Exploring Dynamics in the Far-Infrared with Terahertz Spectroscopy

Charles A. Schmuttenmaer*

Yale University, Department of Chemistry, 225 Prospect St., P. O. Box 208107
New Haven, CT 06520-8107, USA

April, 2004

Contents

References with Titles

S1

References

- (1) Nuss, M. C.; Orenstein, J. In *Millimeter and Submillimeter Wave Spectroscopy of Solids*; Gruner, G., Ed.; Springer-Verlag: Berlin, 1998; Vol. 74.
- (2) Mittleman, D. *Sensing with Terahertz Radiation*; Springer-Verlag: Berlin, 2003.
- (3) Siegel, P. H., "Terahertz technology", *IEEE Trans. Microw. Theory Tech.* **2002**, *50*, 910.
- (4) Beard, M. C.; Turner, G. M.; Schmuttenmaer, C. A., "Terahertz spectroscopy", *J. Phys. Chem. B* **2002**, *106*, 7146.
- (5) Han, P. Y.; Zhang, X. C., "Free-space coherent broadband terahertz time-domain spectroscopy", *Meas. Sci. Technol.* **2001**, *12*, 1747.
- (6) Ferguson, B.; Zhang, X. C., "Materials for terahertz science and technology", *Nature Mater.* **2002**, *1*, 26.
- (7) Averitt, R. D.; Taylor, A. J., "Ultrafast optical and far-infrared quasiparticle dynamics in correlated electron materials", *J. Phys.: Condens. Matter* **2002**, *14*, R1357.
- (8) Shan, J.; Nahata, A.; Heinz, T. F., "Terahertz time-domain spectroscopy based on nonlinear optics", *J. Nonlinear Opt. Phys. Mater.* **2002**, *11*, 31.
- (9) Davies, A. G.; Linfield, E. H.; Johnston, M. B., "The development of terahertz sources and their applications", *Phys. Med. Biol.* **2002**, *47*, 3679.
- (10) Kawase, K.; Shikata, J.; Ito, H., "Terahertz wave parametric source", *J. Phys. D-Appl. Phys.* **2002**, *35*, R1.
- (11) Kimmitt, M. F., "Restrahlen to T-rays - 100 years of terahertz radiation", *J. Biol. Phys.* **2003**, *29*, 77.
- (12) *Special Issue: Proceedings of the First International Conference on Biomedical Imaging and Sensing Applications of THz Technology* *Phys. Med. Biol.*, **2002**; Vol. 47.
- (13) *J. Biol. Phys.*, **2003**; Vol. 29.
- (14) Smith, P. R.; Auston, D. H.; Nuss, M. C., "Subpicosecond photoconducting dipole antennas", *IEEE J. Quantum Electron.* **1988**, *24*, 255.
- (15) Fittinger, C.; Grischkowsky, D., "Terahertz Beams", *Appl. Phys. Lett.* **1989**, *54*, 490.
- (16) van Exter, M.; Fittinger, C.; Grischkowsky, D., "High-Brightness Terahertz Beams Characterized with an Ultrafast Detector", *Appl. Phys. Lett.* **1989**, *55*, 337.
- (17) van Exter, M.; Grischkowsky, D. R., "Characterization of an Optoelectronic Terahertz Beam System", *IEEE Trans. Microw. Theory Tech.* **1990**, *38*, 1684.
- (18) Ralph, S. E.; Grischkowsky, D., "Trap-Enhanced Electric-Fields in Semi-Insulators - the Role of Electrical and Optical Carrier Injection", *Appl. Phys. Lett.* **1991**, *59*, 1972.
- (19) Katzenellenbogen, N.; Grischkowsky, D., "Efficient Generation of 380 Fs Pulses of THz Radiation by Ultrafast Laser-Pulse Excitation of a Biased Metal-Semiconductor Interface", *Appl. Phys. Lett.* **1991**, *58*, 222.
- (20) Warren, A. C.; Katzenellenbogen, N.; Grischkowsky, D.; Woodall, J. M.; Melloch, M. R.; Otsuka, N., "Subpicosecond, Freely Propagating Electromagnetic Pulse Generation and Detection Using GaAs-as Epilayers", *Appl. Phys. Lett.* **1991**, *58*, 1512.
- (21) Ludwig, C.; Kuhl, J., "Studies of the temporal and spectral shape of terahertz pulses generated from photoconducting switches", *Appl. Phys. Lett.* **1996**, *69*, 1194.
- (22) Heiliger, H. M.; Vosseburger, M.; Roskos, H. G.; Kurz, H.; Hey, R.; Ploog, K., "Application of liftoff low-temperature-grown GaAs on transparent substrates for THz signal generation", *Appl. Phys. Lett.* **1996**, *69*, 2903.
- (23) Tani, M.; Matsuura, S.; Sakai, K.; Nakashima, S., "Emission characteristics of photoconductive antennas based on low-temperature-grown GaAs and semi-insulating GaAs", *Appl. Optics* **1997**, *36*, 7853.
- (24) Lin, P. I.; Chen, S. F.; Wu, K. H.; Juang, J. Y.; Uhn, T. M.; Gou, Y. S., "Characteristics of photogenerated bipolar terahertz radiation in biased photoconductive switches", *Jpn. J. Appl. Phys. Part 2 - Lett.* **2002**, *41*, L1158.
- (25) Liu, T. A.; Tani, M.; Pan, C. L., "THz radiation emission properties of multienergy arsenic-ion-implanted GaAs and semi-insulating GaAs based photoconductive antennas", *J. Appl. Phys.* **2003**, *93*, 2996.
- (26) Pedersen, J. E.; Keiding, S. R.; Sorensen, C. B.; Lindelof, P. E.; Ruhle, W. W.; Zhou, X. Q., "5-THz Bandwidth from a GaAs-on-Silicon Photoconductive Receiver", *J. Appl. Phys.* **1993**, *74*, 7022.
- (27) Zhang, J. Z.; Chen, Z. Z.; Chen, X. M., "FDTD analysis of photoconducting antennas for millimeter-wave generation", *Int. J. RF Microw. Comput.-Aid. Eng.* **2000**, *10*, 213.
- (28) Chung, Y. S.; Cheon, C.; Son, J. H.; Hahn, S. Y., "FDTD analysis of propagation characteristics of terahertz electromagnetic pulses", *IEEE Trans. Magn.* **2000**, *36*, 951.
- (29) Jepsen, P. U.; Jacobsen, R. H.; Keiding, S. R., "Generation and detection of terahertz pulses from biased semiconductor antennas", *J. Opt. Soc. Am. B-Opt. Phys.* **1996**, *13*, 2424.
- (30) Duvillaret, L.; Garet, F.; Roux, J. F.; Coutaz, J. L., "Analytical modeling and optimization of terahertz time-domain spectroscopy experiments using photoswitches as antennas", *IEEE J. Sel. Top. Quantum Electron.* **2001**, *7*, 615.

