

Review Article

Variation of Phonons Self-energy - Frequency and Linewidth - of Permanent Phonons in YBCO/LCMO Superlattices Thin Films Due to the Change of Temperature Using Raman Light Scattering

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Abstract

In order to write this article, we looked at the impact of temperatures variation going from low to high temperature starting from 10 K to 300 K on my samples. The work was performed by using Raman light scattering which is a powerful technique to fulfill that aim perfectly on thin films of YBCO/LCMO superlattices - with different thickness of both YBCO layers and LCMO layers -, bulk YBCO and bulk LCMO as seen in table 1. During this work, we focus our study on the permanent phonons of YBCO/LCMO as a thin film, which were 240 cm^{-1} , 340 cm^{-1} , 440 cm^{-1} and 505 cm^{-1} phonon modes. Depending on our data, which we obtained from experiment's measurement we could confirm that the variation of temperature gives rise to change in frequency and linewidth in all phonons were observed during this study. Therefore, we could conclude that the all phonons studied in this article collapse depending on the increasing of the temperature in the form of suppression of phonons self-energy in the form of softening and hardening, but with different degrees. Because of that, we clearly observed expected and unexpected behaviour of frequency and linewidth of all permanent phonons of YBCO/LCMO thin films - where we partially build up our work on this observation in this article - at T_C and T_{Curie} , respectively.

Keywords

Temperature Variation, Phonon Self-energy, Superlattices, Thin Film

1. Introduction

In this work, we focus our study on changes in material structure and phonons anomaly of YBCO/LCMO superlattices that occur due to the gradual change in temperature starting from 10 K to 300 K using Raman scattering technique, which is one of the powerful tool in such situation. Here we concentrate on phonon modes which originate from YBCO and LCMO. The Copper-oxide planes, which consist of su-

perconducting charge carriers like Cooper pairs, are the building blocks of high temperature superconductors [9, 15]. The primary source of superconductivity is copper planes. Nevertheless, it was found that even while the ruthenate compound Sr_2RuO_4 with layered perovskite system lacks copper-oxide planes, it becomes superconductor following suitable annealing [1, 4]. Furthermore, an experimental ob-

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servation of the coexistence of ferromagnetism and superconductivity in the ($\text{RuSr}_2\text{GdCu}_2\text{O}_8$) combination was made in 1995. $\text{RuSr}_2\text{GdCu}_2\text{O}_8$ material becomes ferromagnetic at temperature $T_{\text{curie}} = 135$ K, according to a previous study additional cooling causes the superconducting phase transition to occur in the range of $T_c = 50$ K depending on the conditions which applied on the superconductor material itself [5, 28].

A traditional concept of superconductivity is at odds with the fascinating coexistence of FM and Sc. A new field in the physics of condensed matter and solid state was opened by the coexistence of superconductivity and ferromagnetism in the naturally occurring combination of materials as well as we study (YBCO/LCMO). The preparation of artificial superconducting and ferromagnetic interfaces is the main emphasis in order to explore the physical processes at these interfaces specially when a specific conditions are applied such as changing temperature (our work), changing of layer thickness and using different doping [12]. Superlattices of YBCO/LCMO are leading the way in this regard. Furthermore, high-quality superlattices of oxide materials, such as YBCO/LCMO have prepared for this study.

In this paper we use samples of different thicknesses, see Table 1. We found out that increasing the temperature affected

the phonons in our samples in general and caused them all to collapse but with different degrees see Figure 1 and Figure 2.

2. Experiments

In this article, Raman light scattering used as a powerful tool to gain information about our samples under specific conditions which we determined before. Our samples which we studied here were deposited by pulsed laser deposition (PLD) on SrTiO_3 535 mm^2 as a substrate. In Raman technique, an Argon-Krypton gas laser was used as an excitation source, which provides a collection of 11 discrete laser lines ranging from the red line with wavelength of 647 nm to the violet one of 407 nm, but in our study, we used the blue laser line with wavelength 488 nm. In order to avoid heating of the sample, the power of the laser at the sample position was kept below 10 mW. The laser spot size on the sample was $100 \mu\text{m}$. In order to reduce the stray light, the laser light passes through pin holes placed in the optical track. Afterwards, the laser light passes through a plasma filter. In this way, discrete plasma lines can be excluded from observed spectra. See table 1 of samples studied in this paper.

