

ERRATUM



## Erratum to: Terahertz spectroscopy of high temperature superconductors and their photonic applications

Choongwon Seo<sup>1</sup> · Jeonghoon Kim<sup>2</sup> · Seonhye Eom<sup>2</sup> · Kyungwan Kim<sup>1</sup> · Hyeong-Ryeol Park<sup>2</sup>

Published online: 30 March 2022  
© The Korean Physical Society 2022

### Erratum to: Journal of the Korean Physical Society <https://doi.org/10.1007/s40042-022-00403-3>

In the list of the references, we added the missing volume and page numbers of the references and revised the incorrect journal name as the following:

The original article has been corrected.

## References

5. D. N. Basov, T. Timusk, Electrodynamics of high-T<sub>C</sub> superconductors. Rev. Mod. Phys. **77**, 721 (2005). <https://doi.org/10.1103/RevModPhys.77.721>
6. Ø. Fischer et al., Scanning tunneling spectroscopy of high-temperature superconductors. Rev. Mod. Phys. **79**, 353 (2007). <https://doi.org/10.1103/RevModPhys.79.353>
7. J. Oh et al., Role of interlayer coupling in alkaline-substituted (Bi, Pb)-2223 superconductors. J. Alloys Compd. **804**, 348 (2019). <https://doi.org/10.1016/j.jallcom.2019.07.029>
11. C. C. Homes et al., Optical conductivity of nodal metals. Sci. Rep. **3**, 3446 (2013). <https://doi.org/10.1038/srep03446>
12. C. C. Homes et al., Sum rules and energy scales in the high-temperature superconductor YBa<sub>2</sub>Cu<sub>3</sub>O<sub>6+x</sub>. Phys. Rev. B **69**, 024514 (2004). <https://doi.org/10.1103/PhysRevB.69.024514>
13. A. Pashkin et al., Femtosecond response of quasiparticles and phonons in superconducting YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> studied by wideband terahertz spectroscopy. Phys. Rev. Lett. **105**, 067001 (2010). <https://doi.org/10.1103/PhysRevLett.105.067001>
16. P. Tassin, T. Koschny, M. Kafesaki, C. M. Soukoulis, A comparison of graphene, superconductors and metals as conductors for metamaterials and plasmonics. Nat. Photonics **6**, 259 (2012). <https://doi.org/10.1038/nphoton.2012.27>
17. A. Tsiatmas, V. A. Fedotov, F. J. G. de Abajo, N. I. Zheludev, Low-loss terahertz superconducting plasmonics. New J. Phys. **14**, 115006 (2012). <https://doi.org/10.1088/1367-2630/14/11/115006>
18. Y. K. Srivastava, R. Singh, Impact of conductivity on Lorentzian and Fano resonant high-Q THz metamaterials: superconductor, metal and perfect electric conductor. J. Appl. Phys. **122**, 183104 (2017). <https://doi.org/10.1063/1.4994951>
22. V. Savinov et al., Modulating sub-THz radiation with current in superconducting metamaterial. Phys. Rev. Lett. **109**, 243904 (2012). <https://doi.org/10.1103/PhysRevLett.109.243904>
24. W. Cao et al., Plasmon-induced transparency in metamaterials: active near field coupling between bright superconducting and dark metallic mode resonators. Appl. Phys. Lett. **103**, 101106 (2013). <https://doi.org/10.1063/1.4819389>
26. C. Li et al., Electrical dynamic modulation of THz radiation based on superconducting metamaterials. Appl. Phys. Lett. **111**, 092601 (2017). <https://doi.org/10.1063/1.4997097>
27. Y. K. Srivastava et al., A superconducting dual-channel photonic switch. Adv. Mater. **30**, 1801257 (2018). <https://doi.org/10.1002/adma.201801257>
29. C. S. Tang et al., Terahertz conductivity of topological surface states in Bi<sub>1.5</sub>Sb<sub>0.5</sub>Te<sub>1.8</sub>Se<sub>1.2</sub>. Sci. Rep. **3**, 3513 (2013). <https://doi.org/10.1038/srep03513>
30. T. Hong et al., Terahertz electrodynamics and superconducting energy gap of NbTiN. J. Appl. Phys. **114**, 243905 (2013). <https://doi.org/10.1063/1.4856995>
31. B. C. Park et al., Terahertz single conductance quantum and topological phase transitions in topological insulator Bi<sub>2</sub>Se<sub>3</sub> ultrathin films. Nat. Commun. **6**, 6552 (2015). <https://doi.org/10.1038/ncomms7552>
33. B. Cheng et al., Terahertz conductivity of the magnetic Weyl semi-metal Mn<sub>3</sub>Sn films. Appl. Phys. Lett. **115**, 012405 (2019). <https://doi.org/10.1063/1.5093414>
35. H. T. Lee et al., Measuring complex refractive indices of a nanometer-thick superconducting film using terahertz time-domain spectroscopy with a 10 femtoseconds pulse laser. Crystals. **11**, 651 (2021). <https://doi.org/10.3390/cryst11060651>
37. O. G. Vendik, I. B. Vendik, D. I. Kaparkov, Empirical model of the microwave properties of high-temperature superconductors. IEEE Trans. Microw. Theory Tech. **46**, 469 (1998). <https://doi.org/10.1109/22.668643>
38. A. J. Berlinsky, C. Kallin, G. Rose, A. C. Shi, Two-fluid interpretation of the conductivity of clean BCS superconductors. Phys.