- (31) Kindt, J. T.; Schmuttenmaer, C. A., "Far-infrared dielectric properties of polar liquids probed by femtosecond terahertz pulse spectroscopy", *J. Phys. Chem.* **1996**, *100*, 10373.
- (32) Melloch, M. R.; Woodall, J. M.; Harmon, E. S.; Otsuka, N.; Pollak, F. H.; Nolte, D. D.; Feenstra, R. M.; Lutz, M. A., "Low-Temperature-Grown In-V Materials", *Ann. Rev. Mater. Sci.* **1995**, *25*, 547.
- (33) Wang, H. H.; Whitaker, J. F.; Chin, A.; Mazurowski, J.; Ballingall, J. M., "Subpicosecond Carrier Response of Unannealed Low-Temperature-Grown GaAs Vs Temperature", *J. Electron. Mater.* **1993**, *22*, 1461.
- (34) Beard, M. C.; Turner, G. M.; Schmuttenmaer, C. A., "Subpicosecond carrier dynamics in low-temperature grown GaAs as measured by time-resolved terahertz spectroscopy", *J. Appl. Phys.* **2001**, *90*, 5915.
- (35) Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K.; Hangyo, M.; Wada, N.; Murakami, Y., "Enhanced THz radiation from YBCO thin film bow-tie antennas with hyper-hemispherical MgO lens", *IEEE Trans. Appl. Supercond.* **1997**, *7*, 2913.
- (36) Tani, M.; Tonouchi, M.; Hangyo, M.; Wang, Z.; Onodera, N.; Sakai, K., "Emission properties of YBa₂Cu₃O₇-delta-film photoswitches as Terahertz radiation sources", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **1997**, *36*, 1984.
- (37) Tanichi, N.; Wada, N.; Nagashima, T.; Tonouchi, M.; Hangyo, M.; Tani, M.; Sakai, K., "Terahertz radiation from a-axis oriented YBCO thin films", *Physica C* **1997**, *293*, 229.
- (38) Shikii, S.; Tanichi, N.; Nagashima, T.; Tonouchi, M.; Hangyo, M.; Tani, M.; Sakai, K., "Enhanced THz radiation from YBCO using a-axis oriented thin films excited by ultrashort optical pulses", *IEICE Trans. Electron.* **1997**, *E80C*, 1297.
- (39) Pedersen, J. E.; Balslev, I.; Hvam, J. M.; Keiding, S. R., "Terahertz Pulses from Semiconductor-Air Interfaces", *Appl. Phys. Lett.* **1992**, *61*, 1372.
- (40) Andrews, S. R.; Armitage, A.; Huggard, P. G.; Hussain, A., "Optimization of photoconducting receivers for THz spectroscopy", *Phys. Med. Biol.* **2002**, *47*, 3705.
- (41) Xu, L.; Zhang, X. C.; Auston, D. H.; Jalali, B., "Terahertz Radiation from Large Aperture Si P-I-N-Diodes", *Appl. Phys. Lett.* **1991**, *59*, 3357.
- (42) Zhang, X. C.; Auston, D. H., "Optically Induced THz Electromagnetic-Radiation from Planar Photoconducting Structures", *J. Electromagn. Waves Appl.* **1992**, *6*, 85.
- (43) Hu, B. B.; Weling, A. S.; Auston, D. H.; Kuznetsov, A. V.; Stanton, C. J., "DC-Electric-Field Dependence of THz Radiation-Induced by Femtosecond Optical-Excitation of Bulk GaAs", *Phys. Rev. B* **1994**, *49*, 2234.
- (44) Leitenstorfer, A.; Hunsche, S.; Shah, J.; Nuss, M. C.; Knox, W. H., "Detectors and sources for ultrabroadband electro-optic sampling: Experiment and theory", *Appl. Phys. Lett.* **1999**, *74*, 1516.
- (45) Zhang, X. C.; Darrow, J. T.; Hu, B. B.; Auston, D. H.; Schmidt, M. T.; Tham, P.; Yang, E. S., "Optically Induced Electromagnetic-Radiation from Semiconductor Surfaces", *Appl. Phys. Lett.* **1990**, *56*, 2228.
- (46) Jin, Y.; Ma, X. F.; Wagoner, G. A.; Alexander, M.; Zhang, X. C., "Anomalous Optically Generated THz Beams from Metal GaAs Interfaces", *Appl. Phys. Lett.* **1994**, *65*, 682.
- (47) Zhang, X. C.; Hu, B. B.; Darrow, J. T.; Auston, D. H., "Generation of Femtosecond Electromagnetic Pulses from Semiconductor Surfaces", *Appl. Phys. Lett.* **1990**, *56*, 1011.
- (48) Greene, B. I.; Saeta, P. N.; Dykaar, D. R.; Schmittink, S.; Chuang, S. L., "Far-Infrared Light Generation at Semiconductor Surfaces and Its Spectroscopic Applications", *IEEE J. Quantum Electron.* **1992**, *28*, 2302.
- (49) Li, M.; Sun, F. G.; Wagoner, G. A.; Alexander, M.; Zhang, X. C., "Measurement and Analysis of Terahertz Radiation from Bulk Semiconductors", *Appl. Phys. Lett.* **1995**, *67*, 25.
- (50) Kondo, T.; Sakamoto, M.; Tonouchi, M.; Hangyo, M., "Terahertz radiation from (111) InAs surface using 1.55 μ m femtosecond laser pulses", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1999**, *38*, L1035.
- (51) Han, P. Y.; Huang, X. G.; Zhang, X. C., "Direct characterization of terahertz radiation from the dynamics of the semiconductor surface field", *Appl. Phys. Lett.* **2000**, *77*, 2864.
- (52) Kono, S.; Gu, P.; Tani, M.; Sakai, K., "Temperature dependence of terahertz radiation from n-type InSb and n-type InAs surfaces", *Appl. Phys. B-Lasers Opt.* **2000**, *71*, 901.
- (53) Gu, P.; Tani, M.; Kono, S.; Sakai, K.; Zhang, X. C., "Study of terahertz radiation from InAs and InSb", *J. Appl. Phys.* **2002**, *91*, 5533.
- (54) Malevich, V. L., "Monte Carlo simulation of THz-pulse generation from semiconductor surface", *Semicond. Sci. Technol.* **2002**, *17*, 551.
- (55) Nakajima, M.; Takahashi, M.; Hangyo, M., "Strong enhancement of THz radiation intensity from semi-insulating GaAs surfaces at high temperatures", *Appl. Phys. Lett.* **2002**, *81*, 1462.
- (56) Zhang, X. C.; Jin, Y.; Hewitt, T. D.; Sangsiri, T.; Kingsley, L. E.; Weiner, M., "Magnetic Switching of THz Beams", *Appl. Phys. Lett.* **1993**, *62*, 2003.
- (57) Sarukura, N.; Ohtake, H.; Izumida, S.; Liu, Z. L., "High average-power THz radiation from femtosecond laser-irradiated InAs in a magnetic field and its elliptical polarization characteristics", *J. Appl. Phys.* **1998**, *84*, 654.
- (58) Izumida, S.; Ono, S.; Liu, Z. L.; Ohtake, H.; Sarukura, N., "Spectrum control of THz radiation from InAs in a magnetic field by duration and frequency chirp of the excitation pulses", *Appl. Phys. Lett.* **1999**, *75*, 451.
- (59) Ono, S.; Tsukamoto, T.; Sakai, M.; Liu, Z. L.; Ohtake, H.; Sarukura, N.; Nishizawa, S.; Nakanishi, A.; Yoshida, M., "Compact THz-radiation source consisting of a bulk semiconductor, a mode-locked fiber laser, and a 2 T permanent magnet", *Rev. Sci. Instrum.* **2000**, *71*, 554.
- (60) McLaughlin, R.; Chen, Q.; Corchia, A.; Ciesla, C. M.; Arnone, D. D.; Zhang, X. C.; Jones, G. A. C.; Lindfield, E. H.; Pepper, M., "Enhanced coherent terahertz emission from indium arsenide", *J. Mod. Opt.* **2000**, *47*, 1847.
- (61) Ohtake, H.; Ono, S.; Sakai, M.; Liu, Z. L.; Tsukamoto, T.; Sarukura, N., "Saturation of THz-radiation power from femtosecond-laser-irradiated InAs in a high magnetic field", *Appl. Phys. Lett.* **2000**, *76*, 1398.
- (62) Ohtake, H.; Ono, S.; Sakai, M.; Liu, Z.; Sarukura, N., "Intense THz radiation from femtosecond laser pulses irradiated InAs in a strong magnetic field", *J. Lumines.* **2000**, *87-9*, 902.
- (63) Liu, Z. L.; Ohtake, H.; Izumida, S.; Ono, S.; Sarukura, N., "Intense THz-radiation from semiconductors under magnetic field irradiated with femtosecond laser pulses", *Opt. Quantum Electron.* **2000**, *32*, 521.
- (64) Heyman, J. N.; Neocleous, P.; Hebert, D.; Crowell, P. A.; Muller, T.; Unterrainer, K., "Terahertz emission from GaAs and InAs in a magnetic field", *Phys. Rev. B* **2001**, *64*, 085202.
- (65) Ono, S.; Tsukamoto, T.; Kawahata, E.; Yano, T.; Ohtake, H.; Sarukura, N., "Terahertz radiation from a shallow incidence-angle InAs emitter in a magnetic field irradiated with femtosecond laser pulses", *Appl. Optics* **2001**, *40*, 1369.
- (66) Migita, M.; Hangyo, M., "Pump-power dependence of THz radiation from InAs surfaces under magnetic fields excited by ultrashort laser pulses", *Appl. Phys. Lett.* **2001**, *79*, 3437.
- (67) Ohtake, H.; Suzuki, Y.; Sarukura, N.; Ono, S.; Tsukamoto, T.; Nakanishi, A.; Nishizawa, S.; Stock, M. L.; Yoshida, M.; Ender, H., "THz-radiation emitter and receiver system based on a 2T permanent magnet, 1040 nm compact fiber laser and pyroelectric thermal receiver", *Jpn. J. Appl. Phys. Part 2 - Lett.* **2001**, *40*, L1223.
- (68) Hangyo, M.; Migita, M.; Nakayama, K., "Magnetic field and temperature dependence of terahertz radiation from InAs surfaces excited by femtosecond laser pulses", *J. Appl. Phys.* **2001**, *90*, 3409.
- (69) Ohtake, H.; Murakami, H.; Yano, T.; Ono, S.; Sarukura, N.; Takahashi, H.; Suzuki, Y.; Nishijima, G.; Watanabe, K., "Anomalous power and spectrum dependence of terahertz radiation from femtosecond-laser-irradiated indium arsenide in high magnetic fields up to 14 T", *Appl. Phys. Lett.* **2003**, *82*, 1164.
- (70) Weiss, C.; Wallenstein, R.; Beigang, R., "Magnetic-field-enhanced generation of terahertz radiation in semiconductor surfaces", *Appl. Phys. Lett.* **2000**, *77*, 4160.
- (71) Johnston, M. B.; Corchia, A.; Dowd, A.; Linfield, E. H.; Davies, A. G.; McLaughlin, R.; Arnone, D. D.; Pepper, M., "Magnetic-field-induced

