10^3 \) Torr | \( 5.7 \times 10^3 \) Torr |
| Discharge current | 0.36 A | 0.55 A | 0.36 A |
| Discharge voltage | 351 V | 348 V | 348 V |
| Discharge power | 121 W | 185 W | 133 W |
| Deposition rate | \( 6 \times 10^{-10} \) cm/s | \( 7 \times 10^{-10} \) cm/s | \( 3 \times 10^{-10} \) cm/s |
| Thickness (t) | 2200 Å | 3000 Å | 2000 Å |
| Base pressure | \( 3 \times 10^{-6} \) Torr | \( 7 \times 10^{-6} \) Torr | \( 8 \times 10^{-6} \) Torr |
| Target-substrate distance | 800 mm | 900 mm | 900 mm |
nonlinear evolution of the resonance response as the input power is increased. The interesting characteristics of this nonlinear evolution could be summarized as follows:

1) In the power range between 23.5 dBm and 23.25 dBm, the resonance is symmetrical and broad.

2) At input power level of 23.25 dBm, a sudden jump of about 15 dB occurs in the resonance curve at the minima where the slope of the resonance response is small.

3) As the input power is increased in steps of 0.05 dBm the resonance becomes asymmetrical, and the left jump shifts towards the lower frequencies gradually.

4) As we continue to increase the input power, the jumps decrease their height but the resonance curve following the jumps becomes more symmetrical and deeper, and at certain input power level we even witness a critical coupling phenomenon where $S_{11}$ (!) at resonance is almost zero, no power reflection is present.

5) The resonance becomes symmetrical again and broader and the bifurcations disappear.

6) All previously listed effects occur within a frequency span of 10 MHz, power range of about 5 dBm, and power step of 0.05 dBm.

Moreover, in order to estimate how narrow this resonance could be in the vicinity of critical coupling, a separate $S_{11}$ measurement has been applied near critical coupling power, using 1601 measurement points and frequency span of 2 MHz. The bandwidth of the resonance curves measured, according to the +3 dB method, was about 0.25 $10^5$ GHz; whereas the ratio $f = f_3 = 16$.

Similar behavior to that exhibited by the nonlinear third mode of resonator B1 can be clearly seen in Fig. 4 and Fig. 5, which show the nonlinear dynamic evolution of the second mode of resonator B2 and the first of B3 respectively. The main differences between the figures are:

1) The power levels at which these nonlinear effects take place. Whereas in B1 case they happen between 23 dBm and 18 dBm, in B2 case they happen between 9.5 dBm and 18 dBm and in B3 case they happen around 1 dBm.

2) In Fig. 4 corresponding to B2 resonator we witness two apparent bifurcations within the resonance band as indicated by circles on the figure, a feature that we did not encounter in Figs. 3 and 4.

B. Verifications

In order to verify that the bifurcation feature, previously measured using NA $S_{11}$ parameter, is not a measurement artifact, we applied a different measurement configuration, shown in Fig. 6, where we scanned the frequency axis with CW mode of an Agilent synthesizer and measured the reflected power from the resonator by a power diode and voltage meter. The load that appears in Fig. 6 following the diode is an
Agilent load used in order to extend the linear regime of the power diode. The results of this measurement configuration are shown in Fig. 4. The frequency scan around the resonance was done using 201 points in each direction (forward and backward). A small hysteresis loop can be seen around the two bifurcations.

**C. Abrupt Bifurcations**

In attempt to find out whether the resonance curve of these nonlinear resonances changes its form along two or more frequency points, further measurements were carried out using NA, where we scanned the frequency axis in the vicinity of the jumps. The resonance curves corresponding to different input powers were shifted by a constant offset for clarity.

**D. Frequency Hysteresis**

Applying forward and backward frequency sweeps to these resonators, reveals a very interesting hysteretic behavior. In Fig. 9 we show a representative frequency scan of B2 second mode, applied in both directions, featuring the following nonlinear dynamic behavior:

1) At low input powers $8.05 \text{ dBm}$ and $8.04 \text{ dBm}$, the resonance is symmetrical and there is no hysteresis.

2) As the power is increased by $0.01 \text{ dBm}$ to $8.03 \text{ dBm}$, two bifurcations occur at both sides of the resonance response and hysteresis loops form at the bistable regions.

