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Microscopic Imaging of RF Current Distribution and Intermodulation Sources in Superconducting Microwave Devices

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ABSTRACT

We have developed a new version of the Laser Scanning Microscope (LSM) that images changes in the third-order intermodulation (IM) signal as a laser-spot perturbation is scanned over the sample. We directly image the regions of maximum IM generation in a meandering microstrip resonator, and compare them to the simultaneously measured RF current distribution.

INTRODUCTION

The nonlinear response of high temperature superconductors (HTS) limits the performance of superconducting microwave devices. The sources of nonlinearity are mainly extrinsic in origin, including impurities, weak links, defects, heating, non-uniform supercurrent and flux line distribution, as well as other spatially inhomogeneous effects. The method of two-tone, third-order IM product distortion is commonly used as a sensitive tool to measure microwave nonlinearities. However, it constitutes averaged data and does not show where and how the nonlinear effects are generated locally. This is due, in part, to the lack of knowledge on the role of the inhomogeneous RF current density $J_{RF}(x, y)$ on forming the local sources of inductive-nonlinear response (IM current density scale $J_{IM}(x, y)$) that can arise from the RF current-dependent magnetic penetration depth [1]. Here we present a new type of microscope that investigates the local origins of the IM response. Earlier, we have used a low-temperature (LT) LSM for simultaneous imaging of $J_{RF}(x, y)$ and $J_{IM}(x, y)$ in an operating microwave resonator to understand the spatial amplitude correlation between RF and IM signals [2]. However, images of the IM photoresponse (PR) were much noisier than the RF PR ones due to the poor spectral resolution of the measuring electronics. In this work we developed a new idea to visualize $J_{IM}(x, y)$ in the device with a high degree of signal-to-noise.

EXPERIMENTAL DETAILS

The resonator was fabricated from a $YB_2C_3O_{7-\delta}$ film deposited on a $LaAlO_3$ substrate. By using ion beam-milling, the film was patterned into a meandering microstrip shown in the top of Figure 1 (a). The sample was housed in an aluminum microwave package, connected to room temperature electronics by two coaxial lines delivering applied RF power P_{RF}. The sample is cooled from T_C down to near 77 K inside a variable temperature optical cryostat. The film transition temperature $T_C \sim$ 89-90 K was estimated from the temperature dependence of the transmittance at a frequency of 1 GHz. The resonant frequency for the device at 77 K was approximately f_0 = 1.85 GHz with a loaded Q ~ 2200. The *Global* third-order IM product was found to vary as the cube of P_{RF} for P_{RF} < -5 dBm, but began to saturate at higher power, partly motivating our study of the *local* LSM response.

The LSM typically produces a 4 μm diameter heating probe in the 1 μm diameter laser beam focus. Its operation and performance is close to that of the microwave LSM technique reported earlier [2, 3]. Two microwave signals at frequencies f_1 and f_2 were centered near f_0 and injected into the resonator. The nonlinear mixing in the device generates third-order IM signals at $2f_1$- f_2 and $2f_2$- f_1 frequencies. The probe-induced changes in the resonator transmittance constitute the LSM PR. The PR amplitude is measured at either a main tone or at an IM frequency by a spectrum analyzer operating in the single-frequency receiver mode. The probe beam is TTL modulated in intensity by a 100 kHz oscillator, and raster scanned over the surface of the device. The oscillating LSM PR is then lock-in amplified at each *x, y* point of the scan range and used for plotting the spatio-amplitude 3-D map of both quantities. In addition, a coherent mixing of the output spectrum of the resonator with the phase-inverted signal of both primary tones was applied to get a clear IM PR in a wide range of circulating power. By using this new procedure of depressing the primary tones before they reach the spectrum analyzer, it is possible to image the exact position where nonlinear microwave response is generated in the device.