- enhancement of terahertz emission from III-V semiconductor surfaces", *Physica E* **2002**, *13*, 896.
- (72) Takahashi, H.; Suzuki, Y.; Sakai, M.; Ono, S.; Sarukura, N.; Sugiura, T.; Hirosumi, T.; Yoshida, M., "Significant enhancement of terahertz radiation from InSb by use of a compact fiber laser and an external magnetic field", *Appl. Phys. Lett.* **2003**, *82*, 2005.
 - (73) Shan, J.; Weiss, C.; Wallenstein, R.; Beigang, R.; Heinz, T. F., "Origin of magnetic field enhancement in the generation of terahertz radiation from semiconductor surfaces", *Opt. Lett.* **2001**, *26*, 849.
 - (74) Johnston, M. B.; Whittaker, D. M.; Corchia, A.; Davies, A. G.; Linfield, E. H., "Theory of magnetic-field enhancement of surface-field terahertz emission", *J. Appl. Phys.* **2002**, *91*, 2104.
 - (75) Johnston, M. B.; Whittaker, D. M.; Corchia, A.; Davies, A. G.; Linfield, E. H., "Simulation of terahertz generation at semiconductor surfaces", *Phys. Rev. B* **2002**, *65*, 165301.
 - (76) Andrews, S. R.; Armitage, A.; Huggard, P. G.; Shaw, C. J.; Moore, G. P.; Grey, R., "Magnetic field dependence of terahertz emission from an optically excited GaAs p-i-n diode", *Phys. Rev. B* **2002**, *66*, 085307.
 - (77) Sarukura, N.; Liu, Z.; Ohtake, H.; Izumida, S.; Yamanaka, T.; Segawa, Y.; Itatani, T.; Sugaya, T.; Nakagawa, T.; Sugiyama, Y., "All-solid-state, THz radiation source using a saturable Bragg reflector in a femtosecond mode-locked laser", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1997**, *36*, L560.
 - (78) Sarukura, N.; Ohtake, H.; Liu, Z.; Itatani, T.; Sugaya, T.; Nakagawa, T.; Sugiyama, Y., "THz-radiation generation from an intracavity saturable Bragg reflector in a magnetic field", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1998**, *37*, L125.
 - (79) Liu, T. A.; Huang, K. F.; Pan, C. L.; Liu, Z. L.; Ono, S.; Ohtake, H.; Sarukura, N., "THz radiation from intracavity saturable Bragg reflector in magnetic field with self-started mode-locking by strained saturable Bragg reflector", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1999**, *38*, L1333.
 - (80) Liu, Z. L.; Ono, S.; Ohtake, H.; Sarukura, N.; Liu, T. A.; Huang, K. F.; Pan, C. L., "Efficient terahertz radiation generation from a bulk InAs mirror as an intracavity terahertz radiation emitter", *Jpn. J. Appl. Phys. Part 2 - Lett.* **2000**, *39*, L366.
 - (81) Darrow, J. T.; Hu, B. B.; Zhang, X. C.; Auston, D. H., "Subpicosecond Electromagnetic Pulses from Large-Aperture Photoconducting Antennas", *Opt. Lett.* **1990**, *15*, 323.
 - (82) Darrow, J. T.; Zhang, X. C.; Auston, D. H., "Power Scaling of Large-Aperture Photoconducting Antennas", *Appl. Phys. Lett.* **1991**, *58*, 25.
 - (83) Benicewicz, P. K.; Roberts, J. P.; Taylor, A. J., "Scaling of Terahertz Radiation from Large-Aperture Biased Photoconductors", *J. Opt. Soc. Am. B-Opt. Phys.* **1994**, *11*, 2533.
 - (84) You, D.; Jones, R. R.; Bucksbaum, P. H.; Dykaar, D. R., "Generation of High-Power Sub-Single-Cycle 500-Fs Electromagnetic Pulses", *Opt. Lett.* **1993**, *18*, 290.
 - (85) Hattori, T.; Tukamoto, K.; Nakatsuka, H., "Time-resolved study of intense terahertz pulses generated by a large-aperture photoconductive antenna", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **2001**, *40*, 4907.
 - (86) Zhao, G.; Schouten, R. N.; van der Valk, N.; Wenckebach, W. T.; Planken, P. C. M., "Design and performance of a THz emission and detection setup based on a semi-insulating GaAs emitter", *Rev. Sci. Instrum.* **2002**, *73*, 1715.
 - (87) Auston, D. H.; Nuss, M. C., "Electrooptic Generation and Detection of Femtosecond Electrical Transients", *IEEE J. Quantum Electron.* **1988**, *24*, 184.
 - (88) Carrig, T. J.; Rodriguez, G.; Clement, T. S.; Taylor, A. J.; Stewart, K. R., "Scaling of Terahertz Radiation Via Optical Rectification in Electrooptic Crystals", *Appl. Phys. Lett.* **1995**, *66*, 121.
 - (89) Chen, Q.; Zhang, X. C., "Polarization modulation in optoelectronic generation and detection of terahertz beams", *Appl. Phys. Lett.* **1999**, *74*, 3435.
 - (90) Hu, B. B.; Zhang, X. C.; Auston, D. H.; Smith, P. R., "Free-Space Radiation from Electrooptic Crystals", *Appl. Phys. Lett.* **1990**, *56*, 506.
 - (91) Nahata, A.; Welington, A. S.; Heinz, T. F., "A wideband coherent terahertz spectroscopy system using optical rectification and electro-optic sampling", *Appl. Phys. Lett.* **1996**, *69*, 2321.
 - (92) Rice, A.; Jin, Y.; Ma, X. F.; Zhang, X. C.; Bliss, D.; Larkin, J.; Alexander, M., "Terahertz optical rectification from (110) zincblende crystals", *Appl. Phys. Lett.* **1994**, *64*, 1324.
 - (93) Xu, L.; Zhang, X. C.; Auston, D. H., "Terahertz Beam Generation by Femtosecond Optical Pulses in Electrooptic Materials", *Appl. Phys. Lett.* **1992**, *61*, 1784.
 - (94) Zhang, X. C.; Jin, Y.; Ma, X. F., "Coherent Measurement of THz Optical Rectification from Electrooptic Crystals", *Appl. Phys. Lett.* **1992**, *61*, 2764.
 - (95) Han, P. Y.; Zhang, X. C., "Coherent, broadband midinfrared terahertz beam sensors", *Appl. Phys. Lett.* **1998**, *73*, 3049.
 - (96) Beard, M. C.; Turner, G. M.; Schmuttenmaer, C. A., "Transient photoconductivity in GaAs as measured by time-resolved terahertz spectroscopy", *Phys. Rev. B* **2000**, *62*, 15764.
 - (97) Reimann, K.; Smith, R. P.; Weiner, A. M.; Elsaesser, T.; Woerner, M., "Direct field-resolved detection of terahertz transients with amplitudes of megavolts per centimeter", *Opt. Lett.* **2003**, *28*, 471.
 - (98) Han, P. Y.; Cho, G. C.; Zhang, X. C., "Broad band mid-infrared THz pulse: Measurement technique and applications", *J. Nonlinear Opt. Phys. Mater.* **1999**, *8*, 89.
 - (99) Huber, R.; Brodschelm, A.; Tauser, F.; Leitenstorfer, A., "Generation and field-resolved detection of femtosecond electromagnetic pulses tunable up to 41 THz", *Appl. Phys. Lett.* **2000**, *76*, 3191.
 - (100) Sinyukov, A. M.; Hayden, L. M., "Generation and detection of terahertz radiation with multilayered electro-optic polymer films", *Opt. Lett.* **2002**, *27*, 55.
 - (101) Han, P. Y.; Tani, M.; Pan, F.; Zhang, X. C., "Use of the organic crystal DAST for terahertz beam applications", *Opt. Lett.* **2000**, *25*, 675.
 - (102) Carey, J. J.; Bailey, R. T.; Pugh, D.; Sherwood, J. N.; Cruickshank, F. R.; Wynne, K., "Terahertz pulse generation in an organic crystal by optical rectification and resonant excitation of molecular charge transfer", *Appl. Phys. Lett.* **2002**, *81*, 4335.
 - (103) Jiang, Z. P.; Zhang, X. C., "Terahertz imaging via electrooptic effect", *IEEE Trans. Microw. Theory Tech.* **1999**, *47*, 2644.
 - (104) Wu, Q.; Hewitt, T. D.; Zhang, X. C., "Two-dimensional electro-optic imaging of THz beams", *Appl. Phys. Lett.* **1996**, *69*, 1026.
 - (105) Wu, Q.; Zhang, X. C., "Free-space electro-optics sampling of mid-infrared pulses", *Appl. Phys. Lett.* **1997**, *71*, 1285.
 - (106) Wu, Q.; Litz, M.; Zhang, X. C., "Broadband detection capability of ZnTe electro-optic field detectors", *Appl. Phys. Lett.* **1996**, *68*, 2924.
 - (107) Wu, Q.; Zhang, X. C., "Ultrafast electro-optic field sensors", *Appl. Phys. Lett.* **1996**, *68*, 1604.
 - (108) Bakker, H. J.; Cho, G. C.; Kurz, H.; Wu, Q.; Zhang, X. C., "Distortion of terahertz pulses in electro-optic sampling", *J. Opt. Soc. Am. B-Opt. Phys.* **1998**, *15*, 1795.
 - (109) Gallot, G.; Grischkowsky, D., "Electro-optic detection of terahertz radiation", *J. Opt. Soc. Am. B-Opt. Phys.* **1999**, *16*, 1204.
 - (110) Planken, P. C. M.; Nienhuys, H. K.; Bakker, H. J.; Wenckebach, T., "Measurement and calculation of the orientation dependence of terahertz pulse detection in ZnTe", *J. Opt. Soc. Am. B-Opt. Phys.* **2001**, *18*, 313.
 - (111) Vosseburger, M.; Brucherseifer, M.; Cho, G. C.; Roskos, H. G.; Kurz, H., "Propagation effects in electro-optic sampling of terahertz pulses in GaAs", *Appl. Optics* **1998**, *37*, 3368.
 - (112) Jiang, Z. P.; Zhang, X. C., "Single-shot spatiotemporal terahertz field imaging", *Opt. Lett.* **1998**, *23*, 1114.
 - (113) Jiang, Z. P.; Zhang, X. C., "Electro-optic measurement of THz field pulses with a chirped optical beam", *Appl. Phys. Lett.* **1998**, *72*, 1945.
 - (114) Jiang, Z. P.; Zhang, X. C., "Measurement of spatio-temporal terahertz field distribution by using chirped pulse technology", *IEEE J. Quantum Electron.* **2000**, *36*, 1214.
 - (115) Sun, F. G.; Jiang, Z. P.; Zhang, X. C., "Analysis of terahertz pulse measurement with a chirped probe beam", *Appl. Phys. Lett.* **1998**, *73*, 2233.