3) As we continue to increase the input power gradually, the hysteresis loop, associated with the right bifurcation, changes direction. At first it circulates counterclockwise between $8.03 \text{ dBm}$ and $7.99 \text{ dBm}$, at $7.98 \text{ dBm}$ the two opposed bifurcations, at the right side, meet and no hysteresis is detected, as we increase the power further the right hysteresis loop appears again, circulating, this time, in the opposite direction, clockwise.

Furthermore, it is worth mentioning that the hysteresis loops changing direction are not unique to this resonator, or to the bifurcation occurring on the right side of the resonance. It appears also in the modes of B1, and it occurs at the left side bifurcation as well, but at different power level.

**E. Multiple Bifurcations**

Frequency sweep applied to B3 first resonance in both directions, exhibits yet another feature, in addition to the two bifurcations at the sides of the resonance curve, which we have seen earlier, there are another two smaller bifurcations accompanied with hysteresis within the resonance lineshape, adding up to 4 bifurcations in each scan direction, as can be seen in Fig. 10. This feature may have a special significance in explaining the physical origin of these nonlinearities.
V. Discussion

This unusual dynamic behavior of our NbN films, demonstrated earlier, highly suggest built-in Josephson junctions, forming at the boundaries of the granular NbN columnar structure [21],[22], as the underlying physical mechanism responsible for the observed nonlinearities [1]. Another physical mechanism that may be considered as a strong candidate for explaining the effects, is the local heating mechanism which was hypothesized as the source of notches and switching effects observed in HTS films [14],[15],[16]. Nevertheless recent measurements done on SQUID ring containing a single Josephson junction inductively coupled to a radio frequency resonant circuit [23], [24], [25] exhibiting opposed bifurcations, hammerhead resonance lineshape and similar effects, suggest similar physical mechanism and further support the former hypothesis.

VI. Conclusion

In the course of this experimental work we have fabricated several stripline NbN resonators dc-magnetron sputtered on sapphire substrates at room temperature implementing different geometries. The resonators have exhibited similar and unusual nonlinear effects in their resonance response curves. The onset of the nonlinear effects in these NbN resonators varied between the different resonators, but usually occurred at relatively low powers, typically 2-3 orders of magnitude lower than Nb for example. Among the nonlinear effects observed: abrupt and multiple bifurcations in the resonance curve, power dependent resonance frequency shift, hysteresis loops in the vicinity of the bifurcations, hysteresis loops changing direction, and critical coupling phenomenon. Weak links forming in the NbN films are hypothesized as the source of the nonlinearities. Further study of these effects under other modes of operation and measurement conditions would be carried in the future, in order to substantiate our understanding of these extraordinary effects.

APPENDIX I

Resonance Frequency Calculation of B1, B2, B3 Resonators

The calculation process of the resonance frequencies of B1 and B2 makes use of opposite traveling voltage-current waves method [26], [27]. For this purpose we model B1 and B2 resonators as a straight transmission line extending in the z-direction with two characteristic impedance regions $Z_1$ and $Z_2$ as shown in Fig. 11.

The equivalent voltage along the resonator transmission line would be given, in general, by a standing waves expression in the form:

$$ V(z) = \frac{8}{\pi} \int_{-\infty}^{\infty} (z + a) \cos \left( \frac{\pi}{a} z \right) \left( B \sin \left( \frac{\pi}{a} z \right) + A \cos \left( \frac{\pi}{a} z \right) \right) \, dz $$

where $\frac{8}{\pi} \int_{-\infty}^{\infty} \frac{1}{\sqrt{1 + k^2}}$ is the propagation constant along the transmission line, and $A$, $B$, $z$, $z_0$, $z_1$, $z_2$ are constants that can be determined using boundary conditions and
applied power amplitude. However due to the symmetry of the problem we expect the solutions to have defined parity, where $V(z) = V(-z)$ for symmetric solution and $V(z) = V(-z)$ for antisymmetric solution. Thus by taking advantage of this property and demanding that $V(z)$ be continuous at $z = a$ and $z = -a$, one gets:

$$V_{\text{sym}}(z) = \frac{\cos(az) + \cos(az + a)\cos z}{\cos z} z (a; b)$$

$$V_{\text{anti}}(z) = \frac{\sin a \sin (z + a) + B_a \sin z}{\sin z} z (a; a)$$

