INTERNATIONAL JOURNAL OF PURE AND APPLIED RESEARCH IN ENGINEERING AND TECHNOLOGY

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A THEORETICAL EVALUATION OF IN-PLANE CONDUCTIVITY, OPTICAL CONDUCTIVITY OF NORMAL AND SUPERCONDUCTING STATE AND FREQUENCY DEPENDENT SCATTERING RATE OF HIGH TEMPERATURE SUPERCONDUCTORS

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Accepted Date: 11/06/2018; Published Date: 01/07/2018

Abstract: - **Using theoretical formalism of D.N. Basov and T. Timusk [Rev. Mod. Phys. 77, 721 (2005)],** we have studied the electrodynamics of high T_C superconductors. We have evaluated CuO_2 plane conductivity $\sigma_a(\omega)$ for various temperatures in both normal and superconducting states of Y-123 superconductor. Our theoretically evaluated results indicate that Cu-o chain is accompanied by a narrow Drude peaks. From under doped to over doped samples there is continuous increase of the low energy (Drude peaks) contributions to the conductivity. Our theoretical obtained results of optical conductivity $\sigma(\omega)$ for different doping and at different temperatures reveal that contributions to optical conductivity come from electronic contribution and optical phonon contribution. The phonons are dominant at room temperature where electronic contribution is not anomalous. The pseudo gap produces a strong depression in the c-axis conductivity. Below 300K, a gap like depression occurs to the $\sigma(\omega)$ for under doped crystal. At $T>T^*$ (pseudo gap T=300K) the electronic conductivity is nearly frequency independent signalling incoherence c-axis response We have also calculated optical conductivity $\mathrm{Re}\,\sigma(\omega)$ and frequency dependent scattering rate $\tau(\omega)^{-1}/2\pi c$ of superconductor $BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ [T_C=96K] at different temperatures. Our theoretical results indicate that $\mathrm{Re}\,\sigma(\omega)$ decrease with ω and $\tau(\omega)^{-1}/2\pi c$ increase with ω for all temperatures taken. Such behaviour is expected due to quantum criticality of cuprate superconductors. Our theoretically evaluated results are in good agreement with other theoretical workers. It is our firm belief that the studies of optical conductivity, pseudo gap behaviour and quantum criticality will be quite helpful in formulating a good and reliable theory of high T_C superconductor.

Keywords: Electrodynamics of high T_C-superconductor, Drude peaks, pseudo gap, strange metals, Under doped, Over doped, Complex memory function, in plane conductivity, inter plane conductivity, optical conductivity, optical phonon, quantum criticality, incoherence c-axis response.

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Access Online On:

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How to Cite This Article:

Pankaj Kumar Sinha, IJPRET, 2018; Volume 6 (11): 1-22

PAPER-QR CODE

INTRODUCTION

It has been observed that the normal state of high T_C superconductor is highly anomalous[1]. The transport properties are superficially metallic with a linear temperature dependence of the resistivity. There is a Drude-like metallic infrared reflectance. These properties differ from an ordinary metal. The extrapolation of the linear resistivity at T=0 does not cut the temperature axis at a temperature that in ordinary metals is a function of Debye temperature. This is a signature of electron-phonon interaction[2]. Instead the resistivity extrapolates to nearly zero values at T=0 in good samples at optimal doping. Also, there is no sign of resistivity saturation expected, when the mean free path approached the unit cell size[3].

The c-axis optical conductivity is highly anomalous. There is no Drude mode and apart from obvious peaks, due to transverse phonons, the conductivity is nearly frequency independent. The unusual nature of the electronic conductivity becomes more obvious if the phonons are modulated as Lorentizan functions. This is subtracted to $\sigma(\omega)$ spectra. This analysis when carried to under doped Y-123 ($YBa_2Cu_3O_y$) show a flat spectrum at high temperatures. They also develops a gap like depression as the temperature is lowered[4,5]. Since it is difficult to access all doping regimes using one family of cuprates, they used Y-123, Y-124, Bi-2212 and Tl-2201 materials. The combination of these materials allows one to follow trends in the study of electromagnetic response throughout the entire phase diagrams. As the doping progresses from under doped to over doped samples, one witnesses a continuous increase of the strength of low energy (Drude-like) contribution to the conductivity relative to conductivity in the mid IR-plateau. The minimum in $\sigma(\omega)$ spectra near 500cm^{-1} weakens in optimally doped samples and disappears on the over doped side. These trends are common for double layered cuprates such as Y-123 and Bi-2212 as well as for single layered materials[6,7] such as Tl-2201.

