Probing microwave properties of high-T_c films via small dc magnetic fields

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It is demonstrated that the combination of vortex matter and rf measurements yields new insight into the microwave properties of superconducting thin-film devices, both in small magnetic fields and zero field. The comparison of field-cooled and different types of field-sweep experiments on coplanar high-T_c thin-film resonators shows that the microwave properties strongly depend on magnetization and vortex distribution in the superconducting film as well. Thus, using vortices as a kind of local probe for the microwave properties leads to a consistent explanation of the microwave power handling in nonzero and zero magnetic fields. In a model that is derived from the experiments, the nonlinear microwave behavior is explained by the limitation of the total current density in the device considering contributions of the rf field and the screening of the magnetic field and vortices to the current. The limiting current value seems to be related to the dc critical current of the superconductor. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1487902]

The use of superconducting thin films in microwave devices allows a dramatic reduction of the device dimension at comparable or higher performance with respect to conventional nonsuperconducting devices.[1] As a consequence, larger power densities are encountered in these devices. However, in contrast to their normal-conducting competitors, the power handling capability of superconducting microwave devices is limited by the onset of nonlinear effects in form of a strong increase of the dissipation or intermodulation products at large rf power. Although various physical origins are discussed (e.g. weak links and thermal or magnetic effects), the physical mechanism, that is responsible for the nonlinear surface resistance is not fully understood. In this letter, we demonstrate that the combination of vortex matter and microwave properties leads to insight into the nature of the nonlinear microwave properties of superconducting material.

Coplanar thin film resonators (1.4 GHz) are patterned from YBCO films (thickness $d = 300$ nm) on sapphire. The width of the central conductor is $w = 100$ μm and the distance of the groundplane is $a = 182$ μm. The current densities of coplanar microwave devices can be approximated by[2]

$$j_z(x) = \frac{I}{wK(w')\sqrt{(1-(2x/w)^2)(1-(2x/a)^2)}} \quad (1a)$$

and

$$j_z(x) = \frac{I}{wK(w')\sqrt{(1-(w/a)^2)\frac{\lambda}{w}}} \quad (1b)$$

for $|x| \leqslant w/2 - \lambda$ and $w/2 - \lambda \leqslant |x| \leqslant w/2$, respectively. Eq. (1) describes the 1D current density of the cross section of the central conductor, λ and K are the London penetration depth and complete elliptic integral, respectively, and $w' = w/a$.

The current distribution across the width of the coplanar line shows pronounced maxima at the outer edges of the the center conductor.[2] Due to this characteristic current distribution, first the power handling capability is relatively small and, thus, thermal effects can be neglected.[3] Since the rf current is strongly peaked at the edge of the central conductor, these devices turn out to be highly sensitive to field or vortex penetration. Furthermore, by establishing different vortex distributions in the resonator, the impact of vortices on the microwave properties can be analyzed locally.

Figure 1 represents an overview of the field dependence of the power handling capability of a typical coplanar $\lambda/2$-resonator. The power handling is characterized by the oscilating rf power P_{max} at which the unloaded quality factor Q_0 is degraded to 80% of its low-power value, i.e., $Q_0(P_{max}) = 0.8\ Q_0(P \to 0)$ and $Q_0 \approx 20\,000-30\,000$ for $P \to 0$ and $T \to 0$. In FC and zero-field cooled (ZFC) experiments the resonator is cooled to the superconducting state in an applied magnetic field or in zero-field, respectively. In FC sweep (FCS) experiments, the sample is first cooled to the superconducting state in an applied field B_{FC} and subsequently the field is modified by ΔB.

The power handling capability P_{max} depends strongly upon the way the magnetic field is established. Whereas FC measurements show a gradual decrease of P_{max}, in ZFC experiments, a strong decrease of the power handling capability within a few μT is followed by an almost constant P_{max}. The different behavior seems to be a consequence of the vortex distribution in the resonator. A homogeneous vortex distribution in the superconductor is expected for FC experiments. The linear increase of the vortex density with increasing field seems to lead to the gradual decrease of P_{max}. In contrast to the FC experiments, an inhomogeneous vortex distribution is expected for the ZFC case. Due to the flux penetration into the field-free superconductor in the ZFC case, the position of the largest vortex density coincides with the maximum of the rf current at the edge of the central conductor. This explains the strong reduction of P_{max} already at extremely small fields of a few μT. A further increase of the field in the ZFC case

