LA-UR- 99-3090

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AND THIN-FILM STRONTIUM TITANATE

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Submitted to: Invited presentation at the Ferroelectrics Workshop in Puerto Rico
Guanica, Puerto Rico, May 13-14, 1999.
To be published in Integ. Ferroelec.

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ELECTRODYNAMIC PROPERTIES OF SINGLE-CRYSTAL AND THIN-FILM STRONTIUM TITANATE

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We present a comparative study of broadband electrodynamic properties of coplanar waveguides made from nonlinear dielectric single-crystal and thin-film SrTiO_3 (STO) with high-temperature superconducting thin-film $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$ electrodes. The waveguides that use single-crystal STO exhibit a monotonic increase in refractive index, dielectric nonlinearity, and dissipation with decreasing temperature (from 80 K to 20 K), whereas those based on thin-film STO show similar but weaker effects with increasing temperature. Under dc bias, both types of waveguides show reduced refractive index, but dissipation increases in the case of single-crystal STO, while it decreases in the case of STO thin-films.

Keywords: nonlinear dielectric; strontium titanate; high-temperature superconductor; loss tangent; refractive index; large-signal regime.

INTRODUCTION

Most potential applications of nonlinear dielectric (NLD) materials such as SrTiO_3 (STO) would require thin films of both the NLD and appropriate electrodes on a low-loss substrate. However, at present, even the highest quality NLD films show much smaller dielectric

constant and nonlinearity, and higher dielectric losses than their single-crystal NLD counterparts.^[1] Also, the functional dependence of dielectric properties on external electric field bias seems to be quite different in thin films (for example, whereas the dielectric loss decreases with bias in thin films, it increases in single crystals).^[2] To assess the practical implications of such differences in electrodynamic characteristics, we have studied the comparative performance of single-crystal and thin-film STO in prototype waveguide device configurations.

To facilitate extensive study of nonlinear and dissipative effects, we have adopted a time-domain measurement technique,^[3] which allows for separation of dc-bias effects and high-frequency effects, and uses electrically-distributed transmission line concepts for analysis. The use of distributed coplanar waveguides has enabled us to investigate the high-frequency properties of STO with high resolution because of the long interaction lengths. Further, the use of narrow Gaussian pulses has allowed us to characterize the waveguides in a broad frequency band, from dc up to 3 GHz.

EXPERIMENTS AND RESULTS

For this study, we have designed, fabricated and characterized three prototype coplanar waveguide devices (CPWs), schematic cross-sections of which are shown in Fig. 1. The details of device fabrication and materials characterization can be found elsewhere.^[4,5] All three devices are 8-cm-long meanderline coplanar waveguides made from 0.4- μm -thick $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$ (YBCO) electrodes on 1 cm x 1 cm substrates, with centerline widths of 16 to 22 μm and centerline-to-groundplane widths of 15 to 16 μm . The first device Waveguide-A uses 1-mm-thick single-crystal STO. The second device Waveguide-B uses 0.6- μm -thick bottom STO film, and the third device Waveguide-C uses 0.3- μm -thick bottom and top STO films on 0.5-mm-thick LaAlO_3 .

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substrates.

FIGURE 1. Schematic cross-section of devices.

For high-frequency device characterization, we have used two different measurement configurations; the step-pulse time-domain transmission (TDT), and the impulse-TDT configuration. The step-pulse TDT configuration uses a 0.2 V step-pulse with a 10%-90% risetime of about 30 ps as the excitation signal, and monitors the transmitted signals through the device as a function of time, whereas the impulse-TDT configuration uses a Gaussian-like pulse with about 0.4 ns full-width-at-half-maximum and about 0.35 V pulse amplitude as the excitation signal. The details of the measurement technique and the method of analysis can be found elsewhere.^[5]

Time-Domain Transmission (TDT) for Step-Pulse Input

Figure 2 shows TDT for step-pulse excitation along the three waveguide devices at temperatures of 20, 40, and 60 K. The steps in the response are due to reflections from device boundaries. From the propagation difference between the steps and the step heights (and ignoring dissipative and dispersive effects for the time being), we can readily calculate shunt capacitance (i.e., effective dielectric constant) as a function of temperature, and dc bias applied between the centerline and groundplanes.