- (116) Shan, J.; Weling, A. S.; Knoesel, E.; Bartels, L.; Bonn, M.; Nahata, A.; Reider, G. A.; Heinz, T. F., "Single-shot measurement of terahertz electromagnetic pulses by use of electro-optic sampling", *Opt. Lett.* **2000**, 25, 426.
- (117) Kaindl, R. A.; Eickemeyer, F.; Woerner, M.; Elsaesser, T., "Broadband phase-matched difference frequency mixing of femtosecond pulses in GaSe: Experiment and theory", *Appl. Phys. Lett.* **1999**, 75, 1060.
- (118) Bonvalet, A.; Joffe, M.; Martin, J. L.; Migus, A., "Generation of Ultrabroadband Femtosecond Pulses in the Midinfrared by Optical Rectification of 15 Fs Light-Pulses at 100 Mhz Repetition Rate", *Appl. Phys. Lett.* **1995**, 67, 2907.
- (119) Kono, S.; Tani, M.; Sakai, K., "Coherent detection of mid-infrared radiation up to 60THz with an LT-GaAs photoconductive antenna", *IEE Proc.-Optoelectron.* **2002**, 149, 105.
- (120) Kono, S.; Tani, M.; Sakai, K., "Ultrabroadband photoconductive detection: Comparison with free- space electro-optic sampling", *Appl. Phys. Lett.* **2001**, 79, 898.
- (121) Park, S. G.; Melloch, M. R.; Weiner, A. M., "Comparison of terahertz waveforms measured by electro-optic and photoconductive sampling", *Appl. Phys. Lett.* **1998**, 73, 3184.
- (122) Park, S. G.; Melloch, M. R.; Weiner, A. M., "Analysis of terahertz waveforms measured by photoconductive and electrooptic sampling", *IEEE J. Quantum Electron.* **1999**, 35, 810.
- (123) Kawase, K.; Sato, M.; Taniuchi, T.; Ito, H., "Coherent tunable THz-wave generation from LiNbO₃ with monolithic grating coupler", *Appl. Phys. Lett.* **1996**, 68, 2483.
- (124) Kawase, K.; Sato, M.; Nakamura, K.; Taniuchi, T.; Ito, H., "Unidirectional radiation of widely tunable THz wave using a prism coupler under noncollinear phase matching condition", *Appl. Phys. Lett.* **1997**, 71, 753.
- (125) Kawase, K.; Shikata, J.; Sato, M.; Taniuchi, T.; Ito, H., "Widely tunable coherent terahertz wave generation using nonlinear optical effect", *Electron. Commun. Jpn. Pt. II-Electron.* **1998**, 81, 10.
- (126) Ito, H.; Kawase, K.; Shikata, J., "Widely tunable THz-wave generation by nonlinear optics", *IEICE Trans. Electron.* **1998**, E81C, 264.
- (127) Shikata, J.; Sato, M.; Taniuchi, T.; Ito, H., "Enhancement of terahertz-wave output from LiNbO₃ optical parametric oscillators by cryogenic cooling", *Opt. Lett.* **1999**, 24, 202.
- (128) Shikata, J.; Kawase, K.; Karino, K.; Taniuchi, T.; Ito, H., "Tunable terahertz-wave parametric oscillators using LiNbO₃ and MgO : LiNbO₃ crystals", *IEEE Trans. Microw. Theory Tech.* **2000**, 48, 653.
- (129) Sato, A.; Kawase, K.; Minamide, H.; Wada, S.; Ito, H., "Tabletop terahertz-wave parametric generator using a compact, diode-pumped Nd : YAG laser", *Rev. Sci. Instrum.* **2001**, 72, 3501.
- (130) Lee, Y. S.; Norris, T. B., "Terahertz pulse shaping and optimal waveform generation in poled ferroelectric crystals", *J. Opt. Soc. Am. B-Opt. Phys.* **2002**, 19, 2791.
- (131) Kawase, K.; Hatanaka, T.; Takahashi, H.; Nakamura, K.; Taniuchi, T.; Ito, H., "Tunable terahertz-wave generation from DAST crystal by dual signal-wave parametric oscillation of periodically poled lithium niobate", *Opt. Lett.* **2000**, 25, 1714.
- (132) Weiss, C.; Torosyan, G.; Avetisyan, Y.; Beigang, R., "Generation of tunable narrow-band surface-emitted terahertz radiation in periodically poled lithium niobate", *Opt. Lett.* **2001**, 26, 563.
- (133) Weiss, C.; Torosyan, G.; Meyn, J. P.; Wallenstein, R.; Beigang, R.; Avetisyan, Y., "Tuning characteristics of narrowband THz radiation generated via optical rectification in periodically poled lithium niobate", *Opt. Express* **2001**, 8, 497.
- (134) Hamster, H.; Sullivan, A.; Gordon, S.; White, W.; Falcone, R. W., "Subpicosecond, Electromagnetic Pulses from Intense Laser-Plasma Interaction", *Phys. Rev. Lett.* **1993**, 71, 2725.
- (135) Hamster, H.; Sullivan, A.; Gordon, S.; Falcone, R. W., "Short-Pulse Terahertz Radiation from High-Intensity-Laser- Produced Plasmas", *Phys. Rev. E* **1994**, 49, 671.
- (136) Löffler, T.; Jacob, F.; Roskos, H. G., "Generation of terahertz pulses by photoionization of electrically biased air", *Appl. Phys. Lett.* **2000**, 77, 453.
- (137) Cook, D. J.; Hochstrasser, R. M., "Intense terahertz pulses by four-wave rectification in air", *Opt. Lett.* **2000**, 25, 1210.
- (138) Chen, Q.; Jiang, Z. P.; Tani, M.; Zhang, X. C., "Electro-optic terahertz transceiver", *Electron. Lett.* **2000**, 36, 1298.
- (139) Chen, Q.; Tani, M.; Jiang, Z. P.; Zhang, X. C., "Electro-optic transceivers for terahertz-wave applications", *J. Opt. Soc. Am. B-Opt. Phys.* **2001**, 18, 823.
- (140) Tani, M.; Jiang, Z. P.; Zhang, X. C., "Photoconductive terahertz transceiver", *Electron. Lett.* **2000**, 36, 804.
- (141) Greene, B. I.; Federici, J. F.; Dykaar, D. R.; Jones, R. R.; Bucksbaum, P. H., "Interferometric Characterization of 160 Fs Far-Infrared Light-Pulses", *Appl. Phys. Lett.* **1991**, 59, 893.
- (142) Prabhu, S. S.; Ralph, S. E.; Melloch, M. R.; Harmon, E. S., "Carrier dynamics of low-temperature-grown GaAs observed via THz spectroscopy", *Appl. Phys. Lett.* **1997**, 70, 2419.
- (143) Ralph, S. E.; Chen, Y.; Woodall, J.; McInturff, D., "Subpicosecond photoconductivity of In_{0.53}Ga_{0.47}As: Intervalley scattering rates observed via THz spectroscopy", *Phys. Rev. B* **1996**, 54, 5568.
- (144) Nahata, A.; Heinz, T. F., "Detection of freely propagating terahertz radiation by use of optical second-harmonic generation", *Opt. Lett.* **1998**, 23, 67.
- (145) Bromage, J.; Walmsley, I. A.; Stroud, C. R., "Dithered-edge sampling of terahertz pulses", *Appl. Phys. Lett.* **1999**, 75, 2181.
- (146) Jacobsen, R. H.; Birkelund, K.; Holst, T.; Jepsen, P. U.; Keiding, S. R., "Interpretation of photocurrent correlation measurements used for ultrafast photoconductive switch characterization", *J. Appl. Phys.* **1996**, 79, 2649.
- (147) Nemec, H.; Pashkin, A.; Kuzel, P.; Khazan, M.; Schnull, S.; Wilke, I., "Carrier dynamics in low-temperature grown GaAs studied by terahertz emission spectroscopy", *J. Appl. Phys.* **2001**, 90, 1303.
- (148) Leitenstorfer, A.; Hunsche, S.; Shah, J.; Nuss, M. C.; Knox, W. H., "Femtosecond charge transport in polar semiconductors", *Phys. Rev. Lett.* **1999**, 82, 5140.
- (149) Leitenstorfer, A.; Hunsche, S.; Shah, J.; Nuss, M. C.; Knox, W. H., "Femtosecond high-field transport in compound semiconductors", *Phys. Rev. B* **2000**, 61, 16642.
- (150) Markelz, A. G.; Heilweil, E. J., "Temperature-dependent terahertz output from semi-insulating GaAs photoconductive switches", *Appl. Phys. Lett.* **1998**, 72, 2229.
- (151) Sekine, N.; Hirakawa, K.; Sogawa, F.; Arakawa, Y.; Usami, N.; Shiraki, Y.; Katoda, T., "Ultrashort lifetime photocarriers in Ge thin films", *Appl. Phys. Lett.* **1996**, 68, 3419.
- (152) Nakajima, M.; Takahashi, M.; Hangyo, M., "Temperature dependence of THz radiation from semi-insulating InP surface", *J. Lumines.* **2001**, 94, 627.
- (153) Nakajima, M.; Takahashi, M.; Hangyo, M., "Reversal of subpicosecond carrier transport direction with temperature observed in semi-insulating InP using THz radiation", *Physica B* **2002**, 314, 176.
- (154) Xu, L.; Hu, B. B.; Xin, W.; Auston, D. H.; Morse, J. D., "Hot-Electron Dynamics Study by Terahertz Radiation from Large-Aperture GaAs P-I-N-Diodes", *Appl. Phys. Lett.* **1993**, 62, 3507.
- (155) Kersting, R.; Unterrainer, K.; Strasser, G.; Kauffmann, H. F.; Gornik, E., "Few-cycle THz emission from cold plasma oscillations", *Phys. Rev. Lett.* **1997**, 79, 3038.
- (156) Leitenstorfer, A.; Hunsche, S.; Shah, J.; Nuss, M. C.; Knox, W. H., "Ultrafast high-field transport in semiconductors", *Physica B* **1999**, 272, 348.
- (157) Yu, P. Y.; Cardona, M. *Fundamentals of Semiconductors*; 3rd ed.; Springer: New York, 2001.
- (158) Hirakawa, K.; Wilke, I.; Yamanaka, K.; Roskos, H. G.; Vosseburger, M.; Wolter, F.; Waschke, C.; Kurz, H.; Grayson, M.; Tsui, D. C., "Coherent submillimeter-wave emission from non-equilibrium two-dimensional free carrier plasmas in AlGaAs/GaAs heterojunctions", *Surf. Sci.* **1996**, 362, 368.