The original article can be found online at <https://doi.org/10.1007/s40042-022-00403-3>.

- ✉ Kyungwan Kim  
kyungwan@cbnu.ac.kr
- ✉ Hyeong-Ryeol Park  
nano@unist.ac.kr

<sup>1</sup> Department of Physics, Chungbuk National University, Cheongju, Chungbuk 28644, Republic of Korea

<sup>2</sup> Department of Physics, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea

- Rev. B **48**, 4074 (1993). <https://doi.org/10.1103/PhysRevB.48.4074>
39. R. A. Kaindl et al., Dynamics of cooper pair formation in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . Phys. Rev. B **72**, 060510(R) (2005). <https://doi.org/10.1103/PhysRevB.72.060510>
40. Y. S. Lee, Quasiparticle dynamics and superconductivity in the 60-K phase of  $\text{YBa}_2\text{Cu}_3\text{O}_y$ . J. Korean Phys. Soc. **50**, 1109 (2007). <https://doi.org/10.3938/jkps.50.1109>
41. J. Hwang, T. Timusk, G. D. Gu, Doping dependent optical properties of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . J. Phys. Condens. Mat. **19**, 125208 (2007). <https://doi.org/10.1088/0953-8984/19/12/125208>
42. R. Buhleier et al., Anomalous behavior of the complex conductivity of  $\text{Y}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_7$  observed with THz spectroscopy. Phys. Rev. B **50**, 9672(R) (1994). <https://doi.org/10.1103/PhysRevB.50.9672>
43. S. M. Quinlan, P. J. Hirschfeld, D. J. Scalapino, Infrared conductivity of a  $d_{x^2-y^2}$ -wave superconductor with impurity and spin-fluctuation scattering. Phys. Rev. B **53**, 8575 (1996). <https://doi.org/10.1103/PhysRevB.53.8575>
44. J. Corson et al., Nodal quasiparticle lifetime in the superconducting state of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . Phys. Rev. Lett. **85**, 2569 (2000). <https://doi.org/10.1103/PhysRevLett.85.2569>
45. C. Giannetti et al., Discontinuity of the ultrafast electronic response of underdoped superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  strongly excited by ultrashort light pulses. Phys. Rev. B **79**, 224502 (2009). <https://doi.org/10.1103/PhysRevB.79.224502>
46. A. Pashkin et al., Ultrafast insulator–metal phase transition in  $\text{VO}_2$  studied by multiterahertz spectroscopy. Phys. Rev. B **83**, 195120 (2011). <https://doi.org/10.1103/PhysRevB.83.195120>
47. C. Giannetti et al., Revealing the high-energy electronic excitations underlying the onset of high-temperature superconductivity in cuprates. Nat. Commun. **2**, 353 (2011). <https://doi.org/10.1038/ncomms1354>
48. G. Coslovich et al., Evidence for a photoinduced nonthermal superconducting-to-normal-state phase transition in overdoped  $\text{Bi}_2\text{Sr}_2\text{Ca}_{0.92}\text{Y}_{0.08}\text{Cu}_2\text{O}_{8+\delta}$ . Phys. Rev. B **83**, 064519 (2011). <https://doi.org/10.1103/PhysRevB.83.064519>
