Intermodulation distortion in YBCO at the intrinsic limit: Implications for filters

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Abstract. Recently, evidence has been presented by this group that the measured intermodulation distortion (IMD) in YBa₂Cu₃O₇₋ₓ (YBCO) films of high quality is consistent with the intrinsic limit, given by the d-wave order parameter. This intrinsic nonlinearity is also known as the nonlinear Meissner effect. The measurements and theory of the IMD agree in magnitude, temperature dependence, and power dependence. We present our latest results of IMD measurements that strongly support the agreement with the d-wave theory. Thus, a detailed understanding of the nonlinearity in YBCO is emerging from the measurements and calculations. We present results of modeling the IMD in YBCO resonators with very good agreement with measurement. We also present simulations of the IMD in multipole filters assuming intrinsic nonlinearity. While the IMD results depend on geometry and filter design parameters, our simulation results can be used to draw some conclusions regarding IMD in filters and the effect on the dynamic ranges of systems with YBCO filters at the front end.

1. Introduction
The nonlinear behavior of the cuprate high-temperature superconductors (HTS) at microwave frequencies has important consequences in practical devices and in the theory of the d-wave order parameter. In HTS filters and delay lines, the nonlinear behavior limits the performance because of the intermodulation distortion (IMD) it generates. This limits the dynamic range of receive filters and thus is important even in low-power applications of HTS filters. Filters with large numbers of poles or with very narrow bandwidths are the most sensitive to the IMD.

The theory of d-wave superconductivity predicts a nonlinear Meissner effect (NLME) in which the penetration depth $\lambda$ for small values of microwave current $j$ is given by [1,2,3]

$$\lambda(T, j) = \lambda_l(T) + \lambda_n(T) j^2,$$

(1)

where $\lambda_l(T)$ is the linear penetration depth, $\lambda_n$ is the nonlinear part of the penetration depth, and $T$ is the temperature. For larger currents, $\lambda$ is given by

$$\lambda(T, j) = \lambda_l(T) + \lambda_n(T) |j|.$$

(2)

The theory predicts an increase in $\lambda_n(T)$ at low temperatures, diverging as $1/T$. This divergence is the signature of intrinsic nonlinearity in d-wave superconductors.
2. The case for intrinsic nonlinearity

Measurements of the third-order intermodulation distortion have been reported in detail in previous publications. [4,5,6] The third-order IMD was measured in the usual way, in which two closely spaced tones of equal power at frequencies $f_1$ and $f_2$ are combined and applied to the resonator. The frequencies are centered about the resonant frequency with a tone separation of approximately 1/32 of the low-power 3-dB bandwidth. The third-order mixing products at frequencies $2f_1 - f_2$ and $2f_2 - f_1$ are then measured in a spectrum analyzer as a function of the input power to the resonator and temperature.

Because of the sensitivity of the IMD measurements, observation of the nonlinear Meissner effect (NLME) has been demonstrated in the YBCO films of the highest quality, where the measure of quality is the level of IMD at approximately 50 K. In superconductors with d-wave symmetry, the nonlinear Meissner effect results in a characteristic increase of nonlinearity and thus IMD, which diverges at low temperatures with $1/T^2$. This results from entirely intrinsic causes and does not depend on sample specific quantities, other than the fundamental ones of penetration depth and energy gap. While some sample variation is possible within the framework of the theory, we conclude that high-quality films are exhibiting the intrinsic nonlinearities, and further material improvements would have minimal effect on IMD. However, as discussed in [4], according to [3] improvement in IMD is still possible by increasing the film thickness while maintaining the high quality that enabled observation of the NLME. However, growth of films thicker than approximately 300 nm has proven to be challenging because of the loss of good epitaxy as the film grows thicker.[11]

Our earlier reports of the measurement of the NLME [4,5,6] included measurements from a limited number of films that showed the clear signature of the NLME. Some films, however, did not show the behavior, and it was concluded that extrinsic causes producing higher values of IMD in these films prevent the clear observation of the NLME. Here, we report more films from different sources and different deposition methods showing the clear $1/T^2$ low-temperature behavior. Figure 1 is a plot of the IMD vs $T$ in several films as noted in the figure caption. Booth et al.[12] have also reported measurements of nonlinearity exhibiting the NLME.