Table 1. Shows YBCO, LCMO layers thickness and their transition temperatures T_c and T_{Curie} .

Sample	YBCO Thickness	LCMO Thickness	T_c	T_{Curie}
LCMO	0	3000 Å	-	280 K
Y/L1	100 Å	100 Å	30K	235 K
Y/L2	200 Å	100 Å	60K	252 K
Y/L3	100 Å	50 Å	76K	217 K
YBCO	3000 Å	0 Å	85K	-

Table 1. Shows YBCO, LCMO layers thickness and their transition temperatures T_c and T_{Curie} .

For polarized Raman scattering experiment, a specific polarization configuration of the incident and scattered lights allows us to selectively measure different Raman symmetries. Therefore, a polarizer and an analyzer were placed before and after the sample. In our experiments, we will mainly focus our study on the parallel polarization where the electric field of the incident and scattered lights will be parallel. In this case, the polarizer and the analyzer were kept always parallel during the experiment. A polarization rotator can be used to change the direction of the electric field of the incident light.

After passing through the polarizer, the laser light was guided to the sample through a convex lens. In order to get a sharp spot on the sample surface, the sample was placed at the focal length of the lens. Experiments were performed in

back-scattering geometry. The radiation scattered from the sample is collected by the same lens and guided to the spectrometer. Temperature dependent Raman measurements were performed on superconducting and ferromagnetic (YBCO/LCMO) thin film superlattices as shown in Figure 1 and Figure 2.

For low temperature measurements, the sample was placed in a standard liquid helium flow cryostat. A calibrated digital thermometer (i.e. Si-diode) was placed at the sample position inside the cryostat. This allows the direct control of the sample temperature which important for our study. After that, weak Raman signals were obtained using a triple-grating spectrometer. Its stray light reduction ratio of as little as 10-14 is sufficient to obtain the Raman signal independently. This triple monochromator setup is crucial because two of them are positioned back-to-back to block off stray light, while the

third one separates the Raman signal from the laser light. Finally, due to their high sensitivity and efficiency, CCD detectors are particularly well-suited for Raman investigations when it comes to gathering the Raman signal.

3. Results and Discussion

Raman spectra were obtained at various temperatures below and above the superconducting and ferromagnetic transition temperatures in order to study the behavior of phonon anomalies (phonons self-energy) and the range of collapse, which occur, on LCMO/YBCO thin film superlattice (SLs) around these phase transitions depending on the increase and decrease of the temperature (See Figure 1). The electronic signal exhibits a spectrum redistribution both above and below the superconducting transition temperature. The superconducting gap is opening [12], as seen by this distribution of the spectral weight below T_c .

In order to study the temperature dependence effect on YBCO/LCMO we should assign phonon modes of the YBCO/LCMO superlattice. For more confirmation, spectra of

our samples were compared our thin films data in Figure 1 with bulk YBCO and bulk LCMO spectra in Figure 2. For more concentration part of this study, we apply the light polarization along the crystallographic b-axis and c-axis, respectively as shown in Figure 3, whereas axes were determined by X-ray scattering. The Raman spectrum of the YBCO/LCMO superlattice, YBCO and LCMO single crystal consist of phonon modes arising from both YBCO and LCMO layers. In this article, the most dominant modes are at 240 cm^{-1} , 340 cm^{-1} , 440 cm^{-1} , 505 cm^{-1} phonon modes. The 240 cm^{-1} phonon corresponds to LCMO (O1) due to in-phase rotational vibration of MnO6 octahedra [17, 30], whereas the 340 cm^{-1} phonon corresponds to YBCO layer and reflects the out-of-phase vibrations of planar oxygen (O2-O3) [3, 13]. The 440 cm^{-1} phonon mode corresponding to the in-phase vibration of the O (2) and O (3) (O2+ O3) along the z direction in YBCO or belong to out-of-phase rotations of the MnO6 octahedron in LCMO. The 505 cm^{-1} mode belong to the vibrations of the apical oxygen O (1) along the z direction [2, 18].