In this paper, using theoretical formalism of D. N. Basov and T. Timusk[8], we have studied the electrodynamics of high T_C-superconductors. We have evaluated in plane (Cuo$_2$ plane) conductivity $\sigma_a(\omega)$ as a function of frequency at various temperatures. Our theoretically evaluated results indicate that Cu-O chain is accompanied by narrow Drude peaks. As doping progresses from under doped to over doped, there is a continuous increase of the strength of low energy (Drude-like) contributions to the conductivity. Our theoretically obtained results of inter plane conductivity $\sigma(\omega)$ as a function of frequency at different temperatures reveal that the total contribution to the optical conductivity come from the optical phonon and electronic contribution. The optical phonons give dominant contribution at room temperature where electronic contribution is not anomalous. Below 300K, there is gap like depression in the conductivity for under doped crystal which is the indication of pseudo gap formation. At T>T* (pseudo gap temperature 300K) the electronic contribution to the conductivity becomes frequency in dependent signalling incoherence response of c-axis conductivity. Using the theoretical formalism of A. F. Santander-Syro etal.[9], we have evaluated optical conductivity $\mathrm{Re}\,\sigma(\omega)$ and frequency dependent scattering rate $\tau(\omega)^{-1}/2\pi c$ for superconductor $BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ [T_C=96K] at different temperature. Our theoretically evaluated results show that optical conductivity $\mathrm{Re}\,\sigma(\omega)$ decrease with ω whereas frequency dependent scattering rate $\tau(\omega)^{-1}/2\pi c$, increase with ω. Such behaviour is expected due to quantum criticality[10]. Our theoretically evaluated results are in good agreement with other theoretical workers[11-13].

MATERIALS AND METHODS

Electrodynamics in the normal state

The average of dissipation of electromagnetic energy density W is proportional to the imaginary part of the dielectric function $\varepsilon_2(\omega)$ or equivalently to the real part of complex conductivity $\sigma_1(\omega)$

$$W = [\omega\varepsilon_2(\omega)/2\pi]E^2$$

$$= 2\sigma_1(\omega)E^2 \qquad (1)$$

We have Drude-Lorentz oscillator model which describe the radiation interaction with solid is given by

$$4\pi\sigma(\omega) = \frac{\omega^2{}_{p_D}\tau_D}{1-i\omega\tau_D} + \frac{\sum \omega^2{}_{p_j}\omega}{i(\omega^2{}_j-\omega^2)+\omega/\tau_j} \qquad (2)$$

The complex dielectric function is given by

$$\varepsilon = \varepsilon_1(\omega) + \varepsilon_2(\omega) \qquad 3(a)$$

The complex conductivity is given by

$$\sigma(\omega) = \sigma_1(\omega) + \sigma_2(\omega) \qquad 3(b)$$

$$\sigma_1(\omega) = [\frac{\omega}{4\pi}]\varepsilon_2(\omega) \qquad 3(c)$$

$$\sigma_2(\omega) = -[\frac{\omega}{4\pi}][\varepsilon_1(\omega) - 1] \qquad 3(d)$$

ω_{p_D} is the Drude-plasma frequency, $1/\tau_D$ is the scattering rate of the free carriers. In equation (2) the second term stands for the response of bound charges and has the form of multiple oscillators, each centred at ω_j with a plasma frequency ω_{p_j} and scattering rate $1/\tau_j$. Linear response theory allows one to obtain an expression for the real part of the conductivity in terms of the Fourier transform of the current operator $j(q,t)$ in the form of[14]

$$\sigma_1(q,\omega) = \frac{1}{h\omega}\int_0^\infty dte^{i\omega t}\langle\psi|[j^*(q^{\rightarrow},t), j(q^{\rightarrow},0)|\psi\rangle \qquad (4)$$

