TUNABLE HIGH TEMPERATURE SUPERCONDUCTOR MICROSTRIP RESONATORS

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ABSTRACT

We have fabricated and characterized electrically tunable high temperature superconductor microstrip resonators incorporating $YBa_2Cu_3O_{7-x}$ superconductor and $SrTiO_3$ ferroelectric films. Early versions of these and similar devices were described previously[1]. The resonators consist of two co-linear microstrip line-sections separated by a 5 µm gap. The capacitance of the gap influences the frequencies of the odd-order coupled resonances. Inductively choked dc bias lines are attached to each line section so that a bias voltage can be applied to the gap. When the gap is filled with a ferroelectric material, the odd resonances can be tuned. Frequency shifts of 300 MHz have been observed with a bias voltage of 50 V for resonances at 5.6 GHz and 11.6 GHz. The tunability is independent of temperature from 4 K to 80 K. An upper bound for the loss tangent of the $SrTiO_3$ capacitor is extracted from the resonance Q, and we find $\tan(\delta) < 0.07$ at 4 K. We believe that the Q values are limited by external loading, rather than by losses in the $SrTiO_3$, so the true value of $\tan(\delta)$ is certainly less than our upper bound.

INTRODUCTION

Low cost, tunable microwave circuit elements which are compatible with monolithic thin-film technology are desired for many applications, *e.g.* frequency-agile signal processing components and phase shifters for phased-array antennas. The existing techniques for providing tunability or variable phase shift are either too lossy, too bulky, or too costly for many applications. Ferroelectric materials may provide the necessary properties to realize a small, low loss, inexpensive, tunable microwave capacitor[2,3]. In bulk, at least, various stoichiometries of $Ba_{1-x}Sr_xTiO_3$ appear to have the necessary combination of a highly voltage-tunable dielectric constant with a low enough loss tangent to be useful[4-8]. The tunability that has been observed in films is substantially smaller and qualitatively different from that seen in bulk samples[1,9]. Our hope is to maximize the tunability of thin-films while minimizing their losses. Superconducting devices that take advantage low temperatures seem especially promising, because the losses of ferroelectric films may decrease at low temperatures.

RESONATOR DESIGN

The layout of the tunable resonator is shown in Figure 1. Coaxial launchers are attached to the two silver contact pads so that the resonator modes can be observed in transmission. The silver contact pads are coupled to the microstrip sections by 5 µm wide dc bias lines. These lines provide weak inductive coupling of the microstrip to the coaxial launchers and also allow us to apply a dc bias to the tunable capacitor. A very wide microstrip line with a low impedance (Z_0=7.2 Ω) is used for the resonator to increase the reflection at the bias lines and thereby improve the loaded Q value. Standard photolithographic techniques and ion milling were used to pattern the 300 nm thick laser ablated $YBa_2Cu_3O_{7-x}$ films grown on 0.43 mm thick $LaAlO_3$ substrates. After the superconductor was patterned, a 400 nm thick film of $SrTiO_3$ was deposited by laser ablation over the 5 µm gap to form the tunable capacitor. Although the geometry of the capacitor is rather inefficient from the point of view of achieving a large capacitance in a small volume, we have used this design to avoid a second layer of superconductor. Lead was evaporated onto the opposite side of the substrate to provide a ground plane. The resonator substrate was packaged in a small gold-plated cavity. Indium was used to connect the coaxial launchers to the silver contact pads of the resonator. The package was inserted in a liquid helium dewar and measurements were made at temperatures from 4 K to 80 K.

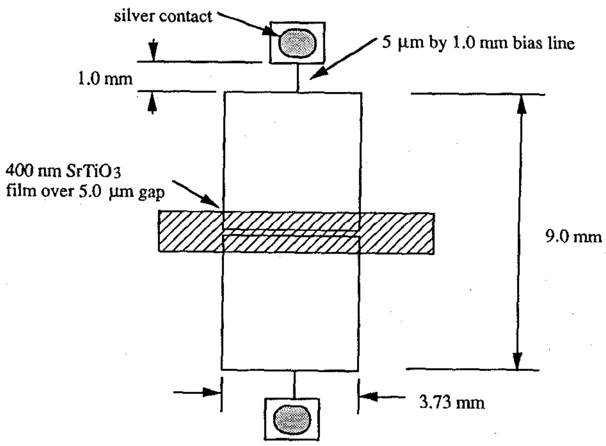

Figure 1: Layout of the tunable resonator. The two microstrip sections, the bias lines, and the launcher pads are made of 300 nm thick YBCO superconductor. The substrate is 0.43 mm thick $LaAlO_3$.

