# Final Report

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**Title: Nonlinear Microwave Properties of Atomic Layer Controlled HTS Multilayers**

**Contract number: FA9550-06-1-0415**

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We have studied the nonlinear microwave response of epitaxial HTS multilayers and single layers thick films in collaboration with Dr. Dan Oates at MIT Lincoln Lab. In order to make highest quality control we have used multi-YBCO target PLD with in situ high pressure RHEED. The nonlinearity of YBCO thick films improves. as increasing the films thickness. and approaches the lowest values ever reported.

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**Background:**

One of the first areas of practical application for high temperature superconductor devices is passive microwave circuits. Future DOD systems such as AMRFS and CRYORADAR depend on extremely sharp filter and resonator functions. However, nonlinear effects and intermodulation distortion (IMD) can defeat the advantages gained by going to HTS components. In order to maximize device performance, much effort has been expended in learning how to fabricate HTS thin film materials with very low surface resistance. In addition to low microwave loss, however, HTS materials can exhibit detrimental nonlinear behavior at microwave frequencies. Since the origins of nonlinearity in HTS devices are not well understood, it is not immediately obvious if the same film growth conditions that lead to low surface resistance will also produce low nonlinearity.

**Objectives:**

- Exploring methods to lower nonlinear effects in YBCO multilayers and thick films. Thicker films grown by multi-target PLD techniques and YBCO/$CeO_2$ multilayers are expected to lower intermodulation distortion (IMD), based upon recent theoretical calculations.
- Measurements of intermodulation distortion (IMD) as a function of temperature and power of YBCO thin films and YBCO/$CeO_2$ multilayers by atomic-layer-controlled growth in order to understand the loss mechanisms and the nonlinear mechanisms.
- Characterization by four-circle x-ray diffraction, AFM, STM, resistivity vs. temperature, $J_c$ vs. temperature and magnetic field.
- This study will point to the direction where we should go to improve the microwave properties and determine what kind of defects and disorder affect on the surface resistance and nonlinearity, in order to develop films and devices optimized for both low surface resistance and low nonlinearlity.

**Activities**

We have studied the nonlinear microwave response of epitaxial HTS thin films and multilayers in collaboration with Dr. Dan Oates at MIT Lincoln Lab. In order to make highest quality control, $YBa_2Cu_3O_{7-d}$ epitaxial films were fabricated on single-surface-terminated (001) $LaAlO_3$ and (001) $(LaAlO_3)_{0.3}(Sr_2AlTaO_6)_{0.35}$ (LSAT) substrates by atomic layer controlled pulsed laser deposition. We explored the effects of various deposition parameters which include deposition temperatures, film thicknesses and substrate types and miscut angles. Films were characterized by four-circle x-ray diffraction, AFM, STM, resistivity vs. temperature, $J_c$ vs. temperature and magnetic field. Finally, films were patterned and characterized for their nonlinear microwave properties, and compared with results from other deposition techniques by Dan Oates at MIT Lincoln Laboratory.

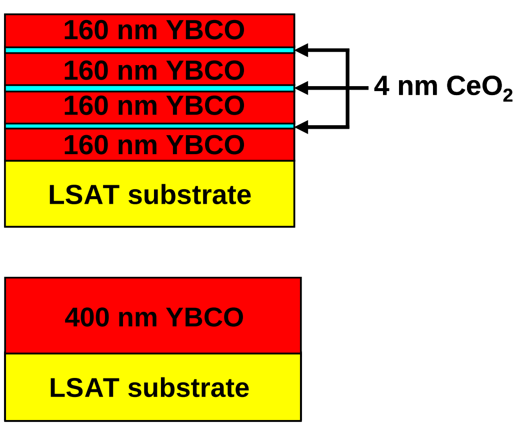
**Accomplishments/New Findings**

*Growth and IMD of YBCO/$CeO_2$ Multilayers*

In order to overcome the degradation of the crystalline quality of YBCO and enhance the flux pinning we have grown epitaxial YBCO/$CeO_2$ multilayers stacks on 2 degree miscut (001) single crystal LSAT substrates by multi-target PLD at different substrate temperatures. Recently, it has been reported that multilayer films maintain high $J_c$ values even in the case of thicknesses for which a single-layer film would show significant degradation. Figure 1 show the schematic of the multilayer structure. The multilayer structures have substantially higher $J_c$ than single layer YBCO thin films with the same thickness. The $J_c$ of the single layer YBCO with the same thickness is only 0.94A/$cm^2$. Furthermore, the multilayer films grown at lower substrate temperature (780 C) has much higher $J_c$ (4.1 MA/$cm^2$) than multilayer films grown at high substrate temperature (825 C) (see Figure 10).