49. K. W. Kim et al., Ultrafast transient generation of spin-density-wave order in the normal state of  $\text{BaFe}_2\text{As}_2$  driven by coherent lattice vibrations. Nat. Mater. **11**, 497 (2012). <https://doi.org/10.1038/nmat3294>
50. S. Dal Conte et al., Disentangling the electronic and phononic glue in a high- $T_C$  superconductor. Science **335**, 1600 (2012). <https://doi.org/10.1126/science.1216765>
51. G. Coslovich et al., Ultrafast charge localization in a stripe-phase nickelate. Nat. Commun. **4**, 2643 (2013). <https://doi.org/10.1038/ncomms3643>
52. S. Sim et al., Ultrafast terahertz dynamics of hot Dirac-electron surface scattering in the topological insulator  $\text{Bi}_2\text{Se}_3$ . Phys. Rev. B **89**, 165137 (2014). <https://doi.org/10.1103/PhysRevB.89.165137>
53. F. Novelli et al., Witnessing the formation and relaxation of dressed quasi-particles in a strongly correlated electron system. Nat. Commun. **5**, 5112 (2014). <https://doi.org/10.1038/ncomms6112>
54. F. Cilento et al., Photo-enhanced antinodal conductivity in the pseudogap state of high- $T_C$  cuprates. Nat. Commun. **5**, 4353 (2014). <https://doi.org/10.1038/ncomms5353>
55. S. Sim et al., Tunable Fano quantum-interference dynamics using a topological phase transition in  $(\text{Bi}_{1-x}\text{In}_x)_2\text{Se}_3$ . Phys. Rev. B **91**, 235438 (2015). <https://doi.org/10.1103/PhysRevB.91.235438>
56. S. Gerber et al., Direct characterization of photoinduced lattice dynamics in  $\text{BaFe}_2\text{As}_2$ . Nat. Commun. **6**, 7377 (2015). <https://doi.org/10.1038/ncomms8377>
57. S. Sim et al., Composition control of plasmon-phonon interaction using topological quantum-phase transition in photoexcited  $(\text{Bi}_{1-x}\text{In}_x)_2\text{Se}_3$ . ACS Photonics **3**, 1426 (2016). <https://doi.org/10.1021/acspophotonics.6b00021>
58. S. Cha et al., 1s-intraexcitonic dynamics in monolayer  $\text{MoS}_2$  probed by ultrafast mid-infrared spectroscopy. Nat. Commun. **7**, 10768 (2016). <https://doi.org/10.1038/ncomms10768>
59. G. Coslovich et al., Ultrafast dynamics of vibrational symmetry breaking in a charge-ordered nickelate. Sci. Adv. **3**, e1600735 (2017). <https://doi.org/10.1126/sciadv.1600735>
60. W. Yang et al., Time-resolved observations of photo-generated charge-carrier dynamics in  $\text{Sb}_2\text{Se}_3$  photocathodes for photoelectrochemical water splitting. ACS Nano **12**, 11088 (2018). <https://doi.org/10.1021/acsnano.8b05446>
61. C. In et al., Control over electron-phonon interaction by Dirac plasmon engineering in the  $\text{Bi}_2\text{Se}_3$  topological insulator. Nano Lett. **18**, 734 (2018). <https://doi.org/10.1021/acs.nanolett.7b03897>
62. M. C. Lee et al., Abnormal phase flip in the coherent phonon oscillations of  $\text{Ca}_2\text{RuO}_4$ . Phys. Rev. B **98**, 161115(R) (2018). <https://doi.org/10.1103/PhysRevB.98.161115>