- (159) Sekine, N.; Hirakawa, K.; Vosseburger, M.; Haring-Bolivar, P.; Kurz, H., "Excitation process of two-dimensional plasmons excited by femtosecond laser pulses", *Microelectron. Eng.* **1999**, *47*, 289.
- (160) Sekine, N.; Yamanaka, K.; Hirakawa, K.; Vosseburger, M.; Haring-Bolivar, P.; Kurz, H., "Observation of terahertz radiation from higher-order two-dimensional plasmon modes in GaAs/AlGaAs single quantum wells", *Appl. Phys. Lett.* **1999**, *74*, 1006.
- (161) Sekine, N.; Hirakawa, K.; Vosseburger, M.; Haring-Bolivar, P.; Kurz, H. In *Compound Semiconductors 1998*, 1999.
- (162) Planken, P. C. M.; Nuss, M. C.; Brener, I.; Goossen, K. W.; Luo, M. S. C.; Chuang, S. L.; Pfeiffer, L., "Terahertz Emission in Single Quantum-Wells after Coherent Optical-Excitation of Light Hole and Heavy Hole Excitons", *Phys. Rev. Lett.* **1992**, *69*, 3800.
- (163) Planken, P. C. M.; Nuss, M. C.; Knox, W. H.; Miller, D. A. B.; Goossen, K. W., "THz Pulses from the Creation of Polarized Electron-Hole Pairs in Biased Quantum-Wells", *Appl. Phys. Lett.* **1992**, *61*, 2009.
- (164) Planken, P. C. M.; Brener, I.; Nuss, M. C.; Luo, M. S. C.; Chuang, S. L.; Pfeiffer, L. N., "THz Radiation from Coherent Population-Changes in Quantum-Wells", *Phys. Rev. B* **1994**, *49*, 4668.
- (165) Brener, I.; Planken, P. C. M.; Nuss, M. C.; Luo, M. S. C.; Chuang, S. L.; Pfeiffer, L.; Leaird, D. E.; Weiner, A. M., "Coherent Control of Terahertz Emission and Carrier Populations in Semiconductor Heterostructures", *J. Opt. Soc. Am. B-Opt. Phys.* **1994**, *11*, 2457.
- (166) Sha, W. J.; Rhee, J. K.; Norris, T. B.; Schaff, W. J., "Transient Carrier and Field-Dynamics in Quantum-Well Parallel Transport - from the Ballistic to the Quasi-Equilibrium Regime", *IEEE J. Quantum Electron.* **1992**, *28*, 2445.
- (167) Roskos, H. G.; Nuss, M. C.; Shah, J.; Leo, K.; Miller, D. A. B.; Fox, A. M.; Schmittrink, S.; Kohler, K., "Coherent Submillimeter-Wave Emission from Charge Oscillations in a Double-Well Potential", *Phys. Rev. Lett.* **1992**, *68*, 2216.
- (168) Planken, P. C. M.; Brener, I.; Nuss, M. C.; Luo, M. S. C.; Chuang, S. L., "Coherent Control of Terahertz Charge Oscillations in a Coupled-Quantum-Well Using Phase-Locked Optical Pulses", *Phys. Rev. B* **1993**, *48*, 4903.
- (169) Nuss, M. C.; Planken, P. C. M.; Brener, I.; Roskos, H. G.; Luo, M. S. C.; Chuang, S. L., "Terahertz Electromagnetic-Radiation from Quantum-Wells", *Appl. Phys. B-Lasers Opt.* **1994**, *58*, 249.
- (170) Luo, M. S. C.; Chuang, S. L.; Planken, P. C. M.; Brener, I.; Roskos, H. G.; Nuss, M. C., "Generation of Terahertz Electromagnetic Pulses from Quantum-Well Structures", *IEEE J. Quantum Electron.* **1994**, *30*, 1478.
- (171) Sekine, N.; Hirakawa, K.; Arakawa, Y., "Terahertz emission from quantum beats in coupled quantum wells", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **1998**, *37*, 1643.
- (172) Morohashi, I.; Komori, K.; Hidaka, T.; Sugaya, T.; Wang, X. L.; Ogura, M.; Nakagawa, T.; Son, C. S., "Terahertz electromagnetic wave generation from quantum nanostructure", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **2001**, *40*, 3012.
- (173) Camacho, A. S.; Gutierrez, R. M.; Bohorquez, J., "Mechanism of terahertz emission from an asymmetric double quantum well", *Phys. Status Solidi B-Basic Res.* **2002**, *232*, 56.
- (174) Morohashi, I.; Komori, K.; Wang, X. L.; Hidaka, T.; Ogura, M.; Watanabe, M., "Excitation wavelength dependence of terahertz electromagnetic wave generation from quantum wire", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **2002**, *41*, 2710.
- (175) Zhang, W. M.; Meier, T.; Chernyak, V.; Mukamel, S., "Intraband terahertz emission from coupled semiconductor quantum wells: A model study using the exciton representation", *Phys. Rev. B* **1999**, *60*, 2599.
- (176) Waschke, C.; Leisching, P.; Bolivar, P. H.; Schwedler, R.; Bruggemann, F.; Roskos, H. G.; Leo, K.; Kurz, H.; Kohler, K., "Detection of Bloch Oscillations in a Semiconductor Superlattice by Time-Resolved Terahertz Spectroscopy and Degenerate 4-Wave-Mixing", *Solid-State Electron.* **1994**, *37*, 1321.
- (177) Waschke, C.; Roskos, H. G.; Leo, K.; Kurz, H.; Kohler, K., "Experimental Realization of the Bloch Oscillator in a Semiconductor Superlattice", *Semicond. Sci. Technol.* **1994**, *9*, 416.
- (178) Dekorsy, T.; Leisching, P.; Waschke, C.; Kohler, K.; Leo, K.; Roskos, H. G.; Kurz, H., "Terahertz Bloch Oscillations in Semiconductor Superlattices", *Semicond. Sci. Technol.* **1994**, *9*, 1959.
- (179) Roskos, H. G. In *Festkorperprobleme-Advances in Solid State Physics*, 1995; Vol. 34.
- (180) Dekorsy, T.; Ott, R.; Leisching, P.; Bakker, H. J.; Waschke, C.; Roskos, H. G.; Kurz, H.; Kohler, K., "Time-resolved optical investigations of bloch oscillations in semiconductor superlattices", *Solid-State Electron.* **1996**, *40*, 551.
- (181) Shimada, Y.; Matsuno, T.; Hirakawa, K., "Terahertz emission due to miniband transport in GaAs/AlGaAs superlattices", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **2001**, *40*, 3009.
- (182) Shimada, Y.; Hirakawa, K.; Lee, S. W., "Time-resolved terahertz emission spectroscopy of wide miniband GaAs/AlGaAs superlattices", *Appl. Phys. Lett.* **2002**, *81*, 1642.
- (183) Sudzius, M.; Lyssenko, V. G.; Loser, F.; Leo, K.; Dignam, M. M.; Kohler, K., "Optical control of Bloch-oscillation amplitudes: From harmonic spatial motion to breathing modes", *Phys. Rev. B* **1998**, *57*, R12693.
- (184) Shimada, Y.; Hirakawa, K. In *Compound Semiconductors 2001*, 2002.
- (185) Hokomoto, Y.; Kadoya, Y.; Yamanishi, M., "THz electromagnetic wave radiation from coherent oscillation of exciton population in high-Q semiconductor microcavities", *Appl. Phys. Lett.* **1999**, *74*, 3839.
- (186) Sakurada, T.; Kadoya, Y.; Yamanishi, M., "THz electromagnetic wave radiation from bulk semiconductor microcavities excited by short laser pulses", *Jpn. J. Appl. Phys. Part 2 - Lett.* **2002**, *41*, L256.
- (187) Walecki, W. J.; Some, D.; Kozlov, V. G.; Nurmikko, A. V., "Terahertz Electromagnetic Transients as Probes of a 2-Dimensional Electron-Gas", *Appl. Phys. Lett.* **1993**, *63*, 1809.
- (188) Some, D.; Nurmikko, A. V., "Real-Time Electron-Cyclotron Oscillations Observed by Terahertz Techniques in Semiconductor Heterostructures", *Appl. Phys. Lett.* **1994**, *65*, 3377.
- (189) Kersting, R.; Bratschitsch, R.; Strasser, G.; Unterrainer, K.; Heyman, J. N., "Sampling a terahertz dipole transition with subcycle time resolution", *Opt. Lett.* **2000**, *25*, 272.
- (190) Ascazubi, R.; Akin, O. C.; Zaman, T.; Kersting, R.; Strasser, G., "Dephasing in modulation-doped quantum structures probed by THz time-domain spectroscopy", *Appl. Phys. Lett.* **2002**, *81*, 4344.
- (191) Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K.; Tomozawa, S.; Hangyo, M.; Murakami, Y.; Nakashima, S. I., "Ultrashort electromagnetic pulse radiation from YBCO thin films excited by femtosecond optical pulse", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **1996**, *35*, 2624.
- (192) Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K.; Wada, N.; Hangyo, M., "Terahertz emission study of femtosecond time-transient nonequilibrium state in optically excited YBa₂Cu₃O_{7- δ} thin films", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1996**, *35*, L1578.
- (193) Hangyo, M.; Tomozawa, S.; Murakami, Y.; Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K.; Nakashima, S., "Terahertz radiation from superconducting YBa₂Cu₃O_{7- δ} thin films excited by femtosecond optical pulses", *Appl. Phys. Lett.* **1996**, *69*, 2122.
- (194) Jaekel, C.; Roskos, H. G.; Kurz, H., "Emission of picosecond electromagnetic pulses from optically excited superconducting bridges", *Phys. Rev. B* **1996**, *54*, R6889.
- (195) Jaekel, C.; Roskos, H. G.; Kurz, H., "Ultrafast optoelectronic switches based on high-T_c superconductors", *IEEE Trans. Appl. Supercond.* **1997**, *7*, 3722.
- (196) Tani, M.; Tonouchi, M.; Wang, Z.; Sakai, K.; Hangyo, M.; Tomozawa, S.; Murakami, Y., "Enhanced sub-picosecond electromagnetic radiation from YBa₂Cu₃O_{7- δ} thin-film bow-tie antennas excited with femtosecond laser pulses", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1996**, *35*, L1184.
- (197) Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K.; Wada, N.; Hangyo, M., "Novel terahertz radiation from flux-trapped YBa₂Cu₃O_{7- δ} thin films excited by femtosecond laser pulses", *Jpn. J. Appl. Phys. Part 2 - Lett.* **1997**, *36*, L93.