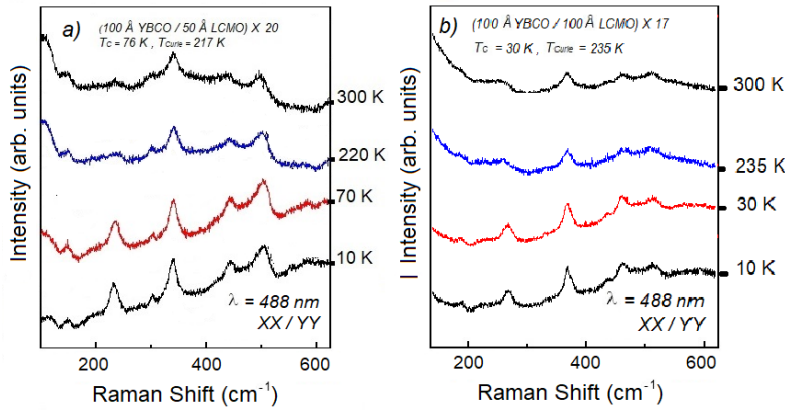


Figure 1. Raman spectra of $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$ thin film superlattice, a) for $(100\text{ Å YBCO}/50\text{ Å LCMO}) \times 20$, b) for $(100\text{ Å YBCO}/100\text{ Å LCMO}) \times 17$ taken in xx/yy polarization at different temperatures.

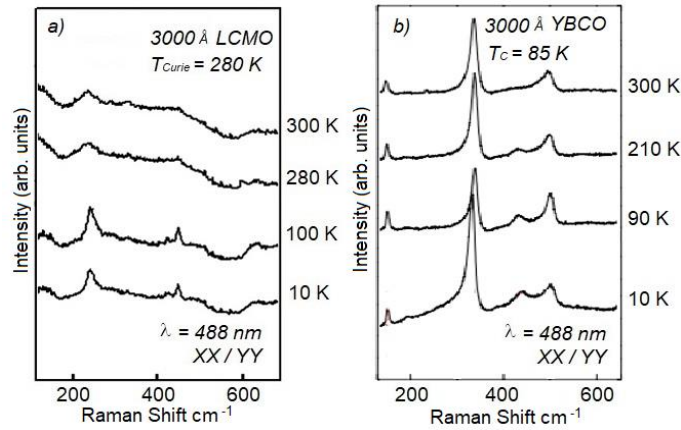


Figure 2. Raman spectra of a) Bulk 3000 Å LCMO where the 240 cm^{-1} phonon anomaly collapses with increasing temperature, b) Bulk 3000 Å YBCO where the 340 cm^{-1} phonon anomaly reduces with increasing temperature and both spectra were taken in xx/yy polarization at different temperatures.

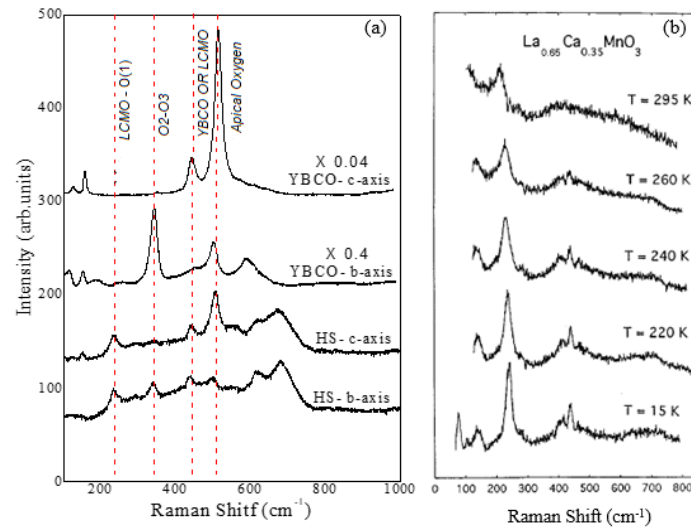


Figure 3. (a) A comparison of YBCO/LCMO thin film Raman spectra to YBCO and LCMO crystals. (b) Right part of the figure is taken from $\text{La}_{0.65}\text{Ca}_{0.35}\text{MnO}_3$ at various temperatures [17].