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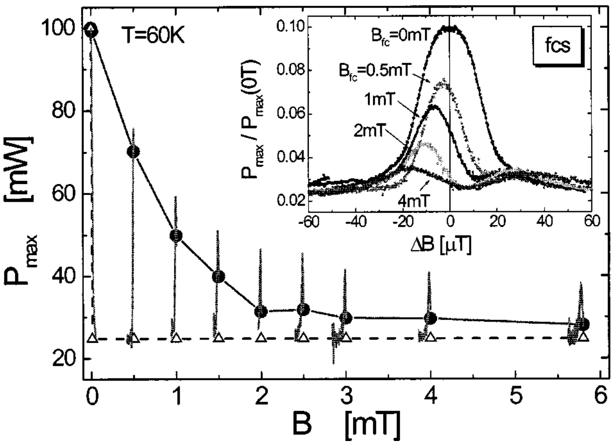

FIG. 1. Field dependence of the power handling capability of a coplanar YBCO resonator for (solid circles), ZFC (open triangles) and FCS (solid lines) experiments. The inset shows the FCS measurement starting at different fields B_{FC} on an enlarged and normalized scale.

does not affect the power-handling capability seriously. This is consistent with other observations of flux penetration at small fields, where an increase of the magnetic field first leads only to a shift of the flux front into the superconductor.[4] Since the interior of the superconductor does not carry large rf currents, this shift does not affect the power-handling capability seriously. Furthermore, the FC and ZFC values of P_{max} seem to merge at large fields. This is expected for the field, for which the ZFC flux front approaches the center of the sample. For these fields, similar vortex densities are expected at the edge of the superconductor for the FC and ZFC case.

The most interesting features are observed for FCS measurements (inset of Fig. 1) that show a characteristic variation of P_{max} with increasing and decreasing field, which provides an ideal fingerprint of flux and vortex penetration. For finite starting fields B_{FC}, a nonsymmetrical ΔB dependence of P_{max} is obtained. For $B_{FC}>0$, first P_{max} increases for decreasing field and decreases for increasing field, then for larger field changes, P_{max} decreases for decreasing field and shows a characteristic small peak for increasing field. The position of the maximum of $P_{max}(\Delta B)$ for $\Delta B<0$ decreases with increasing field B_{FC}.

Field cycles with different amplitudes prove the different underlying mechanisms. For small field amplitudes ΔB, a reversible field penetration of flux ($\Delta B>0$) is observed. The flux penetration leads to a decrease of P_{max}, whereas the flux compensation ($\Delta B<0$) causes an increase of P_{max}. A modification of P_{max} by up to 50% takes place within a few μT. Only for larger amplitudes $|\Delta B|>10\ \mu T$ vortices for $\Delta B>0$ or antivortices for $\Delta B<0$ start to nucleate and penetrate the resonator structure. This leads to an irreversible modification of P_{max}. The penetration of the first vortices is accompanied by a small increase of the P_{max} for the positive branch, that can be interpreted by a relaxation of the field at the edge of the superconducting central conductor. Obviously, this effect is not possible for the negative branch, here P_{max} decreases when the first antivortices penetrate.

In the following, the field dependence of P_{max} will be discussed in terms of a model that considers (i) a superposition and (ii) the limitation of current density in the superconductor. The screening current densities (j_M due to a magnetization and j_V due to vortices) superimpose to the rf current density j_{rf}, thus, yield a total current density $j_{tot}=j_{rf}+j_M+j_V$ in the coplanar resonator. The nonlinearity implies that the total current density is limited by a critical value, i.e., $j_{tot}<j_{max}$, and the linear behavior is restricted to $j_{rf}<j_{max}$. Assuming a field dependence of the limiting current,

$$j_{max}(B,x)=j_{max,B=0}(x)-j_M(B,x)-j_V(B,x), \tag{2}$$

this model automatically yields a power-handling capability that strongly depends on the kind of experiment.