FIGURE 2. Time-domain transmission (TDT) for (a) Waveguide-A and (b) Waveguides-B and -C at 20, 40, and 60 K.

Figure 3 shows fractional changes in shunt capacitance (calculated from changes in delay for TDT step fronts) as a function of dc bias at different temperatures. These results indicate that the dielectric nonlinearity of STO single-crystal device is much stronger than that of the thin-film devices at 20 K, but loses strength rapidly with increasing temperature and becomes approximately equal to that of thin film device at 60 K. On the other hand, the dielectric nonlinearity of the thin film devices changes very little with temperature.

FIGURE 3. Shunt capacitance vs bias at different temperatures for (a) Waveguide-A, and (b) Waveguides-B and -C.

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Time-Domain Transmission for Gaussian-Impulse Input

For quantitative analysis of broadband electrodynamic characteristics of the waveguides we have examined spectral components of Gaussian-pulse TDT response, as shown in Fig. 4. Fig. 4 shows that the delay, i.e., effective refractive index of Waveguide-A is about an order of magnitude larger that of Waveguides-B and -C.

FIGURE 4. TDT for Gaussian input for (a) Waveguide-A, and (b) Waveguides-B and -C at 20 and 60 K.

By Fourier analyzing these and similar TDT responses as a function of temperature and bias, we can obtain frequency-dependent refractive index n (or, more conveniently $\partial(n\omega)/\partial\omega$ where ω is the angular frequency) and attenuation constant.^[5,6] Fig. 5 shows refractive index vs frequency. Apart from magnitude differences, the single-crystal and thin-film waveguides show similarly decreasing refractive index with bias. Both types of waveguides show no significant dispersion up to a few GHz under zero bias, though under bias Waveguide-A shows a slight linear drop of refractive index with frequency. We note that the sharp cut-off for Waveguide-A near 1 GHz at 20 K is probably due to excitation of surface wave modes in the single-crystal substrate.

FIGURE 5. Refractive index vs frequency at 20 and 60 K for (a) Waveguide-A, and (b) Waveguide-B.

Figure 6 shows attenuation vs frequency for Waveguide-A and Waveguide-B (for brevity, we will show only Waveguide-B results for thin films in the remainder of the paper since Waveguide-B and Waveguide-C exhibit very similar characteristics). We note that the waveguides based on single-crystal and thin-film STO show a marked difference in their attenuation characteristics; while Waveguide-A exhibits increasing attenuation with decreasing temperature and increasing bias, Waveguide-B exhibits just the opposite; attenuation decreases with decreasing temperature and increasing bias.

FIGURE 6. Attenuation vs frequency at 20 and 60 K for (a) Waveguide-A, and (b) Waveguide-B.

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By making the plausible assumption that the measured attenuation is dominated by dielectric losses in the waveguide, we can calculate the effective loss tangent of the dielectric medium of the waveguides,^[5] as shown in Fig. 7. It is interesting to note that Waveguide-A based on single-crystal STO shows almost frequency-independent loss tangent, whereas Waveguide-B shows roughly linearly-dependent loss tangent on frequency. Also, both waveguides exhibit no change of the slope of the curves with bias.

FIGURE 7. Loss tangent vs frequency at 20 and 60 K for (a) Waveguide-A and (b) Waveguide-B.

CONCLUSION

We have implemented prototype waveguide devices to investigate the similarities and differences in the electrodynamic characteristics of thin films and single crystals of nonlinear dielectric STO. The waveguide based on single-crystal STO shows increasing refractive index, dielectric nonlinearity, and attenuation with decreasing temperature. The waveguides based on 0.6- μm -thick films of STO, on the other hand, show virtually temperature-independent dielectric nonlinearity, but decreasing refractive index and attenuation with decreasing temperature.

With bias, both types of waveguides show decreasing refractive index. However, the attenuation increases in the waveguide based on single-crystal STO, but decreases in the thin-film waveguide with increasing bias. Neither type of waveguide shows any appreciable dispersion under zero bias up to a few GHz, but under bias and at low temperature, the single-crystal waveguide exhibits a weak linearly decreasing refractive index with increasing frequency.

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