elements of

INFRARED TECHNOLOGY

generation, transmission, and detection

KRUSE · McGLAUCHLIN · McQUISTAN

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To our wives and parents

Preface

The infrared region of the electromagnetic spectrum is generally defined as those wavelengths lying between the visible and microwave regions. Its importance arises from the fact that every material object emits, absorbs, transmits, and reflects infrared radiation in a characteristic manner. This has a twofold implication. First, from a study of the intensity and wavelength distribution of the radiation which has arisen from or interacted with an object, information concerning the object may be obtained. This information may be used, for example, to distinguish a body from its surroundings or to identify an unknown material. Second, the radiation is of itself important. The manner in which it interacts with a material may be used to change the characteristics of that material. Or again, it may be employed as a medium for conveying information from point to point.

Although the existence of infrared radiation was realized well over a century ago, only in the last two decades have applications been widespread. The field of infrared technology, the use of infrared radiation for military and commercial purposes, may be considered to have originated in World War II. Since then interest has increased greatly to the point where infrared technology has become of major military importance. Although the commercial applications have not seen such explosive growth, they have nevertheless increased steadily in recent years.

At the time the manuscript for this book was prepared, little organized information related to infrared technology was available. The existing literature treated selected topics in this area, but did not provide an integrated presentation of the entire subject. This work is an endeavor to fulfill this need.

Broadly speaking, the field of infrared technology can be subdivided into four main categories. The first deals with the nature of infrared radiation. Examples of topics in this area are the spectral and angular distribution of radiation emitted from heated bodies; the reflection, refraction, absorption, diffraction, and scattering of radiation by media; and the several photoelectric effects. The second major category is comprised of infrared components and materials including sources, window materials, and detectors.

The integration of infrared components into systems constitutes the third major category. These include optical, electronic, and cooling systems. Applications, both commercial and military, make up the fourth and final category. This book treats the first two categories. The last two are left to a companion volume now in preparation.*

It is our intent in this volume to provide a discussion useful to two different groups of readers. One of these groups is composed of senior or first-year graduate students having an academic interest in the subject. The other group consists of scientists and engineers in both commercial and military laboratories who are engaged in the development of infrared components and the evaluation of materials and components for use in infrared applications. Accordingly, for the sake of logical completeness, we have included some material which can be found in books treating subjects other than infrared technology. Inclusion of this material will allow the reader to understand the principles underlying the behavior of infrared components while relying on a minimum number of assumptions. As examples of this, we have included a mathematical discussion showing the relationships between the optical constants and more basic parameters; we have developed expressions describing the attenuation of radiation by the atmosphere; and we have treated the interactions between radiation and charged particles leading to such phenomena as dispersion and free carrier absorption. In addition, we have included some material as a matter of convenience for those working in the field of infrared technology. Thus we have included a chapter on the physics of semiconductors to enable the designer of infrared detectors and optical components to make predictions concerning the behavior of new materials; we have treated fluctuation phenomena to clarify the nature of those effects which set a fundamental limit to the performance of detectors and the electronic components of electrical systems; and we have included sections describing the measured characteristics of detectors and optical materials.

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List of most important symbols

Symbol	*Definition*	*Page*
a	ratio of thermal equilibrium values of electron and hole concentrations	327
a	absorption coefficient	102
a'	absorption coefficient per unit of concentration (absorption cross section)	102
A_D, A	sensitive area of detector	270
$A(t)$	amplitude of electromagnetic wave	54
b	mobility ratio	212
b	radius of scattering particle	182
$\mathbf{B}$	magnetic induction vector	89
c	speed of electromagnetic radiation	92
c^*	complex speed of electromagnetic radiation	94
c_0	speed of electromagnetic radiation in free space, 2.9979×10^8 m/sec	92
C	heat capacity	346
C_x	contrast at the distance x	190
C_0	intrinsic contrast at the scene	190
$C_{x=V}$	contrast at the visual range	190
$\mathbf{D}$	electric displacement vector	89
D^*	detectivity	270
D^{**}	detectivity which is independent of field of view of Lambertian detectors	367
D_e	diffusion constant for electrons	225
D_h	diffusion constant for holes	225
D^*_λ	spectral detectivity	271
$D^*_{\lambda,\mathrm{PC}}$	spectral detectivity for photoconductive mode	332
$D^*_{\lambda,\mathrm{PEM}}$	spectral detectivity for photoelectromagnetic mode	336
$D^*_{\lambda,\mathrm{PV}}$	spectral detectivity for photovoltaic mode	342