In FC experiments, a homogeneous distribution of vortices in the superconductor can be assumed and magnetization effects can be neglected for not too small fields, i.e., $j_{tot}\approx j_{rf}+j_V$. Assuming an ideal vortex lattice, the positions of the vortices in the central conductor of the resonator is given by $|x_n|=[w-(2\cdot\gamma\cdot n+1)\cdot a_0]/2$ with $n=0,1,2\ldots$, $a_0=(\phi_o/\gamma B)^{1/2}$ and $\gamma=1$ or 0.866 for a quadratic or hexagonal vortex lattice, respectively. Since the screening current drops exponentially with the characteristic length λ, we assume, that the total current density in the regime $x_n\pm\alpha\lambda$ of the cross-section is dominated by the contribution of the vortex screening current with $\alpha=0.5$–1. Thus, the maximum total current $I_{tot,max}$ can be obtained by summation of the maximum rf current and the redistributed current due to the screening current of vortices at positions x_n:

$$I_{tot,max}=I_{rf,max}+\sum_{\text{Vortices } n} j_z(x_n)\cdot 2\lambda_{eff}\cdot\alpha. \tag{3}$$

The maximum rf current $I_{rf,max}=(2\,P_{max}/Z_L)^{1/2}$ can be derived from the measurement with the line impedance $Z_L=50\ \Omega$. Using Eq. (1) yields the maximum total current

$$I_{tot,max}=I_{rf.max}\left(1+\sum_n \frac{2\lambda_{eff}\cdot\alpha\cdot w^{-1}\cdot K^{-1}(w')}{wK(w')\sqrt{\left[1-\left(\frac{2x_n}{w}\right)^2\right]\left[1-\left(\frac{2x_n}{a}\right)^2\right]}}\right), \tag{4}$$

with $K(w/a)\approx 1.72$ for our geometry.

Figure 2(a) shows the field dependence of the maximum total current calculated using Eq. (4) for a set of FC experiments on a typical resonator. The transformation of the RF current via Eq. (4) to the total current demonstrates the expected field independence of $I_{tot,max}$ [Eq. (2)] for a large magnetic field range, i.e., between 0.5 and 3 mT. The deviation from the field independence at small and large fields can be explained by the effect of magnetization due to the rf field and the overlap of vortices, respectively. Both effects are not accounted for in Eq. (4). The rf magnetic field B_{rf} can be approximated by Ampere's law yielding $B_{rf}\approx\mu_0 I_{rf}/2w$. Inserting the experimental value $I_{rf}\approx 0.14$ A yields a magnetic field $B_{rf}\approx 0.88$ mT which is of the order of the field up to which the deviation is observed. For fields $B>3$ mT, vortices start to overlap ($a_0\leqslant 2\lambda_{eff}$) and, thus, the screening currents of adjacent vortices start to partially cancel each other.

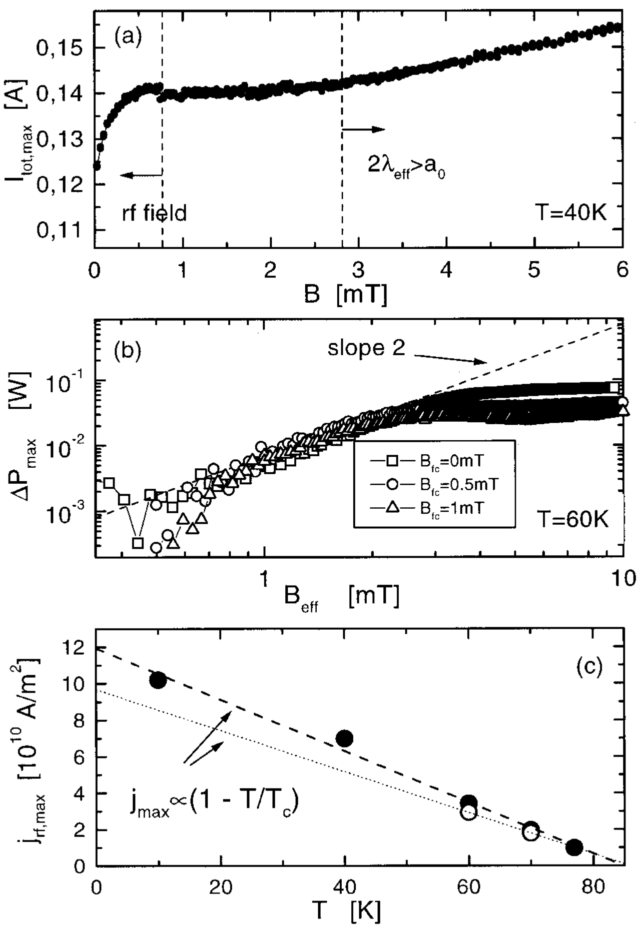

FIG. 2. (a) Field dependence of the calculated total current [Eq. (4)] for a typical resonator. The values for the rf self-field and the onset of overlap and compensation of vortex screening currents are marked and restrict the validity of Eq. (4) and, thus, regime of constant total current. (b) $\Delta P_{\max}$ as function of effective magnetic field for ZFC and FCS experiments for different values of the field cooled magnetic field B_{FC}. (c) Temperature dependence of the maximum rf current density for two resonators patterned of YBCO films of different quality (solid symbols: optimized film quality; open symbol: oxygen depleted YBCO film).