In this work, we confirmed that the variation of temperature causes changes in frequency and linewidth in all phonons were studied in this paper. The variation of temperature enhances the electron-phonon interaction in the superconducting state and that leads to change in the phonon self-energy (Σ) [16, 20], which gives rise to alteration in the phonon linewidth and frequency below T_c . The phonon frequency shift represents the real part of the phonon self-energy, whereas the phonon linewidth represents the imaginary part. The optical phonon frequency shifts to lower values (softens) if it is below the pair threshold energy 2Δ . There will be a noticeable broadening in the phonon's linewidth if the optical phonon's energy is near T_c , or threshold energy 2Δ . In conclusion, the phonon will harden if its energy exceeds 2Δ .

The superlattice spectra's of LCMO and YBCO phonon profile frequencies and linewidths are comparable to those measured in the bulk analogues, despite being significantly larger than the instrumental resolution. This suggests that structural disorder unique to the superlattice geometry does not significantly affect the results. The asymmetric line forms of the modes further show that the electron-phonon interaction, not defects, dominates their widths. Therefore, the strong temperature dependency of these phonons' frequencies and linewidths supports this finding see Figure 4 (a-d).

In the case of the 240 cm^{-1} LCMO phonon, it was predicted to occur during the ferromagnetic phase transition. The surprise came out of our research was that superconductivity caused alterations in this phonon mode, where the frequency softened by 3 cm^{-1} and the linewidth broadened by 5 cm^{-1} (see Figure 4 (a1, a2)). The softening of this mode below the superconducting gap (2Δ) because the superconductivity order parameter - throw cooper pairs - decay exponentially in the ferromagnetic and that behaviour was unexpected. All of that belong to the variation of temperature as we observed in this work.

At first glance, structural changes that take place during the LCMO/YBCO thin film superlattice samples transition from paramagnetic insulator (PI) to ferromagnetic metallic (FM) phase transition could be the reason behind the frequency and linewidth changes of the 240 cm^{-1} phonon mode at T_{curie} were that attributed due to the change of the temperature. A more ordered structure is thus obtained below T_{curie} as a result of these structural modifications, which also lead to a decrease in the number of Jahn-Teller sites. Nevertheless, Jahn-Teller effect results in irreversible phase change and harmful structural instability, which reduces cycling stability. Here, it is shown that controlling the Mn average valence is an effective way to inhibit the Jahn-Teller phenomenon in Mn-based multilayer oxides. [6, 7, 14, 19, 22-24, 26, 29, 30].

On the other hand, the static J-T distortion would eventually vanish and be replaced by slowly varying (dynamic) J-T distortions if the system were doped with a divalent ion. The explanation of the paramagnetic insulator to ferromagnetic metallic phase transition in doped manganites is also dependent on these types of dynamic Jahn-Teller distortions [10, 11, 21, 24, 25] which belongs to the variation of the temperature (see Figure 1 and Figure 2).

The 340 cm^{-1} phonon mode is visible in the thin film superlattices spectra of LCMO/YBCO. At room temperature, this phonon mode is rarely noticeable due to its extreme sensitivity to changes in the c-axis temperature (see Figure 3a). However, the 340 cm^{-1} phonon mode is activated during b-axis measurements and clearly seen, even at ambient temperature (see Figure 3a) and that is similar to the behaviour of the 340 cm^{-1} phonon mode in bulk YBCO. On the other hand the anomaly of the 340 cm^{-1} mode clearly seen where the frequency softened by 2 cm^{-1} and the linewidth broadened by 2.5 cm^{-1} below T_c (see Figure 4 (b1, b2)). The reason behind that the 340 cm^{-1} phonon mode of YBCO is located below the 2Δ gap, yet it is still near to it. As a result, its linewidth and

frequency exhibit broadening and softening, respectively.