Symbol	*Definition*	*Page*
$\mathbf{E}$	electric field vector	89
E	radiant intensity	12
E_λ	spectral radiant intensity	12
$\mathscr{E}$	energy	24
$\mathscr{E}_0$, $\mathscr{E}^*$	Fermi level energy	24, 205
f	electrical frequency	236
Δf	electrical bandwidth	236
g	conductance	246
g_m	transconductance	248
h	Planck's constant, 6.6252×10^{-34} joule sec	25
$\mathbf{H}$	magnetic field intensity vector	89
$\mathscr{H}$	irradiance	13
i_N, $(\overline{i_N^2})^{1/2}$	rms noise current	239
$i_{S,PC}$	photoconductive short circuit current per unit detector width	328
$i_{S,PEM}$	photoelectromagnetic short circuit current per unit detector width	333
I_p	plate current	244
j	imaginary number, $\sqrt{-1}$	92
$\mathbf{J}$	current density vector	89, 211
$\mathbf{J}_e$	electron current density vector	225
$\mathbf{J}_h$	hole current density vector	225
J_s	short circuit current density	341
k	Boltzmann's constant, 1.3805×10^{-23} joules/deg K	23
k	absorption constant	94
k_0	thermal conductivity	349
K	thermal conductance	346
K_e	relative capacitivity	93
K_e	effective thermal conductance	347
K_e^*	complex dielectric constant	94
K_m	relative permeability	93
K_0	thermal conductance at ambient temperature	346
L_D^*	ambipolar diffusion length in a magnetic field	328
L_e	electron diffusion length	227
L_h	hole diffusion length	227
m	reduced dimensionless variable	330
m_e	effective mass of a free electron	205
m_h	effective mass of a free hole	207
M	gram molecular weight	70
M	electric moment	108
$M(b)$	density of particles whose radii are between b and $b + db$	182
$M(\nu, T)$	Planck distribution function	58
n	index of refraction	45
n	electron concentration in conduction band	206
$n(\mathscr{E})$	fraction of particles having energy in the interval $\mathscr{E}$ to $\mathscr{E} + d\mathscr{E}$	26
n_a	concentration of absorbing elements	102
$\bar{n}_a$	average absorber concentration	168
n_e	carrier concentration	126
n_i	intrinsic concentration	207
n_n	electron concentration in n-region	232

Symbol	*Definition*	*Page*
n_p	electron concentration in *p*-region	232
n_s	concentration of scattering elements	107
n_0	electron concentration at thermal equilibrium	326
n_{p0}	electron concentration in *p*-region at thermal equilibrium	338
N	number of photons per unit front surface area per second absorbed by detector	327
$\bar{N}$	average number of photons per second per unit area	58, 357
$\overline{N^2}$	mean square deviation in number of photons per second per unit area	357
N_a	concentration of acceptors	209
N_d	concentration of donors	208
N_s	total number of scattering particles	107
p	hole concentration in valence band	207
p_n	hole concentration in *n*-region	232
$p_N(f)$	mean square deviation in number of emitted photons per unit bandwidth	60
p_P	mean square deviation in emitted power	59
$p_P(f)$	mean square deviation in emitted power per unit bandwidth	59, 351
$\overline{p_P^2}$	mean square deviation in emitted power in a given electrical bandwidth	59, 351
p_0	hole concentration at thermal equilibrium	325
p_{n0}	hole concentration in *n*-region at thermal equilibrium	340
P	radiant power emitted by or incident upon a surface	12
$\mathbf{P}$	electrical polarization	105
P_N	noise power	236
P_N	noise equivalent power	270
P_λ	spectral radiant power emitted or absorbed	12, 329
q	electronic charge	104
Q	quality factor of narrow band quantum counter	372
r	amplitude reflection coefficient	100
$r_\parallel$	amplitude reflection coefficient for parallel polarized radiation	183
$r_\perp$	amplitude reflection coefficient for perpendicularly polarized radiation	183
R	electrical resistance	236
R	radiant emittance	12
R	universal gas constant	70
$\mathscr{R}$	responsivity	272
R_B	bolometer resistance	346
R_L	load resistance	291
R_N	equivalent noise resistance	246
R_λ	spectral radiant emittance	13
$\mathscr{R}_\lambda$	spectral responsivity	272
R_ω	radiance	13
R_{bb}	black body radiant emittance	29
$R_{\omega\lambda}$	spectral radiance	13
s	surface recombination velocity	222
s_1	front surface recombination velocity	326
s_2	back surface recombination velocity	326
S	scattering area ratio	182
S	intensity of an absorption line	169