where $V_{\text{sym}}(z)$ stands for the symmetric solution whereas $V_{\text{anti}}(z)$ for the antisymmetric solution. To calculate the value of the new constants $B_{a,b}$, we require that the equivalent current $I(z)$ along the transmission line, which is given by $I(z) = (i=Z_1)\, dV/dz$ where $Z_1$ is the characteristic impedance of the line, be continuous at $z = a$ and $z = -a$. Following this requirement one gets $B_a = \sin (a) (a)$ and $B_a = \cos (a)$, where $Z_2 = \text{Z}_1$. The symmetric and antisymmetric solutions of $V(z)$ and $I(z)$ are given by:

$$V_{\text{sym}}(z) = \frac{\cos a \cos (z + a) + \sin a \sin (z + a)}{\cos z} z (a; b)$$

$$V_{\text{anti}}(z) = \frac{\sin a \sin (z + a) + B_a \sin z}{\sin z} z (a; a)$$

The antisymmetric case:

From the antisymmetric $V(b) = V(-b)$ and the continuity $V(\phi) = V(-\phi)$ conditions, we get $V(\phi) = V(-\phi) = 0$; which yields:

$$\sin (a) \cos (\phi - a) + \cos (a) \sin (\phi - a) = 0 \quad (3)$$

Substituting the following numerical values $Z_2 = Z_1 = 4.25\Omega; l_1 = a = 13\,\text{mm}; b = b = 6.5\,\text{mm}$ into the above resonance frequency conditions and solving for frequencies below 10 GHz, yields the following solutions (2.5035 GHz; $Z_1 = 5.697$ GHz) to the symmetric case, and (2.9804 GHz; $Z_1 = 5.786$ GHz; $Z_2 = 8.6747$ GHz) to the antisymmetric case, with doubly degenerate mode at 8.1647 GHz. By comparing these calculated resonances to the directly measured resonances of B1 resonator, obtained using a broadband $S_{11}$ measurement (2.5812 GHz; 5.6304 GHz; $Z_2 = 8.188$ GHz), we find that the excited resonances correspond to the symmetrical case only. The antisymmetric modes do not get excited because they have a voltage node at the feeding line position.

B. B2 Resonator

Since the resonator ends are open-circuited we demand $I(\phi) = I(-\phi) = 0$:

The symmetric case:

We require that the current associated with the symmetric voltage, vanishes:

$$\cos (a) \sin (\phi - a) + \sin (a) \cos (\phi - a) = 0 \quad (4)$$

The antisymmetric case:

We require that the current associated with the antisymmetric voltage, vanishes:

$$\sin (a) \sin (\phi - a) + \cos (a) \cos (\phi - a) = 0 \quad (5)$$

Substituting the following numerical values $Z_2 = Z_1 = 4.999 = 10.4\Omega; b = 6.979\,\text{mm}; l_1 = a = 11.97\,\text{mm}; b = b = 6.93\,\text{mm}$ into the above resonance frequency conditions and solving for frequencies below 10 GHz yields the following solutions (2.6486 GHz; $Z_1 = 6.028$ GHz; $Z_2 = 5.5858$ GHz) to the symmetric case, and (1.763 GHz; $Z_1 = 4.5698$ GHz; $Z_2 = 7.4597$ GHz; $Z_2 = 9.7778$ GHz) to the antisymmetric case. By comparing these calculated resonances to the directly measured resonances of B2 resonator, obtained using a broadband $S_{11}$ measurement (2.5152 GHz; 4.425 GHz; $Z_2 = 6.3806$ GHz; $Z_2 = 8.176$ GHz), we find a good agreement between the two results. The missing resonances do not get excited apparently because of the coupling location of the feedline relative to the resonator.

C. B3 resonator

B3 resonator, in contrast, showed some larger discrepancy between the measured value for the first mode 1.56 GHz (seen in Fig. 3) and the theoretical value $f_1 = 2.4462$ GHz calculated according to the approximated equation:

$$f_n = \frac{nc}{2L \sqrt{\epsilon}} \quad (6)$$
where $n$ is the mode number, $c$ is the light velocity, $l$ is the open-circuited line length ($\lambda = \frac{20m}{m}$), and $\varepsilon_r$ is the relative dielectric coefficient of the sapphire ($\varepsilon = 9.4$).

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