The experimental evidence is thus strongly indicative of the achievement of intrinsic nonlinear behavior. Space precludes deeper discussion of the NLME. Other publications contain more detail [4,5,6].
3. Resonator modeling results

The goal is to calculate the IMD of YBCO filters. It is first necessary to model resonator response. To do so, we compare measured IMD in a YBCO resonator with that calculated using the well-known technique of harmonic balance. [13]

We have used the measured changes in center frequency $f_0$ and $Q$ of a YBCO resonator fabricated from a film grown by Koren [7] along with the well-known R-L-C resonant equivalent circuit to calculate the IMD generated. The IMD vs $T$ of the resonator is shown in Figure 1. We have assumed an inductance and resistance with the functional form given by [4]

$$L(I) = L_0 + L_2 I^2$$

$$R(I) = R_0 + R_2 I^2$$

The $L_2$ and $R_2$ were determined by a fit to the measured $f_0(P)$ and $Q(P)$ using the equivalent circuit. As we have argued in the past, the IMD is far more sensitive to the nonlinearities than direct measurement of the surface impedance. Thus the IMD at low power is not necessarily related to the IMD at high power and might arise from different causes or different regimes of the same cause. It is the IMD at high power that can be modeled by measurements of $Z(I)$ because, of necessity, the $Z(I)$ is obtained at much higher power than the range of powers over which IMD can be measured. However, by modeling the IMD at 50 K in this resonator, we can use the experimental fact that the IMD follows slope three on the log-log plot of IMD power vs power below the resonator saturation at approximately 0 dBm, as shown in Figure 2. Thus, in this case it is valid to assume the functional form of (3) and (4) for the resistance and reactance and to apply these forms to the IMD calculation. It should be noted that this procedure may not be valid at all temperatures and for other materials that show, for instance, more complex multiple-slope behavior in the IMD vs circulating power.

The result of the IMD calculation is shown in Figure 2, which plots the measured and calculated values of the output power at the fundamental frequency of the resonator and the measured and calculated values of the output power of one of the third-order IMD tones vs input power. There are no further free parameters in the fitting. The agreement is excellent, verifying that the IMD can be derived from the nonlinear surface impedance. In this measurement, the IMD depends on the third power of the input power as seen by the slope of three in the double logarithmic plot. This is not always the case. The calculation, because of the assumptions of the quadratic dependence of the $R$ and
on current, can only yield a cubic dependence on power. Not all cases will yield such good agreement between this model and experiment. In many experiments, the slope is smaller than three.

4. Filter IMD results

Based on the excellent agreement between measured and calculated IMD in a resonator, we can now extend this method to the calculation of IMD in a multipole filter. The calculation proceeds from the resonator results by the realization that the filters of interest for implementation in HTS are coupled resonator filters. While more universal results may be possible, here we limited the simulation to a specific filter design. In order to calculate the IMD of the filter, one needs to select a particular set of filter parameters. We have chosen a five-pole, 1%-bandwidth, Chebyshev filter design as a benchmark. We further assume that it is implemented with the same $\lambda/2$ resonators as used in the resonator measurements so that we can use the same analytic functions for the resistance and inductance. The filter response calculated using the measured surface impedance of the Koren film (Figure 1.) is shown in Figure 3. The arrows in the figure show the frequencies of the tones used to calculate the IMD. They were chosen to be near the band edge because such frequencies generate the largest IMD.

The results of the simulation are shown in Figure 4. The IMD shows slope three in the double log plot because of the assumptions of the analytic form of the nonlinear resistance and inductance. The acceptability of this level of IMD is dependent on the exact system specifications and the nature of the interference the system is likely to encounter. For this case, the IMD is approximately 70-dB below the fundamental at +10-dBm input power for this set of input frequencies.

5. Conclusions

We have demonstrated that the best YBCO films exhibit the intrinsic nonlinearity. This nonlinearity is lower than that resulting from defects and grain boundaries, but not likely to be lowered by improvements in material quality. We have been able to model numerically the IMD in a resonator with results of the model agreeing well with experiments. The same model has been used to calculate the IMD in a typical superconducting YBCO filter. The results indicate that the IMD could limit the dynamic range in some applications. According to a recently formulated theory of nonlinearity, thicker films of the same quality would show lower IMD [3].

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