# Field Guide to

# Terahertz Sources, Detectors, and Optics

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SPIE Field Guides
Volume FG28

John E. Greivenkamp, Series Editor

SPIE PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

O'Sullivan, Créidhe M. M.
Field guide to terahertz sources, detectors, and optics / Créidhe O'Sullivan, J. Anthony Murphy.
p. cm. – (The field guide series ; FG28)
Includes bibliographical references and index.
ISBN 978-0-8194-9167-1
1. Millimeter wave devices–Handbooks, manuals, etc.
2. Terahertz technology–Handbooks, manuals, etc.
3. Infrared equipment–Handbooks, manuals, etc.
4. Submillimeter waves–Handbooks, manuals, etc.
I. Murphy, J. Anthony. II. Title.
TK7876.5.O88 2012
621.381'33–dc23

2012012372

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1.360.676.3290
Fax: +1.360.647.1445
Email: books@spie.org
Web: http://spie.org



Printed in the United States of America.

First Printing

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## Field Guide to THz

The region of the electromagnetic spectrum between microwaves and infrared radiation has come to be known as the "THz gap," mainly due to the lack of readily available laboratory sources and detectors. For many years technology development was driven by astronomers and planetary scientists, but other potential uses, particularly in medical and security applications, have led to increased activity by the mainstream physics and engineering community in recent times. Because diffraction is important at these frequencies, THz systems cannot be successfully designed using traditional optical techniques alone.

The primary objective of this Field Guide is to provide the reader with a concise description of the quasi-optical techniques used at THz frequencies, as well as the basic principles of operation of the most common THz system components in use today. More detailed accounts of specific devices can be found in the bibliography and references therein.

We would like to thank our families and our colleagues at NUI Maynooth, in particular Neil Trappe, Marcin L. Gradziel, and Ian McAuley of the THz Optics group and also Stafford Withington of the Cavendish Laboratory at Cambridge.

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# Glossary of Symbols and Acronyms