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A circuit model of the device is shown in Figure 2. The two line-sections with impedance Z_0 are coupled by the tunable series capacitance C_s. The inductance of the dc bias lines is represented by L while the capacitance of the pads is represented by C_p. Measurements of the resonant frequencies and quality factors were made in transmission by attaching a vector network analyzer to ports 1 and 2 via 50 Ω coaxial lines. Biasing voltages were supplied to the resonator using the dc bias tees in the network analyzer.

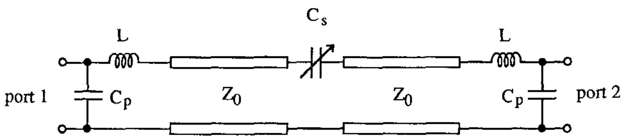

Figure 2: Circuit model of the tunable resonator. C_s is a voltage tunable capacitor. The resonant frequencies and Q's are determined by transmission measurements from port 1 to port 2.

As an aid to extracting the parameters of the tunable capacitor, measurements were made with the devices in three configurations. The devices were first studied before the 5 μm gap was formed. This case is equivalent to having the capacitance C_s shorted. Next the gap was formed by ion milling, and measurements were made with the gap, but without the $SrTiO_3$ film. Finally the devices were studied in the tunable configuration, *i.e.* with the gap and the $SrTiO_3$ film.

The resonant modes of the completed structures are similar to those of a single transmission line with open-circuited terminations, except that the frequencies of the odd modes are shifted upwards by the tunable series capacitor. The even modes are not affected by the capacitor, because for these modes there is a current node at the location of the capacitor. Thus we expect only the odd modes to shift in frequency when the dielectric constant of the ferroelectric is changed by the applied dc bias.

RESONANT FREQUENCIES AND TUNABILITY

We first discuss the observed resonant frequencies, which may be used to extract the capacitance of the tunable series capacitor. Figure 3 shows the resonant frequencies and Q values for the lowest four modes of device A. Similar data was obtained from a second device, and less complete but also similar results were observed for several other devices. The frequencies for the three different configurations are plotted, and the Q values for the resonances are given next to each data point. Besides the modes listed in Figure 3, we also see a width mode of the line at 8.8 GHz.

Before the gap is formed approximately equally spaced modes are seen, as should be expected if the terminations at the ends of the lines are nearly open circuit. The odd modes increase in frequency when the gap is formed, and then go down in frequency when the $SrTiO_3$ is added, as expected. Only the odd modes tune when a dc bias is applied, and the frequencies increase, indicating that the capacitance of the series capacitor C_s decreases with bias.

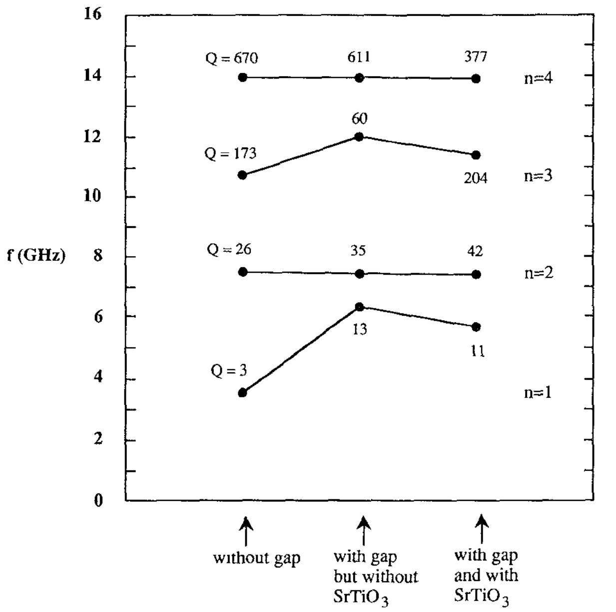

Figure 3: Frequencies of the lowest four resonant modes for device A. The frequencies are shown for 3 different configurations: without the 5 μm gap, with the gap but without the $SrTiO_3$ film, and in the tunable configuration with the gap and the $SrTiO_3$ film at zero bias. The number beside each data point is the mode Q observed at 4 K.