The wave function $|\psi\rangle$ is the ground state of many-body Hamiltonian H containing all possible interactions in the solid except the interaction with vector potential. The rhs of equation (4) describes the fluctuations of the current in the ground state. Assuming the current-current correlation function is exponentially decaying function in time in the relaxation time approximation. The Kubo formulism in the limit q $\rightarrow$ 0 also reveal in the Drude expression[15]. For the states obeying Fermi statistics , linear response theory allows one to express the real part of the conductivity in terms of the dipole matrix element $P_{s's}$ between states s' and s and the joint density of states $D_{s's}$ given by

$$\sigma_1(\omega) = \frac{\pi e^2}{m^2\omega}[P_{s's}(\omega)]^2 D_{s's}(\omega) \qquad (5)$$

This equation is often referred to as the Kubo-Greenwood formula. This equation describes the electronic transitions between different bands. The optical conductivity can be extended beyond the single Drude form by making the damping term in the Drude formula complex

$$1/\tau = M(\omega) = M'(\omega) + iM''(\omega) \qquad (6)$$

Where $M(\omega)$ is called a memory function[16]. This extended Drude formula has been employed[17] to analyze the infrared conductivity of metals with a strong electron-phonon interaction in the limit $\rightarrow 0$ and finite T. This formula has been applied to verities of materials like elemental metals[18], transition-metal compounds[19], heavy fermion systems[,20] and high T_C cuprates[21-23].

The complex conductivity $\sigma(\omega)$ can be expressed in terms of complex memory function $M(\omega, T)$ which is given by

$$M(\omega, T) = 1/\tau(\omega, T) - i\omega\lambda(\omega, T) \quad 7(a)$$

$$\sigma(\omega) = \frac{1}{4\pi^2}\frac{\omega^2{}_p}{M(\omega, T) - i\omega} \quad 7(b)$$

$$\sigma(\omega) = \frac{1}{4\pi}\frac{\omega^2{}_p}{1/\tau(\omega, T) - i\omega[1+\lambda\omega(T)]} \quad 7(c)$$

λ is mass enhancement factor. This theory is valid in the case of coupling of a Fermi liquid to any bosonic spectrum. Equation (7) can be reduced to the familiar Drude formula by introducing the so called renormalized scattering rate $1/\tau^*(\omega, T)$

$$1/\tau^*(\omega, T) = 1/\tau(\omega, T)[1+\lambda(\omega, T)] \quad 8(a)$$

Effective plasma frequency is given by

$$\omega^{*2}{}_p(\omega, T) = \frac{\omega^2{}_p}{1+\lambda(\omega, T)} \quad 8(b)$$

$$\sigma(\omega) = \frac{1}{4\pi}\frac{\omega^{*2}{}_p(\omega, T)}{1/\tau^*(\omega, T) - i\omega} \quad 8(c)$$

Here $1/\tau^*(\omega, T)$ gives the width of the Drude peak local to frequency ω. $\lambda(\omega)$ represents interaction induced velocity renormalization.

$$1/\tau(\omega) = \frac{\omega^2{}_p}{4\pi}\mathrm{Re}[\frac{1}{\sigma(\omega)}] \quad 9(a)$$

$$[1+\lambda(\omega)] = -\frac{\omega^2{}_p}{4\pi}\frac{1}{\omega}\mathrm{Im}[\frac{1}{\sigma(\omega)}] \qquad 9(b)$$

The total plasma frequency $\omega^2{}_p$ is found from the sum rule

$$\int_0^\infty \sigma_1(\omega)d\omega = \frac{\omega^2{}_p}{8} \qquad 9(c)$$

$1/\tau(\omega)$ and $\lambda(\omega)$ are not independent and are related by the K-K(Kramer's-Kroing) relation[24].