- (198) Tonouchi, M.; Wada, N.; Shikii, S.; Hangyo, M.; Tani, M.; Sakai, K., "Terahertz emission properties from flux-trapped YBCO thin films", *Physica C* **1997**, 293, 82.
- (199) Hangyo, M.; Wada, N.; Tonouchi, M.; Tani, M.; Sakai, K., "Ultrafast optical response and terahertz radiation from high-T_c superconductor", *IEICE Trans. Electron.* **1997**, E80C, 1282.
- (200) Hangyo, M.; Tomozawa, S.; Murakami, Y.; Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K., "Ultrafast photoexcited quasiparticle dynamics in YBCO films observed by THz emission", *IEEE Trans. Appl. Supercond.* **1997**, 7, 2909.
- (201) Hangyo, M.; Tomozawa, S.; Murakami, Y.; Tonouchi, M.; Tani, M.; Wang, Z.; Sakai, K., "THz emission from high-T_c superconductors by optical pulse excitation", *IEEE Trans. Appl. Supercond.* **1997**, 7, 3730.
- (202) Iguchi, I.; Kume, E.; Takahashi, H., "Emitted spectra of electromagnetic waves from a tunnel-injected nonequilibrium high-T_c YBa₂Cu₃O_{7-y} superconductor", *Phys. Rev. B* **2000**, 62, 5370.
- (203) Wald, H.; Steigmeier, C.; Seidel, P.; Nashima, S.; Tonouchi, M.; Hangyo, M., "Comparison of the electromagnetic pulse emission from YBa₂Cu₃O_{7-delta} and Y_{0.7}Pr_{0.3}Ba₂Cu₃O₇ excited by femtosecond laser pulses", *Physica C* **2000**, 341, 1899.
- (204) Yoshimura, T.; Kiwa, T.; Tonouchi, M., "Terahertz emission from YBa₂Cu₃O_{7-delta} Josephson junctions excited by femtosecond laser", *Physica C* **2001**, 362, 329.
- (205) Wald, H.; Seidel, P.; Tonouchi, M., "Pump-and-probe terahertz method to investigate YBa₂Cu₃O_{7-delta} thin films", *Physica C* **2002**, 367, 308.
- (206) Wald, H.; Seidel, P.; Tonouchi, M., "Carrier dynamics in YBa₂Cu₃O_{7-x} studied by pump and probe terahertz excitation", *Physica C* **2001**, 362, 324.
- (207) Wald, H.; Seidel, P.; Tonouchi, M., "Pump and probe terahertz beam excitation technique to investigate carrier dynamics in YBa₂Cu₃O_{7-delta} thin films", *Physica C* **2001**, 357, 146.
- (208) Wald, H.; Schmidt, F.; Seidel, P.; Tonouchi, M., "Terahertz radiation emitted by dipole antennas of YBa₂Cu₃O_{7-delta}/PrBa₂Cu₃O₇ multilayers", *Supercond. Sci. Technol.* **2002**, 15, 1494.
- (209) Tominari, Y.; Kiwa, T.; Murakami, H.; Tonouchi, M.; Wald, H.; Seidel, P.; Schneidewind, H., "Resonant terahertz radiation from Ti₂Ba₂CaCu₂O_{8+delta} thin films by ultrafast optical pulse excitation", *Appl. Phys. Lett.* **2002**, 80, 3147.
- (210) Tominari, Y.; Kiwa, T.; Murakami, H.; Tonouchi, M.; Wald, H.; Seidel, P.; Schneidewind, H., "Coherent terahertz radiation from Ti₂Ba₂CaCu₂O_{8+delta} thin films excited by optical laser pulse under magnetic field", *Physica C* **2003**, 388, 481.
- (211) Beard, M. C.; Turner, G. M.; Schmuttenmaer, C. A., "Measurement of electromagnetic radiation emitted during rapid intramolecular electron transfer", *J. Am. Chem. Soc.* **2000**, 122, 11541.
- (212) Beard, M. C.; Turner, G. M.; Schmuttenmaer, C. A., "Measuring intramolecular charge transfer via coherent generation of THz radiation", *J. Phys. Chem. A* **2002**, 106, 878.
- (213) Groot, M. L.; Vos, M. H.; Schlichting, I.; van Mourik, F.; Joffe, M.; Lambry, J. C.; Martin, J. L., "Coherent infrared emission from myoglobin crystals: An electric field measurement", *Proc. Natl. Acad. Sci. U. S. A.* **2002**, 99, 1323.
- (214) Kida, N.; Tonouchi, M., "Terahertz radiation from magnetoresistive Pr_{0.7}Ca_{0.3}MnO₃ thin films", *Appl. Phys. Lett.* **2001**, 78, 4115.
- (215) Kida, N.; Tonouchi, M., "Reversible and bistable terahertz radiation from magnetoresistive Pr_{0.7}Ca_{0.3}MnO₃ thin films", *Appl. Phys. Lett.* **2003**, 82, 3412.
- (216) Wilke, I.; MacLeod, A. M.; Gillespie, W. A.; Berden, G.; Knippels, G. M. H.; van der Meer, A. F. G., "Real-time single-shot electron bunch length measurements", *Nucl. Instrum. Methods Phys. Res. Sect. A-Accel. Spectrom. Dect. Assoc. Equip.* **2002**, 483, 282.
- (217) Wilke, I.; MacLeod, A. M.; Gillespie, W. A.; Berden, G.; Knippels, G. M. H.; van der Meer, A. F. G., "Single-shot electron-beam bunch length measurements", *Phys. Rev. Lett.* **2002**, 88, 124801.
- (218) Pedersen, J. E.; Lyssenko, V. G.; Hvam, J. M.; Jepsen, P. U.; Keiding, S. R.; Sorensen, C. B.; Lindelof, P. E., "Ultrafast Local Field-Dynamics in Photoconductive Thz Antennas", *Appl. Phys. Lett.* **1993**, 62, 1265.
- (219) Brorson, S. D.; Zhang, J. C.; Keiding, S. R., "Ultrafast Carrier Trapping and Slow Recombination in Ion-Bombarded Silicon-on-Sapphire Measured Via Thz Spectroscopy", *Appl. Phys. Lett.* **1994**, 64, 2385.
- (220) Hu, B. B.; Desouza, E. A.; Knox, W. H.; Cunningham, J. E.; Nuss, M. C.; Kuznetsov, A. V.; Chuang, S. L., "Identifying the Distinct Phases of Carrier Transport in Semiconductors with 10-Fs Resolution", *Phys. Rev. Lett.* **1995**, 74, 1689.
- (221) Taylor, A. J.; Rodriguez, G.; Some, D., "Ultrafast field dynamics in large-aperture photoconductors", *Opt. Lett.* **1997**, 22, 715.
- (222) Huggard, P. G.; Cluff, J. A.; Shaw, C. J.; Andrews, S. R.; Linfield, E. H.; Ritchie, D. A., "Coherent control of cyclotron emission from a semiconductor using sub-picosecond electric field transients", *Appl. Phys. Lett.* **1997**, 71, 2647.
- (223) Kersting, R.; Heyman, J. N.; Strasser, G.; Unterrainer, K., "Coherent plasmons in n-doped GaAs", *Phys. Rev. B* **1998**, 58, 4553.
- (224) Tonouchi, M.; Kawasaki, N.; Yoshimura, T.; Wald, H.; Seidel, P., "Pump and probe terahertz generation study of ultrafast carrier dynamics in low-temperature grown-GaAs", *Jpn. J. Appl. Phys. Part 2 - Lett.* **2002**, 41, L706.
- (225) Weling, A. S.; Hu, B. B.; Froberg, N. M.; Auston, D. H., "Generation of Tunable Narrow-Band Thz Radiation from Large-Aperture Photoconducting Antennas", *Appl. Phys. Lett.* **1994**, 64, 137.
- (226) Weling, A. S.; Auston, D. H., "Novel sources and detectors for coherent tunable narrow-band terahertz radiation in free space", *J. Opt. Soc. Am. B-Opt. Phys.* **1996**, 13, 2783.
- (227) Liu, Y. Q.; Park, S. G.; Weiner, A. M., "Enhancement of narrow-band terahertz radiation from photoconducting antennas by optical pulse shaping", *Opt. Lett.* **1996**, 21, 1762.
- (228) Siders, C. W.; Siders, J. L. W.; Taylor, A. J.; Park, S. G.; Melloch, M. R.; Weiner, A. M., "Generation and characterization of terahertz pulse trains from biased, large-aperture photoconductors", *Opt. Lett.* **1999**, 24, 241.
- (229) Sohn, J. Y.; Ahn, Y. H.; Park, D. J.; Oh, E.; Kim, D. S., "Tunable terahertz generation using femtosecond pulse shaping", *Appl. Phys. Lett.* **2002**, 81, 13.
- (230) Haran, G.; Sun, W. D.; Wynne, K.; Hochstrasser, R. M., "Femtosecond far-infrared pump-probe spectroscopy: A new tool for studying low-frequency vibrational dynamics in molecular condensed phases", *Chem. Phys. Lett.* **1997**, 274, 365.
- (231) McElroy, R.; Wynne, K., "Ultrafast dipole solvation measured in the far infrared", *Phys. Rev. Lett.* **1997**, 79, 3078.
- (232) Greene, B. I.; Federici, J. F.; Dykaar, D. R.; Levi, A. F. J.; Pfeiffer, L., "Picosecond Pump and Probe Spectroscopy Utilizing Freely Propagating Terahertz Radiation", *Opt. Lett.* **1991**, 16, 48.
- (233) Saeta, P. N.; Federici, J. F.; Greene, B. I.; Dykaar, D. R., "Intervalley Scattering in GaAs and InP Probed by Pulsed Far-Infrared Transmission Spectroscopy", *Appl. Phys. Lett.* **1992**, 60, 1477.
- (234) Chen, Y.; Prabhu, S. S.; Ralph, S. E.; McInturff, D. T., "Trapping and recombination dynamics of low-temperature-grown InGaAs/InAlAs multiple quantum wells", *Appl. Phys. Lett.* **1998**, 72, 439.
- (235) Messner, C.; Kostner, H.; Hopfel, R. A.; Unterrainer, K., "Time-resolved THz spectroscopy of proton-bombarded InP", *J. Opt. Soc. Am. B-Opt. Phys.* **2001**, 18, 1369.
- (236) Lui, K. P. H.; Hegmann, F. A., "Ultrafast carrier relaxation in radiation-damaged silicon on sapphire studied by optical-pump-terahertz-probe experiments", *Appl. Phys. Lett.* **2001**, 78, 3478.
- (237) Lui, K. P. H.; Hegmann, F. A., "Fluence- and temperature-dependent studies of carrier dynamics in radiation-damaged silicon-on-sapphire and amorphous silicon", *J. Appl. Phys.* **2003**, 93, 9012.
- (238) Jepsen, P. U.; Schairer, W.; Libon, I. H.; Lemmer, U.; Hecker, N. E.; Birkholz, M.; Lips, K.; Schall, M., "Ultrafast carrier trapping in microcrystalline silicon observed in optical pump-terahertz probe measurements", *Appl. Phys. Lett.* **2001**, 79, 1291.
- (239) Yarotski, D. A.; Averitt, R. D.; Negre, N.; Crooker, S. A.; Taylor, A. J.; Donati, G. P.; Stintz, A.; Lester, L. F.; Malloy, K. J., "Ultrafast carrier-