In ZFC and FCS experiments, field changes introduce a magnetization of the superconductor and, subsequently, gradients in the vortex density. Restricting our consideration to small field changes, penetration of vortices can be neglected and, $\Delta j_{\mathrm{tot}} \approx \Delta j_{\mathrm{rf}} + \Delta j_M = 0$ is expected. The effective field drops exponentially at the superconductor surface, i.e., $B(x') = B_{\mathrm{eff}} \exp(-x'/\lambda)$ with $x' = |x \pm w/2|$. The resulting screening current density is given by $j_M(x') = (B_{\mathrm{eff}}/\lambda\mu_0)\exp(-x'/\lambda)$, the total screening current can be approximated in analogy to the description of the skin effect by $j_M(0)\cdot\lambda\cdot t \propto B_{\mathrm{eff}}$, where t represents the film thickness. Thus, the change of the power-handling capability can be approximated by:

$$\Delta P_{\max} \propto (j_M(0)\cdot\lambda_{\mathrm{eff}}\cdot t)^2 \propto B_{\mathrm{eff}}^2. \tag{5}$$

The effective field at the superconductor surface is given by $B_{\mathrm{eff}} = B_{\mathrm{FC}} + s * \Delta B$, where $s = (1\text{-}D)^{-1}$ is the field enhancement due to the demagnetizing factor D. A demagnetization factor $D = 0.99456$ is derived from the FCS experiments for our samples.

The double-logarithmic plot [Fig. 2(b)] of $\Delta P_{\max}$ as a function of effective magnetic field B_{eff} for a typical set of ZFC and FCS experiments demonstrates the excellent agreement of the data with the prediction in Eq. (5). $\Delta P_{\max}$ increases quadratically with B_{eff} and, even more, all data (ZFC and FCS for different fields B_{FC}) fall on one line. A deviation from the quadratic dependence is observed at higher fields. It has to be ascribed to the effect of the geometrical barrier for collective vortex entry.[5] For the geometry of the resonator, the geometrical barrier for flux penetration is $B_{\mathrm{cp}} \approx 15\ \mu\mathrm{T}$ which corresponds to an effective field of 2.8 mT.

Finally, zero-field measurements are discussed in terms of our model. Generally, the rf current density profile shows a maximum at the edges of the superconducting resonator. According to Eq. (1), the maximum current density is given by

$$j_{\mathrm{rf,max}} = \frac{\sqrt{2P_{\max}}}{K(w/a)}[Z\cdot\lambda_{\mathrm{eff}} w t^2 (1-(w/a)^2)]^{-1/2}. \tag{6}$$

Figure 2(c) shows the resulting temperature dependence of $j_{\mathrm{rf,max}}$ for two resonators patterned from YBCO films of different quality. Two interesting aspects should be noticed, i.e., $j_{\mathrm{rf,max}}$ increases linear with temperature and the order of magnitude is $j_{\mathrm{rf,max}}(77\ \mathrm{K}) \approx 10^{10}\ \mathrm{Am}^{-2}$ and $j_{\mathrm{rf,max}}(10\ \mathrm{K}) \approx 10^{11}\ \mathrm{Am}^{-2}$ for the optimized YBCO quality. Both, the temperature dependence and the magnitude of the maximum rf current density agree with the behavior and magnitude of the dc critical current for typical YBCO thin films.[6] This suggests that the nonlinear microwave behavior is strongly related to the dc critical current of the superconductor.

In conclusion, the comparison of the microwave power handling capability of coplanar high-temperature superconductor thin film resonators in FC, ZFC, and FCS experiments shows that (i) the microwave properties depend on magnetization and vortex distribution, (ii) power handling and quality factor of the devices are strongly affected by the way the magnetic field is approached, and (iii) the microwave power handling can be understood in terms of a simple model, that considers all contributions to the current in the superconductor (i.e., rf and screening currents) which seems to be limited by the dc critical current. The model explains the microwave behavior in nonzero- and zero-magnetic field. Thus, flux and vortex penetration can be used to probe the local microwave properties, and reveal the mechanism of nonlinear microwave properties.

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