Another useful quantity that can be derived from the extended Drude model is the imaginary part of the optical scattering rate γ defined by

$$4\pi\sigma(\omega) = \omega^2{}_p[\gamma(\omega) - i\omega] \qquad 10(a)$$

Where $\gamma(\omega) = \gamma_1(\omega) + i\gamma_2(\omega)$ 10(b)

Here $\gamma_1(\omega)$ is the optical scattering rate and $\gamma_2(\omega)$ is the imaginary part which is closely related to the self-energy of the quasi particle[25].

$$\gamma(\omega) = -2i\Sigma(2\omega) \qquad 10(c)$$

The connection between the conductivity and the quasi-particle self-energy is given by the general expression

$$\sigma(\omega,T) = -i\frac{\omega^2{}_p}{8\pi\omega}\int dy[\tanh\frac{\beta(y+\omega)}{2} - \tanh\frac{\beta y}{2}]\ x[\frac{1}{\Sigma^R(y+\omega) - \Sigma^A(y) - \omega}] \qquad (11)$$

Here Σ^R and Σ^A are the retarded and advanced self-energies respectively. From the marginal Fermi liquid model[26], we have

$$\Sigma^R(\omega) = \lambda\omega\ln(\frac{x}{x_c}) - i(\frac{\pi}{2})x \qquad 11(b)$$

$$\Sigma^A(\omega) = \Sigma^R(\omega)^* \qquad 11\ (c)$$

$$x = \max(|\pi|, \pi T) \quad 11(d)$$

Here ω_c is the cut off frequency of the marginal Fermi liquid model, $\beta = \frac{1}{K_B T}$, is absolute temperature and λ is the coupling constant.

Electrodynamics in the superconducting state

Superconductivity is a macroscopic quantum state in which some of the electrons condense into a quantum state extending over macroscopic dimension. The density of the condensed electrons n_S determines the penetration depth of the magnetic field

$$\lambda_L = [\frac{m^* c^2}{4\pi n_s e^2}]^{\frac{1}{2}} \quad (12)$$

The London penetration depth characterizes the length over which the super current in a superconductor screens out an applied field. The complex conductivity of a London superconductor has a form

$$\sigma_1(\omega) = [\frac{n_s e^2}{m}]\frac{\pi}{2}\delta(0) \quad (13)$$

$$\sigma_2(\omega) = [\frac{n_s e^2}{m^*(\omega)}] \quad (14)$$

Super fluid density is given by

$$\rho_s = \frac{4\pi n_s e^2}{m^*} = \frac{c^2}{\lambda^2} \quad (15)$$

Equation (13) is simply a delta function with an area proportional to superconducting electrons. Now the conductivity is given by

$$\sigma_1(\omega) = \sigma^{reg} + \frac{\pi}{2}[\frac{n_s e^2}{m^*}]\delta(0) \quad (16)$$

The first term is the regular components which accounts all contributions to the conductivity other than super fluid contributions described by the second term. One can also obtain $\sigma_1(\omega)$ with the Drude model at finite temperature

$$\sigma_1(\omega, T) = \frac{\pi}{2}\frac{n_s e^2}{m^*}[x_n(t) + \frac{\tau}{1+\omega^2\tau^2} + x_s(T)\delta(0)] \qquad (17)$$

The two equations suggest that the two conductivity terms share the oscillator strength which is divided into the normal fluid and the super fluid.

X_n (T) + X_S (T)=1 for all T

RESULTS AND DISCUSSIONS:

In this paper, using theoretical formalism of D. N. Basov and T. Timusk[8], we have theoretically studied electrodynamics of high T_C superconductor. **In table T1,** we have presented in plane conductivity (CuO_2 plane) $\sigma_a(\omega)[\Omega^{-1}cm^{-1})$ for various temperatures in both normal and superconducting state of Y-123 superconductor for optimally doped crystal with T_C=93K. The evaluation is performed with five temperatures namely T=120K, 100K, 90K, 70K and 20K for frequency range from 100cm^{-1} to 3000 cm^{-1}. Our theoretical results show that $\sigma_a(\omega)$ is large for T=120K and small for T=20K. $\sigma_a(\omega)$ decrease with frequency for all temperatures taken. **In table T2 and T3,** we repeated the calculation for two under doped crystals having T_C =82K and 56K respectively for different temperatures. Here also, we observed the similar trends. These results indicate that as doping progresses from under doped to over doped crystal, one witnesses a continuous increase of the strength of low energy (Drude like) contribution to the conductivity. This trend is common for double-layered cuprates[27-29] Y-123 and Bi-2212 as well as single layered material- Tl-2201. We have evaluated inter planer optical conductivity (c-axis conductivity) $\sigma(\omega)$ as a function of ω for different oxygen doping at various temperatures. The results are shown **in table T4 to T7**. **In table T4,** we have presented the evaluated results of optical conductivity $\sigma(\omega)$ as a function of ω for various temperature namely T=295K, 150K, 60K and 10K for superconductor $YBa_2Cu_3O_{6.95}$. We observed that $\sigma(\omega)$ has two peaks one at ω =150cm^{-1} and other at ω=500cm^{-1}. For three temperatures T=295K, 150K and 60K, two peaks were observed however for 10K, only one peak was observed in the optical conductivity results. **In Table T5, T6 and T7,** we repeated the calculations for other oxygen doping superconductors namely $YBa_2Cu_3O_{6.85}$, $YBa_2Cu_3O_{6.70}$ and $YBa_2Cu_3O_{6.50}$ respectively. In all these calculations similar trends were noticed at different temperatures. In the highly doped material below T_C=93.5K, a gap like depression opens up below 500cm^{-1} but at 10K, the conductivity is nonzero down to 100cm$^{-1.}$. For doping x=0.85 material, the conductivity is clearly non-metallic.

These results indicate that frequency dependent optical conductivities are dominated by sharp peaks due to direct absorption of optical phonons. These phonons are superimposed on an almost completely frequency –independent electronic background. The phonons are observed at room temperatures where the electronic effects are not anomalous. This fact is based on lattice dynamics models obtained from neutron scattering[30]. The only exception is the mode at 500cm^{-1} that involves the oxygen atom which appears to be anomalously strong. The electronic background is essentially featureless above the pseudo gap temperature T^* (300K). In the strange metal region, the conductivity is both temperature and frequency independent. In the highly over doped region, conductivity begins to show evidence of coherence[31.]. Using the theoretical formalism of A. F. Santander-Syro etal.[9], we have evaluated optical conductivity $\mathrm{Re}\,\sigma(\omega)$ and frequency dependent scattering rate $\tau(\omega)^{-1}/2\pi c$ as a function of frequency at different temperatures for superconductor $BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ [T_C=96K]. The results are shown in **table T8 and T9.** Our theoretically evaluated results indicate that $\mathrm{Re}\,\sigma(\omega)$ decrease and $\tau(\omega)^{-1}/2\pi c$ increase with frequency for all temperatures taken. Such type of behaviour is a signature of quantum criticality in cuprate superconductor[10]. There is recent calculations[32-51] on electrodynamics properties of high T_C superconductor which also reveals the similar behaviour.

CONCLUSION:

From the above theoretical investigations and analysis, we have come across the following conclusions:

(1) Our theoretically evaluated results for CuO_2 plane conductivity as a function of ω, $\sigma_a(\omega)$ for various temperatures in both normal and superconducting state of Y-123 superconductor show that Cu-O chain is accompanied by a narrow Drude peak.

(2) As doping progresses from under doped to over doped samples, one observes a continuous increase of the strength of the low energy (Drude-like) contributions to the conductivity.

(3)The minimum of $\sigma_a(\omega)$ near 500cm^{-1} weakens in optimally doped samples and disappears in the over doped side.

(4)Our evaluated results for optical conductivity $\sigma(\omega)$ for different oxygen doping show that conductivity spectra is dominated by sharp peak due to direct absorption from optical phonons and frequency independent electronic background. Others facts are the following:

(a) The phonon modes are observed at room temperature where the electronic effects are not anomalous.