- relaxation dynamics in self-assembled InAs/GaAs quantum dots", *J. Opt. Soc. Am. B-Opt. Phys.* **2002**, *19*, 1480.
- (240) Segsneider, G.; Jacob, F.; Löffler, T.; Roskos, H. G.; Tautz, S.; Kiesel, P.; Döhler, G., "Free-carrier dynamics in low-temperature-grown GaAs at high excitation densities investigated by time-domain terahertz spectroscopy", *Phys. Rev. B* **2002**, *65*, 125205.
- (241) Hegmann, F. A.; Tykewinski, R. R.; Lui, K. P. H.; Bullock, J. E.; Anthony, J. E., "Picosecond transient photoconductivity in functionalized pentacene molecular crystals probed by terahertz pulse spectroscopy", *Phys. Rev. Lett.* **2002**, *89*, 227403.
- (242) Stanton, C. J.; Bailey, D. W., "Rate-Equations For the Study of Femtosecond Intervalley Scattering in Compound Semiconductors", *Phys. Rev. B* **1992**, *45*, 8369.
- (243) Federici, J. F.; Greene, B. I.; Saeta, P. N.; Dykaar, D. R.; Sharifi, F.; Dynes, R. C., "Direct Picosecond Measurement of Photoinduced Cooper-Pair Breaking in Lead", *Phys. Rev. B* **1992**, *46*, 11153.
- (244) Groeneveld, R. H. M.; Grischkowsky, D., "Picosecond Time-Resolved Far-Infrared Experiments on Carriers and Excitons in GaAs-AlGaAs Multiple-Quantum Wells", *J. Opt. Soc. Am. B-Opt. Phys.* **1994**, *11*, 2502.
- (245) Flanders, B. N.; Arnett, D. C.; Scherer, N. F., "Optical pump-terahertz probe spectroscopy utilizing a cavity-dumped oscillator-driven terahertz spectrometer", *IEEE J. Sel. Top. Quantum Electron.* **1998**, *4*, 353.
- (246) Schall, M.; Jepsen, P. U., "Photoexcited GaAs surfaces studied by transient terahertz time-domain spectroscopy", *Opt. Lett.* **2000**, *25*, 13.
- (247) Knoesel, E.; Bonn, M.; Shan, J.; Heinz, T. F., "Charge transport and carrier dynamics in liquids probed by THz time-domain spectroscopy", *Phys. Rev. Lett.* **2001**, *86*, 340.
- (248) Jamison, S. P.; Shen, J. L.; Jones, D. R.; Issac, R. C.; Ersfeld, B.; Clark, D.; Jaroszynski, D. A., "Plasma characterization with terahertz time-domain measurements", *J. Appl. Phys.* **2003**, *93*, 4334.
- (249) Nuss, M. C.; Auston, D. H.; Capasso, F., "Direct Subpicosecond Measurement of Carrier Mobility of Photoexcited Electrons in Gallium-Arsenide", *Phys. Rev. Lett.* **1987**, *58*, 2355.
- (250) Zielbauer, J.; Wegener, M., "Ultrafast optical pump THz-probe spectroscopy on silicon", *Appl. Phys. Lett.* **1996**, *68*, 1223.
- (251) Huber, R.; Tauser, F.; Brodschelm, A.; Bichler, M.; Abstreiter, G.; Leitenstorfer, A., "How many-particle interactions develop after ultrafast excitation of an electron-hole plasma", *Nature* **2001**, *414*, 286.
- (252) Huber, R.; Tauser, F.; Brodschelm, A.; Bichler, M.; Abstreiter, G.; Leitenstorfer, A., "Femtosecond buildup of Coulomb screening in photoexcited GaAs probed via ultrabroadband THz spectroscopy", *J. Lumines.* **2001**, *94*, 555.
- (253) Huber, R.; Tauser, F.; Brodschelm, A.; Leitenstorfer, A., "Femtosecond buildup of a many-body resonance observed via two-dimensional THz time-domain spectroscopy", *Phys. Status Solidi B-Basic Res.* **2002**, *234*, 207.
- (254) Leitenstorfer, A.; Huber, R.; Tauser, F.; Brodschelm, A.; Bichler, M.; Abstreiter, G., "Femtosecond buildup of Coulomb screening in a photoexcited electron-hole plasma", *Physica B* **2002**, *314*, 248.
- (255) Kaindl, R. A.; Carnahan, M. A.; Hagele, D.; Lovenich, R.; Chemla, D. S., "Ultrafast terahertz probes of transient conducting and insulating phases in an electron-hole gas", *Nature* **2003**, *423*, 734.
- (256) Averitt, R. D.; Rodriguez, G.; Siders, J. L. W.; Trugman, S. A.; Taylor, A. J., "Conductivity artifacts in optical-pump THz-probe measurements of YBa₂Cu₃O₇", *J. Opt. Soc. Am. B-Opt. Phys.* **2000**, *17*, 327.
- (257) Averitt, R. D.; Rodriguez, G.; Lobad, A. I.; Siders, J. L. W.; Trugman, S. A.; Taylor, A. J., "Nonequilibrium superconductivity and quasiparticle dynamics in YBa₂Cu₃O_{7-delta}", *Phys. Rev. B* **2001**, *63*, 140502.
- (258) Brorson, S. D.; Buhleier, R.; Trofimov, I. E.; White, J. O.; Ludwig, C.; Balakirev, F. F.; Habermeier, H. U.; Kuhl, J., "Electrodynamics of high-temperature superconductors investigated with coherent terahertz pulse spectroscopy", *J. Opt. Soc. Am. B-Opt. Phys.* **1996**, *13*, 1799.
- (259) Averitt, R. D.; Lobad, A. I.; Kwon, C.; Trugman, S. A.; Thorsmolle, V. K.; Taylor, A. J., "Ultrafast conductivity dynamics in colossal magnetoresistance manganites", *Phys. Rev. Lett.* **2001**, *87*, 017401.
- (260) Beard, M. C.; Schmittenmaer, C. A., "Using the finite-difference time-domain pulse propagation method to simulate time-resolved THz experiments", *J. Chem. Phys.* **2001**, *114*, 2903.
- (261) Beard, M. C.; Turner, G. M.; Schmittenmaer, C. A. In *Liquid Dynamics: Experiment, Simulation, and Theory*, 2002; Vol. 820.
- (262) Beard, M. C.; Turner, G. M.; Schmittenmaer, C. A., "Size-dependent photoconductivity in CdSe nanoparticles as measured by time-resolved terahertz spectroscopy", *Nano Lett.* **2002**, *2*, 983.
- (263) Turner, G. M.; Beard, M. C.; Schmittenmaer, C. A., "Carrier localization and cooling in dye-sensitized nanocrystalline titanium dioxide", *J. Phys. Chem. B* **2002**, *106*, 11716.
- (264) Smith, N. V., "Classical generalization of the Drude formula for the optical conductivity", *Phys. Rev. B* **2001**, *64*, 155106.
- (265) Cook, D. J.; Chen, J. X.; Morlino, E. A.; Hochstrasser, R. M., "Terahertz-field-induced second-harmonic generation measurements of liquid dynamics", *Chem. Phys. Lett.* **1999**, *309*, 221.
- (266) Ahn, J.; Hutchinson, D. N.; Rangan, C.; Bucksbaum, P. H., "Quantum phase retrieval of a Rydberg wave packet using a half-cycle pulse", *Phys. Rev. Lett.* **2001**, *86*, 1179.
- (267) Ahn, J.; Rangan, C.; Hutchinson, D. N.; Bucksbaum, P. H., "Quantum-state information retrieval in a Rydberg-atom data register", *Phys. Rev. A* **2002**, *66*, 022312.
- (268) Jones, R. R.; You, D.; Bucksbaum, P. H., "Ionization of Rydberg Atoms by Subpicosecond Half-Cycle Electromagnetic Pulses", *Phys. Rev. Lett.* **1993**, *70*, 1236.
- (269) Jones, R. R.; Tielking, N. E.; You, D.; Raman, C.; Bucksbaum, P. H., "Ionization of Oriented Rydberg States by Subpicosecond Half-Cycle Electromagnetic Pulses", *Phys. Rev. A* **1995**, *51*, R2687.
- (270) Raman, C.; Conover, C. W. S.; Sukenik, C. I.; Bucksbaum, P. H., "Ionization of Rydberg wave packets by subpicosecond, half-cycle electromagnetic pulses", *Phys. Rev. Lett.* **1996**, *76*, 2436.
- (271) Raman, C.; Weinacht, T. C.; Bucksbaum, P. H., "Stark wave packets viewed with half-cycle pulses", *Phys. Rev. A* **1997**, *55*, R3995.
- (272) Rangan, C.; Bucksbaum, P. H., "Optimally shaped terahertz pulses for phase retrieval in a Rydberg-atom data register", *Phys. Rev. A* **2001**, *64*, 033417.
- (273) Rangan, C.; Ahn, J.; Hutchinson, D. N.; Bucksbaum, P. H., "Control of Rydberg atoms to perform Grover's search algorithm", *J. Mod. Opt.* **2002**, *49*, 2339.
- (274) Reinhold, C. O.; Burgdorfer, J.; Jones, R. R.; Raman, C.; Bucksbaum, P. H., "Scaled-Time Dynamics of Ionization of Rydberg Stark States by Half-Cycle Pulses", *J. Phys. B-At. Mol. Opt. Phys.* **1995**, *28*, L457.
- (275) Manescu, C.; Krause, J. L.; Schafer, K. J., "Ionization of Stark states with half-cycle pulses: Interference effects in the continuum", *Phys. Rev. A* **2003**, *68*.
- (276) Hache, A.; Kostoulas, Y.; Atanasov, R.; Hughes, J. L. P.; Sipe, J. E.; vanDriel, H. M., "Observation of coherently controlled photocurrent in unbiased, bulk GaAs", *Appl. Phys. Lett.* **1997**, *78*, 306.
- (277) Kral, P.; Sipe, J. E., "Quantum kinetic theory of two-beam current injection in bulk semiconductors", *Phys. Rev. B* **2000**, *61*, 5381.
- (278) Cote, D.; Fraser, J. M.; DeCamp, M.; Bucksbaum, P. H.; van Driel, H. M., "THz emission from coherently controlled photocurrents in GaAs", *Appl. Phys. Lett.* **1999**, *75*, 3959.
- (279) Cote, D.; Laman, N.; van Driel, H. M., "Rectification and shift currents in GaAs", *Appl. Phys. Lett.* **2002**, *80*, 905.
- (280) Jepsen, P. U.; Keiding, S. R., "Radiation-Patterns from Lens-Coupled Terahertz Antennas", *Opt. Lett.* **1995**, *20*, 807.
- (281) Joshi, R. P.; Dharamsi, A. N., "Effect of Coherent Electromagnetic-Radiation on the Ultrafast Electron Dynamics of Laser-Excited Bulk Photoconductors", *J. Appl. Phys.* **1993**, *74*, 3215.
- (282) Khurgin, J. B., "Optical Rectification and Terahertz Emission in Semiconductors Excited above the Band-Gap", *J. Opt. Soc. Am. B-Opt. Phys.* **1994**, *11*, 2492.