The results of the first measurements of a YBCO/$CeO_2$ multilayer grown by PLD with *in situ* high pressure RHEED are shown in Figure 2, which compare a single-layer film of 400-nm thickness with a four-layer film with each YBCO layer 160-nm thick interspersed with $CeO_2$ buffer layers 40-nm thick, giving an aggregate thickness of 640 nm of YBCO. *The improvement is dramatic*. YBCO/interlayer multilayers have been expected on theoretical grounds to show improvements in IMD and in power handling. *If verified, these results represent a significant improvement in IMD reduction and power handling increase.*

Thus, the multilayer films may be a method to also provide high-power capabilities to YBCO microwave devices. The outlook, however, is good for two reasons: first, the thicker films reduce the current density, and, second, it is expected that the thinner layers will enhance the pinning and thereby improve losses at high power levels because flux penetration and flux motion are sources of loss.



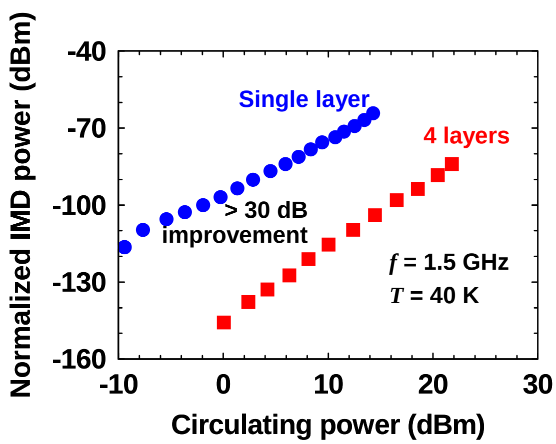




Figure 1 (a) Schematic description of YBCO single layer and YBCO/$CeO_2$ multilayer on (001) LSAT substrates, (b) Third-order intermodulation distortion at 40 K for the single-layer film and the four-layer YBCO/$CeO_2$ multilayer film. The frequency is 1.5 GHz. The IMD is lower for the four-layer film over most of the power range by about 30 dB. At high power the single-layer film is saturated and the IMD is no longer a meaningful quantity

*Thickness dependence of IMD of YBCO thick films*

We have also studied the thickness dependence of IMD for single layer YBCO thick films. The films grown by multi-YBCO target PLD to improve the crystalline quality of the films. The films were patterned using standard photolithography and wet etching. After patterning, the etched striplines were assembled with YBCO ground planes to form stripline resonators. The properties of the patterned line dominate the performance of the resonator because the current density is approximately a factor 100 higher in the line than in the ground plane. 1200 nm thick single layer films shows the lowest IMD as shown in Figure 2 and this agrees well with the local theory of Dahm and Scalapino and the nonlocal theory of Agassi.

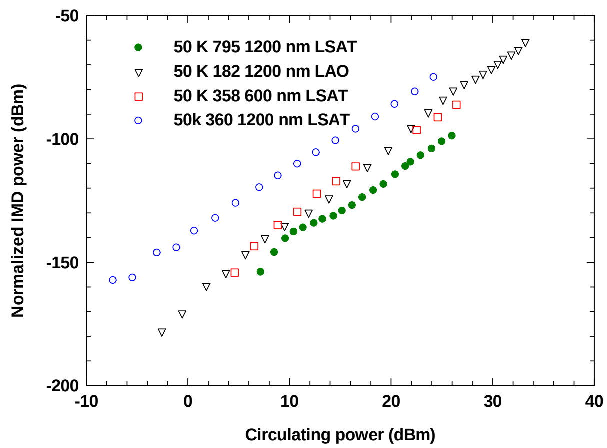



Figure 2. Normalized IMD of single layer YBCO thick films