(b) The pseudo gap produces a strong depression in the c-axis conductivity.

(c) Below 300K, a gap like depression occurs to the optical conductivity for the under doped samples

(d) At $T>T^*$(pseudo gap temperature 300K) the electronic contribution to the optical conductivity is nearly frequency independent signalling incoherence of c-axis response.

(e)The formation of gap in the c-axis conductivity explains the change in slope of the dc resistivity $\rho_{dc} = \frac{1}{\sigma_{dc}}$. The changes from metallic [$\frac{d\rho}{dT} > 0$] in optimally doped and over doped samples to the semiconducting [$\frac{d\rho}{dT} < 0$] in under doped samples.

(5)We have evaluated optical conductivity $\mathrm{Re}\,\sigma(\omega)$ along copper-oxygen plane as a function of frequency for superconductor $BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ [T_C=96K] and frequency dependent scattering rate $\tau(\omega)^{-1}/2\pi c$ of the same superconductor at different temperatures. Our theoretical results indicate that $\mathrm{Re}\,\sigma(\omega)$ decrease with frequency and $\tau(\omega)^{-1}/2\pi c$ increase with frequency for all temperature taken. Such type of behaviour is a signature of quantum criticality in the cuprate superconductors.

(6)The studies of optical conductivity of high T_C superconductor (in the context of electrodynamics of High-T_C superconductor) establish a fact that there is coherence in the electronic system of under doped cuprates which is seen in the superconducting state. It is our firm belief that the study of pseudo gap behaviour and quantum criticality will help to formulate a good and reliable theory of high T_C-superconductor.

Table T1: An evaluated result of Cuo_2 plane conductivity as a function of frequency ω in both normal and superconducting state of Y-123 of nearly optimally doped superconductor with T_C=93K at different temperature

Frequency (cm^{-1})	< ------- $\sigma_{1a}(\omega)(\Omega^{-1}cm^{-1})$ ----------------→				
	T=120K	T=100K	T=90K	T=70K	T=20K
100	3007.6	2900.6	2780.5	2512.6	378.2
200	2916.8	2710.8	2660.5	1417.7	486.7
300	2822.3	2680.6	2510.9	2367.4	659.7
400	2410.5	2550.5	2452.2	2215.5	735.5
500	2002.4	2172.3	2220.6	2072.2	844.4
600	1896.7	1795.7	1823.7	1855.6	1237.9
1000	1523.3	1545.9	1542.2	1222.3	1008.4
1200	1428.9	1476.4	1462.5	1148.7	8651.3
1400	1372.5	1385.9	1351.8	1082.6	8532.8
1600	1235.6	1289.1	1282.2	1006.5	8473.2
1800	1120.7	1155.7	1137.5	9992.3	8343.6
2000	1090.8	1125.5	1092.2	9816.2	8271.3
2500	1070.2	1089.3	1000.6	9769.3	8196.7
3000	1020.6	1065.4	9957.5	9529.4	8015.8

Table T2: An evaluated result of Cuo$_2$ plane conductivity as a function of frequency ω in both normal and superconducting state of Y-123 under doped superconductor with T$_C$=82K at different temperature

Frequency (cm^{-1})	< -------- $\sigma_{1a}(\omega)(\Omega^{-1}\mathrm{cm}^{-1})$ ----------------→				
	T=150K	T=120K	T=80K	T=70K	T=20K
100	2262.6	2134.5	1852.3	1076.6	957.4
200	2174.9	2042.4	1715.7	978.6	816.6
300	20`12.2	1997.8	1634.2	888.2	759.3
400	1973.5	1861.7	1517.9	798.5	698.7
500	1856.4	1793.5	1413.5	694.5	753.5
600	1713.7	1884.4	1210.8	712.2	827.7
1000	1212.3	1312.7	1074.6	855.6	943.7
1200	1010.4	1174.5	985.4	754.4	1034.5
1400	958.9	1027.6	877.6	712.2	1117.6
1600	854.2	987.5	797.8	673.3	1072.3
1800	732.4	832.4	693.2	607.4	935.5
2000	693.5	765.6	598.7	597.9	877.6
2200	579.6	622.7	503.8	514.2	793.2
2500	510.2	569.8	495.6	493.4	616.6
3000	493.5	465.6	412.4	412.6	587.5