63. M. C. Lee et al., Evidence of structural evolution in  $\text{Sr}_2\text{RhO}_4$  studied by time-resolved optical reflectivity spectroscopy. Phys. Rev. B **100**, 235139 (2019). <https://doi.org/10.1103/PhysRevB.100.235139>
64. M. C. Lee et al., Strong spin-phonon coupling unveiled by coherent phonon oscillations in  $\text{Ca}_2\text{RuO}_4$ . Phys. Rev. B **99**, 144306 (2019). <https://doi.org/10.1103/PhysRevB.99.144306>
65. I. Kwak et al., Ultrafast dynamics in the Lifshitz-type 5d pyrochlore antiferromagnet  $\text{Cd}_2\text{Os}_2\text{O}_7$ . Phys. Rev. B **100**, 144309 (2019). <https://doi.org/10.1103/PhysRevB.100.144309>
66. I. Kwak et al., Rotation of reflectivity anisotropy due to uniaxial strain along [110]tetra in the electron-doped Fe-based superconductor  $\text{Ba}(\text{Fe}_{0.955}\text{Co}_{0.045})_2\text{As}_2$ . Phys. Rev. B **101**, 165136 (2020). <https://doi.org/10.1103/PhysRevB.101.165136>
67. Y. Lee et al., Nematic fluctuations in optimally doped  $\text{BaFe}_{1.87}\text{Co}_{0.13}\text{As}_2$  observed in photoinduced reflectivity change. Phys. Status Solidi RRL **14**, 1900584 (2020). <https://doi.org/10.1002/pssr.201900584>
68. W. Hu et al., Optically enhanced coherent transport in  $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$  by ultrafast redistribution of interlayer coupling. Nat. Mater. **13**, 705 (2014). <https://doi.org/10.1038/Nmat3963>
69. S. Kaiser et al., Optically induced coherent transport far above  $T_C$  in underdoped  $\text{YBa}_2\text{Cu}_3\text{O}_{6+\delta}$ . Phys. Rev. B **89**, 184516 (2014). <https://doi.org/10.1103/PhysRevB.89.184516>
70. C. R. Hunt et al., Dynamical decoherence of the light induced interlayer coupling in  $\text{YBa}_2\text{Cu}_3\text{O}_{6+\delta}$ . Phys. Rev. B **94**, 224303 (2016). <https://doi.org/10.1103/PhysRevB.94.224303>
71. B. Liu et al., Pump frequency resonances for light-induced incipient superconductivity in  $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ . Phys. Rev. X **10**, 011053 (2020). <https://doi.org/10.1103/PhysRevX.10.011053>
72. V. V. Kabanov, J. Demsar, D. Mihailovic, Kinetics of a superconductor excited with a femtosecond optical pulse. Phys. Rev. Lett. **95**, 147002 (2005). <https://doi.org/10.1103/PhysRevLett.95.147002>
73. E. E. M. Chia, J. X. Zhu, D. Talbayev, A. J. Taylor, Competing energy scales in high-temperature superconductors: ultrafast pump-probe studies. Phys. Status Solidi RRL **5**, 1 (2011). <https://doi.org/10.1002/pssr.201004371>
74. M. Beck et al., Energy-gap dynamics of superconducting NbN thin films studied by time-resolved terahertz spectroscopy. Phys. Rev. Lett. **107**, 177007 (2011). <https://doi.org/10.1103/PhysRevLett.107.177007>
75. J. Demsar et al., Pair-breaking and superconducting state recovery dynamics in  $\text{MgB}_2$ . Phys. Rev. Lett. **91**, 267002 (2003). <https://doi.org/10.1103/PhysRevLett.91.267002>