| | |
|---|---|
| $A$ | absorbance |
| $A$ | detector area |
| $A$ | profiled horn parameter |
| $a$ | aperture radius |
| $a$ | horn aperture side length |
| $a$ | semi-major axis of an ellipse |
| $a$ | wire radius |
| $A_n, A_n^h, A_n^v$ | $n^{\text{th}}$ mode coefficient of beam $a$, $n^{\text{th}}$ mode coefficient of orthogonal components |
| $\mathbf{a}_n$ | mode coefficients for beam $n$ at the input port |
| ac | alternating current |
| $\mathbf{A}_{12}, \mathbf{A}_{21}$ | scattering matrices for an absorbing stop |
| $\mathbf{B}$ | magnetic field |
| $B$ | magnetic field strength |
| $b$ | horn aperture side width |
| $b$ | semi-minor axis of an ellipse |
| $B_n, B_n^h, B_n^v$ | $n^{\text{th}}$ mode coefficient of beam $b$, $n^{\text{th}}$ mode coefficient of orthogonal components |
| $\mathbf{b}_n$ | mode coefficients for beam $n$ at the output port |
| BWO | backward wave oscillator |
| $C$ | capacitance |
| $C$ | heat capacity |
| $c$ | speed of light |
| $C_e, C_{ph}$ | electron heat capacity, phonon heat capacity |
| c.c. | complex conjugate |
| CMOS | complementary metal-oxide-semiconductor |
| CW | continuous wave |
| $D$ | detectivity |
| $d$ | diameter |
| $d$ | distance between the focal point and the apex of a lens antenna |
| $d$ | propagation distance |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| $D^*$ | specific detectivity |
| $\mathbf{D}_{12},\mathbf{D}_{21}$ | scattering matrices for pure propagation |
| dc | direct current |
| DFG | difference frequency generation |
| $\mathbf{E},\mathbf{E}_a$ | electric field |
| $\mathbf{E}(t),\mathbf{E}(r)$ | electric field |
| $E,E_0$ | electric field amplitude |
| $E(x,y,z),E(\mathbf{r})$ | electric field amplitude |
| $e$ | elementary charge |
| $E_a,E_b$ | electric field amplitude |
| $\mathbf{E}_{ap}$ | electric field across an aperture |
| $\mathbf{e}_F$ | vector field |
| $\mathbf{e}_G$ | vector Gaussian field |
| $E_g,E_C,E_V,E_F$ | energy gap, conduction band energy, valence band energy, Fermi energy |
| $\hat{\mathbf{e}}_h,\hat{\mathbf{e}}_v$ | unit orthogonal vectors |
| $E_i,E_j,E_k$ | electric field amplitude |
| $E_{inc},E_{refl},E_{trans}$ | incident, reflected, transmitted electric field |
| $E_L,E_H$ | light-, heavy-hole energy |
| $E_{OP}$ | optical phonon energy |
| $E_{out}$ | output electric field |
| $E_{p,t},E_{p,r},E_{p,i}$ | transmitted, reflected, incident electric field amplitude for p-polarization |
| $E_{s,t},E_{s,r},E_{s,i}$ | transmitted, reflected, incident electric field amplitude for s-polarization |
| $E_{THz}$ | terahertz electric field amplitude |
| $E_p^+,E_p^-$ | forward and reverse traveling $p^{\text{th}}$ symmetric Laguerre mode |
| EO | electro-optic |
| $F$ | Fresnel number |
| $f$ | focal length |
| FEL | free-electron laser |
| FS | free space |
| FWHM | full width half maximum |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| $G$ | thermal conductance |
| $g$ | wire spacing |
| GBMA | Gaussian beam mode analysis |
| GBT | Gaussian beam telescope |
| $\mathbf{H}, \mathbf{H}_a, \mathbf{H}_b$ | magnetic field |
| $h$ | Planck's constant |
| $H_m(x)$ | $m^{\text{th}}$ Hermite polynomial |
| HEB | hot electron bolometer |
| HIFI | Heterodyne instrument for the far-infrared |
| HPBW | half-power beamwidth |
| $I$ | current |
| $I$ | intensity, transmitted intensity |
| $\mathbf{I}$ | identity matrix |
| $i$ | $\sqrt{-1}$ |
| $i$ | angle of incidence |
| $I_c$ | critical current |
| $I_x, I_y$ | $x, y$ component of intensity |
| $I_0$ | incident intensity |
| IF | intermediate frequency |
| IMPATT | impact ionization avalanche transit time |
| IR | infrared |
| $J$ | free current density |
| $J$ | rotational state number |
| $J$ | screening current |
| $K$ | power coupling coefficient |
| $k$ | wavenumber ($2\pi/\lambda$) |
| $K_{ab}$ | power coupling between two beams |
| $k_B$ | Boltzmann constant |
| $K_G$ | power coupling to a pure Gaussian (Gaussicity) |
| $K_{lost}$ | power lost due to truncation |
| $\mathbf{k}_P, \mathbf{k}_S, \mathbf{k}_I$ | pump wavevector, signal wavevector, idler wavevector |
| $K_{spillover}$ | power lost due to spillover |
| $K_{Xpol}$ | power scattered into the cross-polar direction |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| $L$ | inductance |
| $L, L_x, L_y$ | slant length, slant length along $x$ direction, slant length along $y$ direction |
| $l$ | grating period |
| $L_{mn}$ | operator representing a transfer function |
| $\mathbf{L}_{nn}$ | coupling to reflected modes at port $n$ |
| $L_p^m$ | generalized Laguerre polynomials |
| $l_w$ | walk-off length |
| $l_c$ | coherence length |
| $l_1, l_2$ | path length |
| LO | local oscillator |
| LT-GaAs | low-temperature-grown gallium arsenide |
| $M$ | magnification |
| $\mathbf{M}_n$ | $n^{\text{th}}$ matrix |
| $m_e$ | electron mass |
| N | multiplication factor of a frequency multiplier |
| $n$ | number density |