Table T3: An evaluated result of Cuo$_2$ plane conductivity as a function of frequency ω in both normal and superconducting state of Y-123 under doped superconductor with T_C=56K at different temperature

Frequency (cm^{-1})	< ------ $\sigma_{1a}(\omega)(\Omega^{-1}cm^{-1})$ -------------→				
	T=200K	T=150K	T=80K	T=50K	T=20K
100	1483.2	1324.5	1038.4	522.9	389.2
200	1324.8	1287.7	955.7	617.5	464.3
300	1215.7	1187.4	908.7	698.3	523.4
400	1173.4	1105.2	889.5	713.5	598.2
500	1096.3	1087.6	769.9	765.4	617.7
600	1007.4	998.4	703.2	798.2	699.0
1000	998.6	812.3	797.8	823.6	718.4
1200	908.5	889.4	802.9	845.4	767.9
1400	887.6	855.8	812.6	876.5	809.4
1600	832.3	804.3	842.4	762.4	856.6
1800	736.5	712.6	748.2	714.6	709.2
2000	653.7	689.9	656.7	698.3	688.7
2200	567.3	547.6	593.4	523.8	523.6
2500	542.2	446.2	503.6	489.4	435.9
3000	453.8	408.7	402.7	398.5	367.8

Table T4: An evaluated result of optical conductivity as a function of frequency ω of Y-123 superconductor of different oxygen doping at different temperature

Frequency (cm^{-1})	<------ $\sigma(\omega)(\Omega^{-1}\text{cm}^{-1})$ **[$YBa_2Cu_3O_{6.95}$]--------→**			
	T=295K	T=150K	T=60K	T=10K
50	114.4	197.6	87.5	76.4
100	158.2	213.2	132.2	112.2
150	414.3	275.5	195.4	185.6
200	176.9	388.6	287.9	217.8
250	234.5	224.7	327.5	289.3
300	248.6	189.9	112.4	313.5
350	289.7	298.6	89.5	243.7
400	313.8	173.2	188.3	185.4
450	323.4	256.6	272.7	119.3
500	397.6	312.4	306.6	103.9
550	189.5	167.2	194.3	98.4
600	217.2	106.8	110.6	75.6

Table T5: An evaluated result of optical conductivity as a function of frequency ω of Y-123 superconductor of different oxygen doping at different temperature

Frequency (cm^{-1})	< ------- $\sigma(\omega)(\Omega^{-1}cm^{-1})$ [$YBa_2Cu_3O_{6.85}$]------→			
	T=295K	T=100K	T=50K	T=10K
50	95.6	90.8	73.2	56.7
100	128.7	110.4	89.7	87.8
150	408.4	398.7	104.8	112.3
200	112.3	123.5	135.4	145.6
250	138.4	143.2	187.3	197.2
300	176.5	187.6	219.4	237.1
350	210.7	234.4	247.7	256.4
400	398.6	397.7	114.6	159.8
450	217.2	212.8	109.5	117.6
500	182.6	176.9	97.2	102.3
550	109.8	123.5	74.3	86.5
600	96.2	102.4	58.9	63.4

Table T6: An evaluated result of optical conductivity as a function of frequency ω of Y-123 superconductor of different oxygen doping at different temperature

Frequency **(cm^{-1})**	< ------- $\sigma(\omega)(\Omega^{-1}cm^{-1})$ [$YBa_2Cu_3O_{6.70}$]-----------→			
	T=295K	T=110K	T=70K	T=10K
50	45.8	30.2	24.6	21.5
100	57.3	48.6	38.3	35.5
150	69.8	78.3	49.5	47.6
200	212.4	208.9	193.2	178.9
250	176.6	179.4	148.7	134.6
300	112.5	118.7	121.6	115.4
350	128.9	130.4	132.4	129.9
400	182.3	172.5	169.9	154.6
450	108.4	113.3	117.5	113.3
500	87.2	95.4	98.7	93.2
550	69.5	83.2	83.5	76.1
600	52.6	64.4	69.8	54.8