- (283) Abe, M.; Madhavi, S.; Shimada, Y.; Otsuka, Y.; Hirakawa, K.; Tomizawa, K., "Transient carrier velocities in bulk GaAs: Quantitative comparison between terahertz data and ensemble Monte Carlo calculations", *Appl. Phys. Lett.* **2002**, *81*, 679.
- (284) Piao, Z. S.; Tani, M.; Sakai, K., "Carrier dynamics and terahertz radiation in photoconductive antennas", *Jpn. J. Appl. Phys. Part 1 - Regul. Pap. Short Notes Rev. Pap.* **2000**, *39*, 96.
- (285) You, D.; Bucksbaum, P. H., "Propagation of half-cycle far infrared pulses", *J. Opt. Soc. Am. B-Opt. Phys.* **1997**, *14*, 1651.
- (286) Kuzel, P.; Khazan, M. A.; Kroupa, J., "Spatiotemporal transformations of ultrashort terahertz pulses", *J. Opt. Soc. Am. B-Opt. Phys.* **1999**, *16*, 1795.
- (287) Nekkanti, S.; Sullivan, D.; Citrin, D. S., "Simulation of spatiotemporal terahertz pulse shaping in 3-D using conductive apertures of finite thickness", *IEEE J. Quantum Electron.* **2001**, *37*, 1226.
- (288) Nemec, H.; Kadlec, F.; Kuzel, P., "Methodology of an optical pump-terahertz probe experiment: An analytical frequency-domain approach", *J. Chem. Phys.* **2002**, *117*, 8454.
- (289) Cote, D.; Sipe, J. E.; van Driel, H. M., "Simple method for calculating the propagation of terahertz radiation in experimental geometries", *J. Opt. Soc. Am. B-Opt. Phys.* **2003**, *20*, 1374.
- (290) Lachaine, J. M.; Hawton, M.; Sipe, J. E.; Dignam, M. M., "Asymmetry in the excitonic Wannier-Stark ladder: A mechanism for the stimulated emission of terahertz radiation", *Phys. Rev. B* **2000**, *62*, R4829.
- (291) Okumura, K.; Tanimura, Y., "Two-dimensional THz spectroscopy of liquids: non-linear vibrational response to a series of THz laser pulses", *Chem. Phys. Lett.* **1998**, *295*, 298.
- (292) Kindt, J. T.; Schmittenmaer, C. A., "Theory for determination of the low-frequency time-dependent response function in liquids using time-resolved terahertz pulse spectroscopy", *J. Chem. Phys.* **1999**, *110*, 8589.
- (293) Feise, M. W.; Citrin, D. S., "Semiclassical theory of terahertz multiple-harmonic generation in semiconductor superlattices", *Appl. Phys. Lett.* **1999**, *75*, 3536.
- (294) Asplund, M. C.; Zanni, M. T.; Hochstrasser, R. M., "Two-dimensional infrared spectroscopy of peptides by phase-controlled femtosecond vibrational photon echoes", *Proc. Natl. Acad. Sci. U. S. A.* **2000**, *97*, 8219.
- (295) Golonzka, O.; Khalil, M.; Demirdoven, N.; Tokmakoff, A., "Vibrational anharmonicities revealed by coherent two-dimensional infrared spectroscopy", *Phys. Rev. Lett.* **2001**, *86*, 2154.
- (296) Hybl, J. D.; Albrecht, A. W.; Faeder, S. M. G.; Jonas, D. M., "Two-dimensional electronic spectroscopy", *Chem. Phys. Lett.* **1998**, *297*, 307.
- (297) Cook, D.J., Personal communication, **2003**.
- (298) Dlott, D. D., "Optical Phonon Dynamics in Molecular-Crystals", *Annu. Rev. Phys. Chem.* **1986**, *37*, 157.
- (299) Beard, M. C.; Turner, G. M.; Murphy, J. E.; Micic, O. I.; Hanna, M. C.; Nozik, A. J.; Schmittenmaer, C. A., "Electronic coupling in InP nanoparticle arrays", *Nano Lett.* **2003**, *3*, 1695.
- (300) Service, R. F., "Molecular electronics - Next-generation technology hits an early midlife crisis", *Science* **2003**, *302*, 556.
- (301) Beaurepaire, E.; Turner, G. M.; Harrel, S. M.; Beard, M. C.; Bigot, J.-Y.; Schmittenmaer, C. A., "Coherent THz Emission from Ferromagnetic Films Excited by Visible Femtosecond Laser Pulses", *Appl. Phys. Lett.* **2003**, Submitted.