85. N. Gedik et al., Single-quasiparticle stability and quasiparticle-pair decay in  $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ . Phys. Rev. B **70**, 014504 (2004). <https://doi.org/10.1103/PhysRevB.70.014504>
86. I. M. Vishik et al., Ultrafast dynamics in the presence of antiferromagnetic correlations in electron-doped cuprate  $\text{La}_{2-x}\text{Ce}_x\text{CuO}_{4\pm\delta}$ . Phys. Rev. B **95**, 115125 (2017). <https://doi.org/10.1103/PhysRevB.95.115125>
87. C. L. Smallwood et al., Time- and momentum-resolved gap dynamics in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . Phys. Rev. B **89**, 115126 (2014). <https://doi.org/10.1103/PhysRevB.89.115126>
88. Z. Zhang et al., Photoinduced filling of near-nodal gap in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . Phys. Rev. B **96**, 064510 (2017). <https://doi.org/10.1103/PhysRevB.96.064510>
89. R. Mankowsky et al., Nonlinear lattice dynamics as a basis for enhanced superconductivity in  $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ . Nature **516**, 71 (2014). <https://doi.org/10.1038/nature13875>
90. G. Chiriacò, A. J. Millis, I. L. Aleiner, Transient superconductivity without superconductivity. Phys. Rev. B **98**, 220510(R) (2018). <https://doi.org/10.1103/PhysRevB.98.220510>
91. G. Chiriacò, A. J. Millis, I. L. Aleiner, Negative absolute conductivity in photoexcited metals. Phys. Rev. B **101**, 041105(R) (2020). <https://doi.org/10.1103/PhysRevB.101.041105>
92. N. I. Landy et al., Perfect metamaterial absorber. Phys. Rev. Lett. **100**, 207402 (2008). <https://doi.org/10.1103/PhysRevLett.100.207402>
93. N. Papasimakis et al., Metamaterial with polarization and direction insensitive resonant transmission response mimicking electromagnetically induced transparency. Appl. Phys. Lett. **94**, 211902 (2009). <https://doi.org/10.1063/1.3138868>
94. P. Tassin et al., Low-loss metamaterials based on classical electromagnetically induced transparency. Phys. Rev. Lett. **102**, 053901 (2009). <https://doi.org/10.1103/PhysRevLett.102.053901>
95. H. T. Chen et al., Tuning the resonance in high-temperature superconducting terahertz metamaterials. Phys. Rev. Lett. **105**, 247402 (2010). <https://doi.org/10.1103/PhysRevLett.105.247402>
96. A. Pimenov, A. Loidl, P. Przyluski, B. Dabrowski, Negative refraction in ferromagnet-superconductor superlattices. Phys. Rev. Lett. **95**, 247009 (2005). <https://doi.org/10.1103/PhysRevLett.95.247009>
97. C. G. Du, H. Y. Chen, S. Q. Li, Quantum left-handed metamaterial from superconducting quantum-interference devices. Phys. Rev. B **74**, 113105 (2006). <https://doi.org/10.1103/PhysRevB.74.113105>
98. N. Lazarides, G. P. Tsironis, rf superconducting quantum interference device metamaterials. Appl. Phys. Lett. **90**, 163501 (2007). <https://doi.org/10.1063/1.2722682>
99. H. T. Chen et al., A metamaterial solid-state terahertz phase modulator. Nat. Photonics **3**, 148 (2009). <https://doi.org/10.1038/Nphoton.2009.3>
100. A. L. Rakhmanov et al., Layered superconductors as negative-refractive-index metamaterials. Phys. Rev. B **81**, 075101 (2010). <https://doi.org/10.1103/PhysRevB.81.075101>
101. J. Q. Gu et al., Terahertz superconductor metamaterial. Appl. Phys. Lett. **97**, 071102 (2010). <https://doi.org/10.1063/1.3479909>
102. V. Savinov, K. Delfanazari, V. A. Fedotov, N. I. Zheludev, Giant nonlinearity in a superconducting sub-terahertz metamaterial. Appl. Phys. Lett. **108**, 101107 (2016). <https://doi.org/10.1063/1.4943649>
103. N. K. Grady et al., Nonlinear high-temperature superconducting terahertz metamaterials. New J. Phys. **15**, 105016 (2013). <https://doi.org/10.1088/1367-2630/15/10/105016>
104. V. A. Fedotov et al., Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry. Phys. Rev. Lett. **99**, 147401 (2007). <https://doi.org/10.1103/PhysRevLett.99.147401>
105. Y. G. Jeong et al., Electrical control of terahertz nano antennas on  $\text{VO}_2$  thin film. Opt. Express **19**, 21211 (2011). <https://doi.org/10.1364/OE.19.021211>
106. G. Choi et al., Enhanced surface carrier response by field overlapping in metal nanopatterned semiconductor. ACS Photonics **5**, 4739 (2018). <https://doi.org/10.1021/acspophotonics.8b00724>
107. A. Hammar et al., Terahertz direct detection in  $\text{YBa}_2\text{Cu}_3\text{O}_7$  microbolometers. IEEE Trans. Terahertz Sci. Technol. **1**, 390 (2011). <https://doi.org/10.1109/TTHZ.2011.2161050>
108. U. Welp, K. Kadowaki, R. Kleiner, Superconducting emitters of THz radiation. Nat Photonics **7**, 702 (2013). <https://doi.org/10.1038/nphoton.2013.216>
109. K. Nakade et al., Applications using high- $T_C$  superconducting terahertz emitters. Sci. Rep. **6**, 23178 (2016). <https://doi.org/10.1038/srep23178>
110. D. Headland et al., Tutorial: terahertz beamforming, from concepts to realizations. APL Photonics **3**, 051101 (2018). <https://doi.org/10.1063/1.5011063>
111. T. -T. Kim et al., Electrically tunable slow light using graphene metamaterials. ACS Photonics **5**, 1800 (2018). <https://doi.org/10.1021/acspophotonics.7b01551>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.