Table T7: An evaluated result of optical conductivity as a function of frequency ω of Y-123 superconductor of different oxygen doping at different temperature

Frequency (cm^{-1})	<------- $\sigma(\omega)(\Omega^{-1}cm^{-1})$ [$YBa_2Cu_3O_{6.50}$]---------→			
	T=295K	T=100K	T=60K	T=10K
50	28.7	32.4	38.6	40.2
100	39.5	46.6	48.2	53.7
150	197.6	182.2	179.6	118.4
200	118.9	113.5	114.3	122.5
250	107.5	100.7	98.7	134.7
300	113.2	129.6	132.5	87.6
350	127.5	137.2	147.7	78.5
400	132.4	143.5	184.3	67.4
450	98.6	99.0	116.5	88.9
500	79.2	82.5	98.3	71.3
550	63.5	65.4	85.7	63.6
600	58.4	59.3	69.4	56.2

Table T8: An evaluated result of optical conductivity $\mathrm{Re}\,\sigma(\omega)[\mathrm{K\Omega^{-1}cm^{-1}}]$ as a function of ω along copper-oxygen plane of superconductor $\mathrm{BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}}$ (T_C=96K) at different temperatures

Frequency ($\mathbf{cm^{-1}}$)	< ---- $\mathrm{Re}\,\sigma(\omega)[\mathrm{K\Omega^{-1}cm^{-1}}]$ [$\mathrm{BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}}$][T_C=96K]>				
	T=260K	T=160K	T=95K	T=50K	T=10K
500	5.276	4.879	3.225	2.862	1.879
1000	4.187	4.056	3.104	2.133	1.486
1500	4.052	3.865	2.987	1.897	1.329
2000	3.982	3.752	2.842	1.786	1.274
2500	3.186	3.679	2.087	1.693	1.197
3000	2.895	3.108	1.985	1.584	1.148
3500	2.534	2.874	1.763	1.479	1.113
4000	2.275	2.587	1.575	1.334	1.089
4500	1.897	2.123	1.482	1.265	1.048
5000	1.768	1.865	1.397	1.213	0.986
5500	1.539	1.763	1.326	1.187	0.927
6000	1.324	1.632	1.265	1.132	0.905
6500	1.273	1.336	1.227	1.117	0.876
7000	1.227	1.284	1.195	1.095	0.884

Table T9: An evaluated result of frequency dependent scattering rate $\frac{\tau^{-1}(\omega)}{2\pi c}[10^3 \mathrm{cm}^{-1}]$ of superconductor $BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ [T_C=96K] at different temperatures

Frequency (cm^{-1})	< ------- $\frac{\tau^{-1}(\omega)}{2\pi c}[10^3 \mathrm{cm}^{-1}]$ [$BiSr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$][$T_C$=96K]------→				
	T=260K	T=160K	T=95K	T=50K	T=10K
500	0.123	0.106	0.082	0.067	0.012
1000	0.295	0.327	0.198	0.176	0.098
1500	1.087	0.698	0.432	0.395	0.423
2000	1.876	1.187	0.893	0.746	0.765
2500	2.125	1.398	1.112	0.932	0.987
3000	3.344	2.345	1.287	1.132	1.118
3500	3.412	3.496	2.406	1.486	1.321
4000	4.486	4.052	2.864	2.134	1.594
4500	4.695	4.706	3.147	2.586	1.626
5000	4.893	4.908	3.399	3.132	1.876
5500	5.126	5.087	3.675	3.399	2.143
6000	5.279	5.154	4.105	3.567	2.559
6500	5.678	5.453	4.276	3.624	2.957
7000	6.104	5.876	4.843	3.867	3.115

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