RESULTS AND DISCUSSION

The microwave standing waves were LSM imaged at the fundamental and third harmonic resonances to estimate the electronic transport and HTS material properties in different areas of the patterned strip. In contrast to previous samples, there are no visible microscopic defects or superconducting inhomogeneities found in the $J_{RF}(x, y)$ distributions over the whole resonator topology. As an illustration, the bottom image in figure 1 (a) shows the $J_{RF}(x, y)$ corresponding to the third harmonic pattern at f_2 = 5.9232275 GHz, T = 86.9 K and P_{RF} = -14 dBm. One can see from the $J_{RF}(x, y)$ distribution that the shape of the standing wave pattern is significantly distorted near the hairpin inner corners, leading to RF current densities almost an order of magnitude higher than those expected in a straight resonator. The influence of these peak

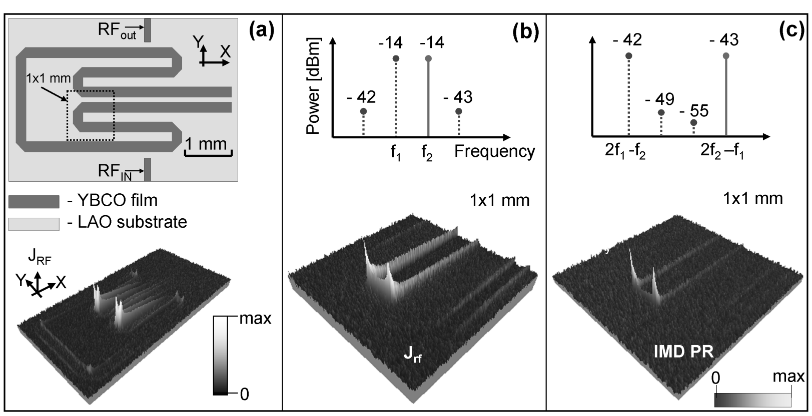

Figure 1. (a) Top view of the resonator topology along with overall and (b, c) detailed 1x1 mm 3-d LTLSM plots (bottom images) showing (b) $J_{RF}(x,y)$ and (c) IMD PR distribution. The upper part of (b) shows the two input tones at –14 dBm as well as the output tones. The upper part of (c) shows the signals entering the spectrum analyzer after the primary tones have suffered partial cancellation.

currents on the nonlinear response of the resonator was studied in detail.

Figures 1(b) and 1(c) compare $J_{RF}(x, y)$ and IM PR images correspondingly obtained in a 1x1 mm^2 area of resonator that is depicted in figure 1(a) by the black dotted box. The LSM PR was measured at the frequency and signal level indicated by the solid line on the diagrams in the upper parts of Fig. 1 (b) and (c). Note, that these spectra of the output signal of the resonator are quite different before they reach the spectrum analyzer. First, the $J_{RF}(x, y)$ distribution was imaged using the original multitone spectrum, where the RF PR is dominated by the main input tones. In this case, the LSM PR is caused by laser-induced change in the $S_{12}(f)$ transmission curve that is proportional to the local RF current density squared $[J_{RF}^2(x, y)]$ [2 - 6]. The second method of canceling the f_1 and f_2 tones before they reach the spectrum analyzer was applied to make the IM PR dominate for $J_{IM}(x, y)$ imaging (see figure 1 (c)) [6]. As evident from the comparison, IM PR is localized near the peaks in $J_{RF}(x, y)$. Only a very small fraction of the structure contributes to the global IM and RF photoresponse.

It should be noted that the very sharp spatial dependence of local IM PR may provide a more precise LSM characterization of operating microwave devices with resolution superior to conventional $J_{RF}(x, y)$ imaging [6]. The spatial resolution can be further improved to the sub-micrometer level by increasing the modulation frequency to 1 MHz, thus reducing the size of the heating probe.

CONCLUSIONS

A new experimental approach was been applied for direct LTLSM imaging of IM current densities in operating microwave devices. Using a modified LTLSM instrument we have presented a preliminary local correlation of RF and IM photoresponse on a micrometer length scale. The spatial resolution of the LSM in IM imaging mode is two times smaller than the decay length of RF current density. It is dominated by local heating with a laser probe and may be shortened to the sub-micrometer scale with an increase of the modulation of the laser beam to about 1 MHz. These results should open a wide window toward understanding the role of RF currents on formation of local sources of inductive nonlinearity in superconducting microwave devices.

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