| $n, n_{signal}, n_{noise}$ | number of photons, signal photons, noise photons detected |
| $n, n_1, n_2$ | refractive index |
| $n$ | rms noise level |
| $n$ | spectral order |
| $n_{optical}, n_{THz}$ | optical, terahertz refractive index |
| NDR | negative differential resistance |
| NEP | noise equivalent power |
| NTD | neutron-transmutation doped |
| OP | optical phonon |
| OPO | optical parametric oscillator |
| OPTL | optically pumped THz laser |
| P, $P_i, P_0, \mathbf{P}$ | polarization |
| $P(r)$ | power contained within a radius $r$ |
| $P$ | vertex-focus distance of a parabola |
| $P_{noise}, P_{signal}$ | noise power, signal power |
| $P_\infty$ | total power |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| PCA | photoconductive antenna |
| p-Ge | p-type germanium laser |
| $q$ | charge |
| $q(z), q_0$ | complex radius of curvature (also known as complex beam parameter or Gaussian beam parameter) |
| $q_{in}, q_{out}$ | complex radius of curvature of input, output beam |
| $q_1, q_2$ | complex radius of curvature of beam 1, 2 |
| QCL | quantum cascade laser |
| $R(z)$ | Gaussian beam phase radius of curvature |
| $R$ | radius |
| $R$ | reflectivity |
| $R$ | resistance |
| $R$ | surface radius of curvature |
| $r$ | complex reflection amplitude coefficient |
| $R_{in}, R_{out}$ | phase radius of curvature |
| $r_{in}, r_{out}$ | ray displacement |
| $R_{surf}$ | surface radius of curvature |
| $r_T$ | truncation radius |
| $R_V$ | responsivity |
| $R_1, R_2$ | surface radius of curvature |
| $R_1, R_2$ | distances to foci of an ellipse |
| RF | radio frequency |
| rms | root-mean-square |
| RTD | resonant tunnel diode |
| $\mathbf{S}, \mathbf{S}^a, \mathbf{S}^b, \mathbf{S}^c$ | full scattering matrix |
| $s$ | phase error |
| $\mathbf{S}_{11}, \mathbf{S}_{12}, \mathbf{S}_{21}, \mathbf{S}_{22}$ | scattering matrices |
| SIS | superconductor–insulator–superconductor |
| SNR | signal-to-noise ratio |
| $\mathrm{SNR}_{dB}$ | signal-to-noise ratio in dBs |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| S/N | signal-to-noise ratio |
| SPR | Smith–Purcell radiation |
| SQUID | superconducting quantum interference device |
| $T$ | temperature |
| $T$ | transmittance |
| $T$ | fractional power transmission |
| $t$ | complex transmission amplitude coefficient |
| $\mathbf{T}, \mathbf{T}^a, \mathbf{T}^b, \mathbf{T}^c$ | full transmission matrix |
| $T_b, T_s$ | bath, heat sink temperature |
| $T_c$ | critical temperature |
| $T_e$ | edge taper |
| $T_e$ (dB) | edge taper expressed in dB |
| $T_e, T_{ph}$ | electron temperature, phonon temperature |
| $\mathbf{T}_{11}, \mathbf{T}_{12}, \mathbf{T}_{21}, \mathbf{T}_{22}$ | transmission matrices |
| TCR | thermal coefficient of resistance |
| TE, TM | transverse electric, magnetic |
| TES | transition edge sensor |
| THz-TDS | terahertz time-domain spectroscopy |
| TUNNETT | tunnel injection transit time |
| $u(x, y, z), u_0$ | non-plane-wave part of the electric field, constant |
| $V, V_{rms}$ | voltage, root-mean-square voltage |
| $v$ | vibrational state number |
| $V_{bi}$ | built-in potential |
| $V_{gap}$ | gap voltage |
| $w, w(z)$ | Gaussian beam radius |
| $w_m$ | beam radius at a mirror |
| $w_0, w_{0,a}, w_{0,b}$ | Gaussian beam waist radius |
| $w_{0,in}, w_{0,out}$ | Gaussian beam waist radius |
| WG | waveguide |
| $x$ | path length |
| $x_c$ | point of intersection, $x$ coordinate |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| $y_c$ | point of intersection, $y$ coordinate |
| $z_c$ | confocal distance, Rayleigh range |
| $\alpha$ | absorption coefficient |
| $\alpha$ | diffraction parameter |
| $\alpha$ | incident beam polarization angle |
| $\alpha, \alpha(T)$ | thermal coefficient of resistance |
| $\alpha$ | tilt of grid wires |
| $\beta$ | mode balance constant |
| $\beta_{trans}, \beta_{refl}$ | transmitted, reflected beam polarization direction |
| $\chi$ | electron affinity (volts) |
| $\chi^{(2)}, \chi^{(2)}_{ijk}$ | second-order susceptibility |
| $\Delta$ | path length difference |
| $\Delta_{IF}$ | IF bandwidth |
| $\Delta_{max}$ | path length difference for maximum transmission |
| $\Delta_{min}$ | path length difference for minimum transmission |
| $\Delta_{SSB}$ | single-sideband path length difference |
| $\Delta_1, \Delta_2$ | energy gap of a semiconductor |
| $\Delta E$ | energy gap |
| $\Delta x$ | lateral shift |
| $\Delta z$ | relative displacement |
| $\Delta z$ | position of beam waist behind aperture |
| $\Delta\theta$ | cone angle |
| $\Delta\nu$ | bandwidth |
| $\delta\nu$ | frequency of successive transmission bands |
| $\varepsilon_0$ | permittivity of free space |
| $\Phi_0$ | flux quantum |
| $\phi$ | grid inclination angle |
| $\phi_c$ | critical emission angle |
| $\phi_m, \phi_{sc}, \phi_B$ | metal, semiconductor, barrier work function |
| $\phi_0(z), \phi_{in}, \phi_{out}$ | Gaussian beam phase slippage |
| $\gamma$ | Lorentz factor $(1/\sqrt{(1-\beta^2)}, \beta = v/c)$, $v$ is velocity |

