Concepts and Applications of Nonlinear Terahertz Spectroscopy

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Author biographies

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Thomas Elsaesser is a director at the Max-Born-Institute, Berlin, Germany, and a full professor for experimental physics at Humboldt University, Berlin. He received a Dr rer. nat. degree from the Technical University of Munich in 1986 and worked there as a research associate until 1993. He spent a postdoc period at AT&T Bell Laboratories, Holmdel, in 1990 and joined the newly established Max-Born-Institute in 1993. His research focuses on ultrafast phenomena in condensed matter, in particular molecular liquids, biomolecules in their aqueous environment, and inorganic solids and nanostructures. Combined in his experimental work are methods of ultrafast spectroscopy and structure research. Thomas is a fellow of the American Physical Society and the Optical Society of America and has received numerous scientific awards.

Klaus Reimann

Klaus Reimann has worked since 1999 as a scientist at the Max-Born-Institute, Berlin, Germany, in the field of ultrafast mid-infrared and THz spectroscopy. He received a Dr rer. nat. degree from the University (now Technical University) of Dortmund in 1987. Afterwards he joined the Max-Planck-Institut für Festkörperforschung in Stuttgart and worked there on the physics of semiconductors under high pressures. Having received a five-year Heisenberg-Stipendium of the Deutsche Forschungsgemeinschaft, he spent this time at the Universität Dortmund and at the University of California at Berkeley doing research on nonlinear optics of semiconductors under high pressure before joining the MBI.

Michael Woerner

Michael Woerner is a department head at the Max-Born-Institute, Berlin, Germany, and holds a lecturer qualification (Habilitation) in physics at Humboldt University, Berlin. He received a Dr rer. nat. degree from the Technical University of Munich in 1991 and worked there as a postdoc until 1993. He then joined the Max-Born-Institute in 1993 and spent a postdoc period at Bell Laboratories (Lucent Technologies), Holmdel, in 1997. Michael's research focuses on ultrafast phenomena in solids and nanostructures with pioneering work in multi-dimensional spectroscopies in the THz frequency range and in femtosecond x-ray diffraction using laser-driven hard x-ray sources.

Symbols

$\mathbf{A}$	vector potential
A	magnitude or relevant component of the vector potential (the same convention is used for the magnitude of all other vectors)
$\hat{a}$, $\hat{a}^+$	electron annihilation and creation operators
α	absorption coefficient
$\mathbf{B}$	magnetic field
$c = 299\,792\,458$ m/s	speed of light in vacuum
χ	electric susceptibility
$\chi^{(2)}$, $\chi^{(3)}$,...	nonlinear susceptibilities
$\mathbf{d}$	dipole moment
δ	Dirac's δ function
ΔT	(pump-induced) transmission change
$e = 1.602 \times 10^{-19}$ C	elementary charge
$\mathbf{E}$	electric field
$\mathbf{E}_{\text{em}}$	emitted electric field
$\mathbf{E}_{\text{in}}$	incident electric field
$\mathbf{E}_{\text{loc}}$	local electric field
$\mathbf{E}_{\text{NL}}$	nonlinear electric field
$\mathbf{E}_{\text{re}}$	reflected electric field
$\mathbf{E}_{\text{tr}}$	transmitted electric field
$\mathbf{E}(t)$	electric field as a function of (real) time t
$\mathbf{E}(\nu_t)$	Fourier transform of $\mathbf{E}(t)$, function of frequency ν_t
$\mathbf{E}(t, \tau)$	electric field as a function of real time t and delay time τ
$\mathbf{E}(\nu_t, \nu_\tau)$	2D Fourier transform of $\mathbf{E}(t, \tau)$, function of frequencies ν_t and ν_τ
$\mathscr{E}$	energy
$\mathscr{E}_F$	Fermi energy
$\mathscr{E}_g$	bandgap
ε	dielectric function
$\varepsilon_0 = 8.854 \times 10^{-12}$ As/Vm	permittivity of vacuum
γ	decoherence rate
$h = 6.626 \times 10^{-34}$ Js $= 4.136 \times 10^{-15}$ eVs	Planck's constant
$\hbar = h/(2\pi) = 1.055 \times 10^{-34}$ Js $= 6.582 \times 10^{-16}$ eVs	
$\hat{H}$	Hamiltonian
I	intensity
$\mathbf{j}$	current density
$\mathbf{k}$	(electron) wavevector
$k_B = 1.381 \times 10^{-23}$ J/K	Boltzmann's constant
κ	imaginary part of the refractive index
ℓ	thickness
m	effective mass of an electron in a crystal
$m_0 = 9.109 \times 10^{-31}$ kg	mass of a free electron
$\mathbf{M}$	magnetization
$\mu_0 = 4\pi \times 10^{-7}$ Vs/Am	permeability of vacuum

n	(real part of the) refractive index
N_e	electron density
ν	frequency
$\tilde{\nu}$	wavenumber
$\omega = 2\pi\ \nu$	angular frequency
$\mathbf{p}$	momentum
$\mathbf{P}$	electric polarization
ϕ, ψ, Ψ	wavefunctions
$\mathbf{q}$	phonon wavevector
$q_e = -e$	electron charge
$\mathbf{Q}$	electric quadrupole polarization
$\mathbf{r}$, $\mathbf{R}$	position
ρ	density matrix
σ	electrical conductivity
$\sigma^{(2)}$, $\sigma^{(3)}$, ...	nonlinear conductivities
σ_a	absorption cross section
t	(real) time
T	waiting time
T	absolute temperature
T_0	linear transmission (before interaction with a pump pulse)
τ	delay time
τ_{Drude}	Drude scattering time
tr	trace (of a matrix)
$u_{i,\,\mathbf{k}}(\mathbf{r})$	cell-periodic part of the Bloch function for an electron in band i with wavevector $\mathbf{k}$
$\mathbf{v}$	velocity
v_F	Fermi velocity
V	volume
$V(\mathbf{r})$	potential