Symbol	*Definition*	*Page*
t	amplitude transmission coefficient	101
t_r	radiative lifetime	69
T	absolute temperature	17
T_c	cathode temperature	245
T_n	equivalent noise temperature	239
T_1	detector temperature	346
T_2	background temperature	357
T_3	black body source temperature	362
$\overline{\Delta T^2}$	mean square deviation in temperature	355
$\overline{\Delta T_f^2}$	mean square deviation in temperature per unit bandwidth	355
v_N, $(\overline{v_N^2})^{1/2}$	rms noise voltage	237
v_{R_L}	voltage developed across load resistor	348
v_0	open circuit voltage per unit detector width	329
V	applied voltage	346
V	visual range	190
V_p	plate voltage	245
V_0	open circuit voltage	341
w	water vapor concentration	177
w_i	value of w at which the absorption in window i undergoes a transition from weak band to strong band absorption	177
Z	atomic number	61
α	absorptivity	13
α	generalized temperature coefficient of resistance	346
α	polarizability	105
α_t	absorptance	139
α_1, α_2	reduced dimensionless variables	330
β	scattering coefficient	102
β	temperature coefficient of resistance of a semiconductor	346
β'	scattering coefficient per unit concentration (scattering cross section)	102
γ	temperature coefficient of resistance of a metal	310
$\gamma_\lambda(\phi)$	differential scattering cross section	107
Γ	propagation coefficient	93
Γ'	complex index of refraction	94
δ	Dirac delta function	58
δ	half-width of an absorption line	169
ε	emissivity	13
ε	absolute capacitivity or absolute permittivity	90
ε_0	capacitivity of free space	91
ε_{eff}	effective hemispherical emissivity	40
$\varepsilon_{\lambda hem}$	spectral hemispherical emissivity	40
$\varepsilon_{\omega\lambda}$	spectral goniometric emissivity	40
$\varepsilon_{n\omega\lambda}$	normal spectral emissivity	46
η	reduced energy	206
$\eta(\nu)$	quantum efficiency	357
η^*	reduced Fermi energy	206
η_a	reduced acceptor ionization energy	210
η_d	reduced donor ionization energy	209
η_i	reduced intrinsic excitation energy	207

Symbol	*Definition*	*Page*
κ	extinction coefficient	103
λ	electromagnetic wavelength	2
λ_0	semiconductor absorption edge	124
λ_0	long wavelength limit of detector	273
μ	absolute magnetic permeability	47
μ_e	electron mobility	213
μ_h	hole mobility	213
μ_0	magnetic permeability of free space	91
ν	electromagnetic frequency	22
ν_0	electromagnetic frequency corresponding to long wavelength limit	289
ρ	electrical resistivity	215
ρ	reflectivity	13
ρ_t	reflectance	139
$\rho_{\parallel}$	reflectivity for radiation polarized parallel to the plane of incidence	46
$\rho_{\perp}$	reflectivity for radiation polarized perpendicular to the plane of incidence	46
σ	electrical conductivity	47, 211
σ	Stefan-Boltzmann constant, 5.6687×10^{-8} watts meter^{-2} (deg K)$^{-4}$	19
$\sigma(\lambda)$	attenuation coefficient	101
σ_0	zero frequency conductivity	126
τ	carrier lifetime	221
τ	detector time constant	274
τ	transmissivity	13
$\bar{\tau}$	average transmittance due to the combined effects of absorption and scattering	174
τ_a	transmissivity as affected by absorption processes only	103
$\bar{\tau}_a$	average transmissivity, as affected by absorption only, within the spectral interval $\Delta\lambda$	168
τ_e	electron lifetime	227
τ_h	hole lifetime	227
τ_r	carrier relaxation time	139
τ_t	transmittance	139
τ_{ai}	transmission of the *i*th window as affected by absorption	173
τ_{si}	transmission of the *i*th window as affected by scattering	173
χ_e	electric susceptibility	105
Ψ	radiant energy density	15
Ψ_λ	spectral radiant energy density	23

1

Definition and history

1.1 DEFINITION

The electromagnetic spectrum is the continuum consisting of the ordered arrangement of radiation according to wavelength, frequency, or photon energy. It has been established experimentally that the electromagnetic spectrum includes waves of every length from an extremely small fraction of a millimeter to many kilometers. There is no single source or detection mechanism that is useful over the entire electromagnetic spectrum, and as a result the spectrum has been separated into rather loosely defined spectral regions. The bases for these broad subdivisions have generally been in accordance with the various means of generating, isolating, and detecting the radiations involved.

Although all electromagnetic radiation when absorbed by matter produces heat, radiation in a certain spectral region, namely, the infrared region, can be more readily detected by the heat it produces. In addition, it turns out that heated bodies provide excellent sources of this type of radiation; thus infrared radiation is sometimes referred to as thermal radiation. The further subdivision of the infrared into near, intermediate and far (depending upon the "distance" from the visible region) has also met with some acceptance.

Another definition of infrared radiation is: it is that portion of the electromagnetic spectrum lying between the visible and microwave regions, that is, the wavelengths between 7.5×10^{-4} mm and approximately 1 mm. These limits can be expressed in various forms involving wavelength, frequency, photon energy, or wave number. In terms of commonly used units, the limits are given in Table 1.1.