## Glossary of Symbols and Acronyms

| | |
|---|---|
| $\gamma$ | reflection coefficient at an interface |
| $\eta_{spillover}$ | Gaussian beam spillover efficiency |
| $\lambda$ | wavelength |
| $\lambda_{FEL}$ | wavelength of radiation from an FEL |
| $\lambda_{IF}, \lambda_{LO}, \lambda_s$ | IF, LO, signal wavelength |
| $\lambda_w$ | wiggler magnet spacing wavelength |
| $\nu$ | frequency |
| $\nu_{IF}, \nu_{LO}, \nu_s$ | IF, LO, signal frequency |
| $\nu_{THz}, \nu_{pump}$ | terahertz, pump frequency |
| $\theta$ | angle from normal |
| $\theta$ | angle with respect to propagation axis |
| $\theta$ | incident field polarization angle |
| $\theta$ | grid tilt angle |
| $\theta'$ | projected grid tilt angle |
| $\theta_c$ | critical angle |
| $\theta_{in}, \theta_{out}$ | ray angle with respect to normal |
| $\theta_0$ | asymptotic beam growth angle |
| $\theta_1, \theta_2$ | angle of incidence, reflection |
| $\sigma$ | absorption cross-section |
| $\tau$ | transmission |
| $\tau_{diff}$ | diffusion time |
| $\tau_{ep}, \tau_{pe}, \tau_{es}$ | electron-phonon, phonon-electron, electron-substrate energy transfer time |
| $\tau_p$ | pulse length |
| $\omega, \omega_1, \omega_2, \omega_3$ | angular frequency |
| $\Psi_n$ | $n^{\text{th}}$ Gaussian beam mode |
| $\Psi_{mn}(x, y, z)$ | Gaussian–Hermite beam mode amplitude (rectangular coordinates) |
| $\Psi_{pm}(r, \phi, z)$ | Gaussian–Laguerre beam mode amplitude (cylindrical coordinates) |
| $\Psi_n^{SC}$ | $n^{\text{th}}$ scattered Gaussian beam mode |
| $\psi_a, \psi_b, \psi_F$ | scalar field |
| $\psi_G$ | scalar Gaussian field |