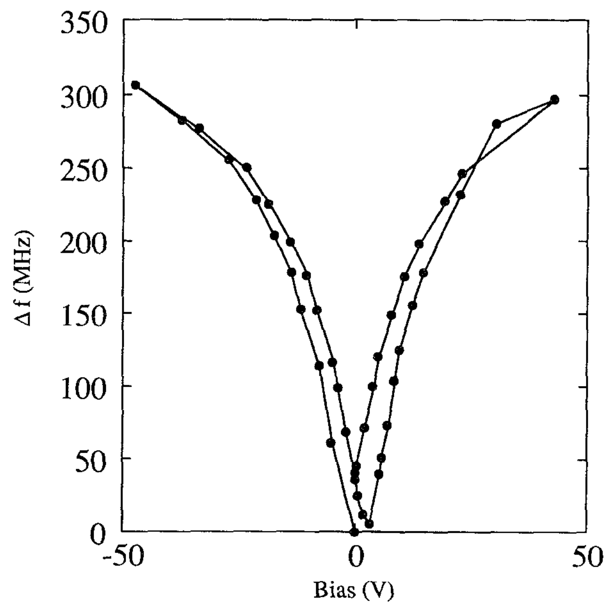

Figure 4: Tunability of the third (n=3) resonant mode for device A. The bias voltage starts at 0 V, decreases to -47 V, increases to +43 V, and then returns to 0 V. The measurements were made at 4 K.

Figure 4 shows the tuning behavior of the third mode at 4 K. For both the first and the third modes, frequency shifts of greater than 300 MHz are seen for a bias of 50 V, corresponding to an electric field of about 10^7 V/m applied to the $SrTiO_3$. The variation of the capacitance saturates at slightly higher fields. A small amount of hysteresis is visible in the data as the applied voltage is cycled. Very similar tuning behavior is seen over the entire temperature range from 4 K to 80 K, in sharp contrast to what is observed in bulk samples. In bulk the dielectric constant of $SrTiO_3$ tunes by approximately a factor of 30 at 4 K for comparable applied fields but is not at all tunable above 65 K [4].

The circuit model of Figure 2 can be used to extract quantitative information about the tunable capacitor. From the geometry of the patterned structure, and using the dielectric constant e_r=24.5 for the $LaAlO_3$ substrate, we find the circuit parameters L=1.0 nH, C_p=0.5 pF, and Z_0=7.2 Ω. These values correctly predict the resonant frequencies without a gap with 6% accuracy. The observed frequency shifts correspond to a series capacitance of C_s of 2.0 pF with the gap but without the $SrTiO_3$, and 5.9 pF with the gap and with the $SrTiO_3$ film at zero bias. The series capacitance then decreases to about 3.0 pF at 50 V bias. These values for the series capacitance are accurate to about 50%. If we suppose the dielectric constant of the $SrTiO_3$ is so high that the electric field lines are confined within the material, then the dielectric constant can be extracted assuming a parallel plate geometry. We find roughly e_r=2,000 for zero applied bias and e_r=500 at 50 V applied bias. Similar behavior of the dielectric constant and its tunability for $SrTiO_3$ films has been reported elsewhere [1,10].

LOADED Q VALUES

The Q values as determined directly from transmission measurements are listed in Figure 3. The broad behavior of the Q's can be predicted from the circuit model of Figure 2 with the circuit parameters given above. In particular the sharp increase of the Q's with increasing frequency is due to the increasing mismatch between the line-sections and the coupling inductance L. There are some unexplained variations in the Q values as the mode frequencies change, particularly for mode 3. We get excellent fits of our (uncalibrated) complex S_{21} data with resonance line-shapes, so we do not believe that the variations are due to measurement errors. There is no suggestion in the data that the observed Q's are limited by losses in the $SrTiO_3$ films. Instead, the Q values appear to be dominated by coupling losses.

We can place a useful upper bound on the loss tangent of the tunable series capacitor by assuming that the observed Q's are dominated by its losses. We again use the circuit model of Figure 2, with the circuit parameters given earlier, and we increase tan(δ) until the model Q drops below the observed Q. The best limit can be obtained from the third mode, and we find $\tan(\delta) < 0.07$ at 11 GHz and 4 K. We are not able to set a limit at higher temperatures, because the Q's of all of the modes decrease dramatically when we go above the critical temperature of our lead ground plane.

CONCLUSIONS

We have shown that a highly tunable and low-loss microwave capacitor can be constructed from a $SrTiO_3$ film with $YBa_2Cu_3O_{7-x}$ electrodes. With some refinement, our technique should allow us to characterize the dielectric properties of thin-film ferroelectric capacitors at a wide range of temperatures, frequencies, and bias conditions. Such data is needed so that the utility of superconductor/ferroelectric microwave components can be fully assessed.

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