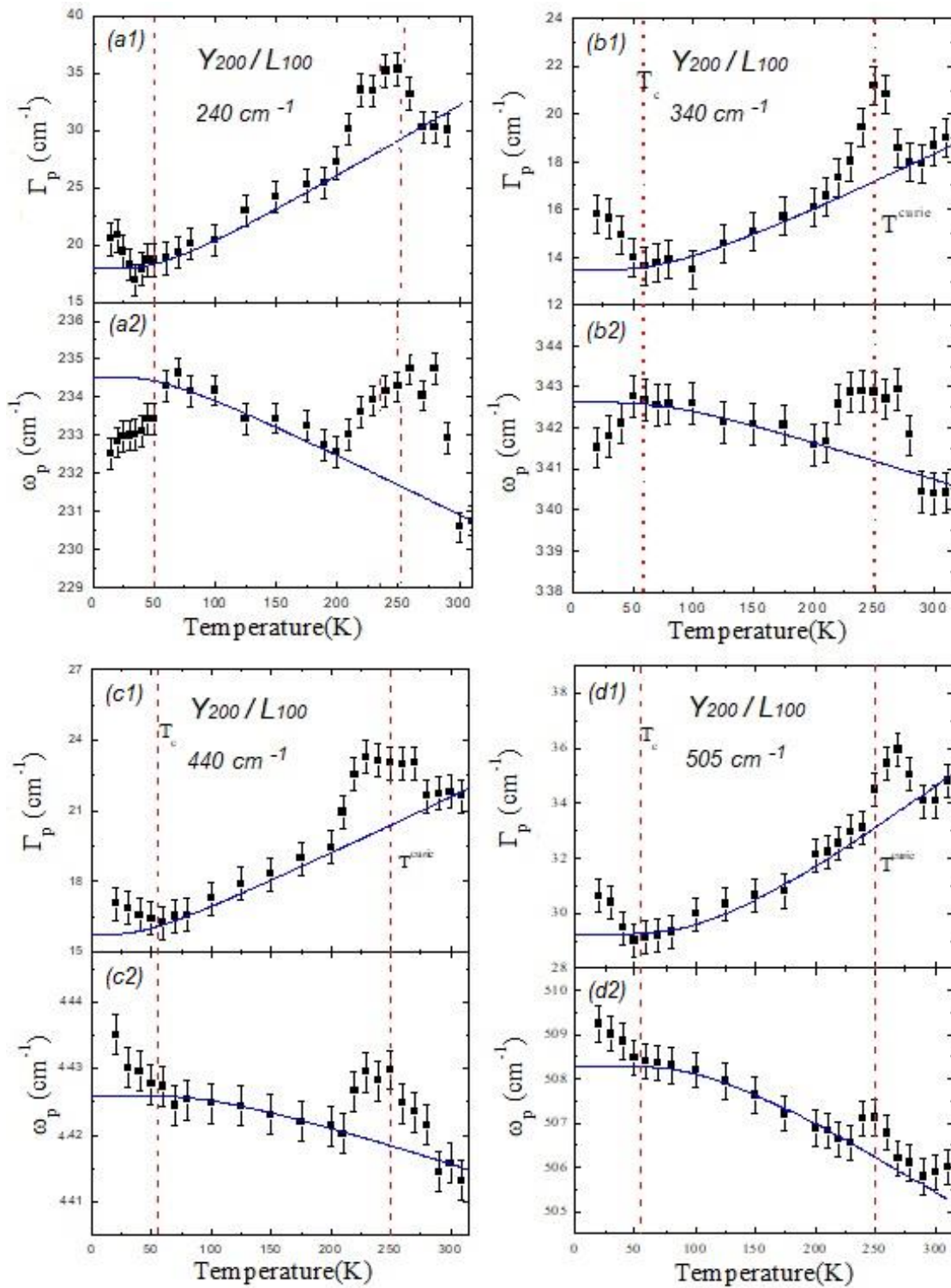


Figure 4. The anomaly observed in frequency and linewidth of 240 cm^{-1} , 340 cm^{-1} , 440 cm^{-1} and 505 cm^{-1} phonons due to variation of temperatures.

According to the concept of the phonon self-energy for the electron-phonon interaction, the linewidth of 440 cm^{-1} mode broadens by 2.5 cm^{-1} and the frequency shows a hardening of

about 1.5 cm^{-1} below T_c and that occur if the superconducting 2Δ gap is below the energy of this mode. On the other hand the frequency and the linewidth of 440 cm^{-1} phonon mode show

abrupt changes when LCMO-films undergo a phase transition from a paramagnetic insulator to a ferromagnetic metal at T_{curie} (250 K) (see Figure 4 (c1, c2)). These kinds of results for this phonon mode have been observed neither in LCMO nor in YBCO alone.

We also found that the apical oxygen phonon mode 505 cm^{-1} of YBCO, has variations in frequency and linewidth in our samples of LCMO/YBCO. This phonon exhibits linewidth broadening by 1.5 cm^{-1} and then frequency softening by 1 cm^{-1} below T_c (see Figure 4 (d1, d2)), respectively. This phonon mode in YBCO is widely known to fluctuate with temperature, and various groups have studied this phenomenon [2, 8]. On the other hand, it was unexpected that the frequency and linewidth of this phonon mode would shift suddenly at the temperature of the ferromagnetic phase transition T_{curie} , but we already have observed that during the increasing of temperature. At the phase transition temperature T_{curie} , the apical phonon experiences magnetism. Hence, the temperature dependence of the phonon frequency and the linewidth as seen in Figure 4 can be described by the next two equations, respectively.

$$\omega_{anh} = \omega_{anh}^0 \left(1 - \frac{a}{\exp(\hbar\omega_p / 2k_B T) - 1} \right)$$

$$\Gamma_{anh} = \Gamma_{anh}^0 \left(1 + \frac{a}{\exp(\hbar\omega_p / 2k_B T) - 1} \right) + \Gamma_b$$

where “a” is a constant. Γ_b is a temperature independent contribution resulting from static defects or charge carriers in the sample.

During our measurements, we have observed variations in the frequency and linewidth of the 240 cm^{-1} phonon and 440 cm^{-1} phonon below T_c , which we attribute to superconductivity effect as cooper pairs penetrate from YBCO to LCMO. One possible reason for these alterations could be the proximity effect [27] -depending on the change of temperature- see Figure 4. Although the 340 cm^{-1} and the 505 cm^{-1} phonons occur due to the superconducting compound YBCO, we observed anomalies at T_{curie} (see Figure 4 (b1, b2) and Figure 4 (d1, d2)) in the form of softening and hardening. This behaviour attributed to the penetration of electrons from the FM to SC due to the increasing of temperature, which enhance the electrons to travel from FM in the direction of SC and that excites this interaction and in fact that behaviour was unexpected.

4. Conclusion

In this paper, we have performed temperature dependence measurements using Raman light scattering to study the effect of the variation of temperature at the interplay between su-

perconductivity and ferromagnetism at YBCO/LCMO interfaces. The study specially concentrate on the change that has occurred of phonons self-energy -change of phonons anomaly at frequency and linewidth- due to the alteration of temperature and how phonons approaching extinction (nearing collapse) with increasing temperature. Therefore, the measurements focused on the variation of the superconducting transition temperature T_c and the ferromagnetic transition temperature T_{curie} for the thin film superlattice sample, respectively, (see Table 1). Depending on that we have observed superconductivity induced changes in phonons self-energy in the linewidth and the frequency of phonons arising from the LCMO/YBCO superlattice whether belong to YBCO alone, LCMO alone or YBCO/LCMO thin films, which we studied in this article. Whereas we have also observed that transition from paramagnetic to ferromagnetic induced changes in the linewidth and the frequency of all phonons, which we studied here. Depending on all of that, we can conclude that the variation of the temperature from lower degrees to the higher degrees leads the phonons to suffer and then undergoes collapse as seen in Figure 1 and Figure 2 but with different degrees, which requires more studies to determine it exactly.

Abbreviations

YBCO	Yttrium Barium Copper Oxide
LCMO	Lanthanum Calcium Manganese Oxide
Sc	Superconductor
PI	Paramagnetic Insulator
FM	Ferromagnetic Metallic
SLs	Superlattice
T_c	Critical Temperature
T_{Curie}	Curie Temperature
PLD	Pulsed Laser Deposition
SrTiO ₃	Strontium Titanate Oxide
CCD	Charge-Coupled Device
Σ	Phonon Self-Energy
J - T	Jahn - Teller
Mn	Manganese
2Δ	Superconducting Gap

Author Contributions

Nadir Driza: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing

Asma Rajab Salem Elgade: Software, Writing - original draft, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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