Appendix B

Refractive indices

B.1 Refractive index definition

The refractive index of a material is defined as

$$n = \frac{c}{v_{ph}} \tag{B.1}$$

in which c is the speed of light and v_{ph} is the phase velocity of the light in the material. The light propagation is described by:

$$U(z) = U_0 e^{-jnk_0 z} \tag{B.2}$$

in which k_0 is the wavenumber in vacuum. Wave propagation in media with absorption or gain can be described with a complex refractive index n_c

complex refractive index

$$n_c = n - j\kappa \tag{B.3}$$

in which n is the refractive index as defined above and the imaginary part κ describes the absorption. It is called the extinction coefficient, often denoted as k, but to avoid confusion with the wavenumber k we use the Greek letter κ. Positive values of κ describe absorption, negative values gain. The propagation of a plane wave in a medium with refractive index n_c is described by:

extinction coefficient

$$\begin{aligned} & U(z) &&= U_0 e^{-j\gamma z} = U_0 e^{-\alpha z} e^{-j\beta z} \\ \text{with} \quad & \alpha &&= 2\pi\kappa/\lambda_0 \\ & \beta &&= 2\pi n/\lambda_0 \\ \text{and} \quad & I(z) &&= |U(z)|^2 = U_0^2 e^{-2\alpha z} \end{aligned} \tag{B.4}$$

Note that α denotes here the extinction coefficient of the field and $z_{1/e} = 1/\alpha$ is the $1/e$ absorption length. The optical light intensity is described by $I(z) = I_0 e^{-2\alpha z}$. For the intensity the $1/e^2$ absorption length equals the $1/e$ absorption length: $z_{I=1/e^2} = 1/\alpha$.

absorption length

B.2 Refractive indices in the C-band (around 1550 nm)

In the literature there is a fairly wide variation for refractive index data of InGaAsP semiconductor materials. In this appendix we list the values that are used for the JePPIX

Table B.1: Refractive indices of some PIC materials in the C-band (@1550 nm) as used by Smart Photonics (SP) and Fraunhofer HHI.

Material	n		κ	
	SP[1]	HHI	SP	HHI
InP	$3.17 - 0.12(\lambda - 1.55)$	3.17		
Q1.06		3.26		
Q1.15		3.39		0.0096
Q1.25	$3.36 - 0.23(\lambda - 1.55)$			
Q1.3		3.41		0.0173
Q1.55	3.69			
InGaAs	3.74	3.78	0.29	0.1054
SiO_2	1.443			
SiN	1.996			
BCB	1.539			
Titanium	3.782		4.42	
Platinum	5.35		7.05	
Gold	0.39		10.98	

Table B.2: Effect of doping on InP properties (approximate)

Material	N(cm^{-3})	A(dB/cm)	2α(cm^{-1})	Δn	κ
n-InP	$3{\cdot}10^{17}$	1.2	0.3	-0.002	$4{\cdot}10^{-6}$
n-InP	$5{\cdot}10^{17}$	2	0.5	-0.003	$6{\cdot}10^{-6}$
n-InP	$1{\cdot}10^{18}$	4	1	-0.007	$12{\cdot}10^{-6}$
p-InP	$3{\cdot}10^{17}$	30	7	-0.002	$8{\cdot}10^{-5}$
p-InP	$5{\cdot}10^{17}$	50	12	-0.003	$14{\cdot}10^{-5}$
p-InP	$1{\cdot}10^{18}$	100	24	-0.007	$28{\cdot}10^{-5}$
n-Q1.25	$6{\cdot}10^{16}$	0.25	0.06	$\sim$0	$7{\cdot}10^{-7}$
p-Q1.25	$1{\cdot}10^{17}$	10	2.4	-0.0006	$3{\cdot}10^{-5}$

foundry platforms Smart Photonics (SP) and the Fraunhofer Heinrich Hertz Institut (HHI). It is noted that measured values show some dependence on the specific measurement methods and equipment, and on the configuration in which the material is used. For applications that are critically dependent on accurate refractive index values more extensive measurements are required.

More information about refractive index values and other optical constants can be found in the following publications:

[1] W. Dumke, M. Lorenz, and G. Pettit, “Intra-and interband free-carrier absorption and the fundamental absorption edge in n-type InP,” Phys. Rev. B, vol. 1, pp. 4668–4673, Aug. 1970.

[2] P. Johnson and R. Christy, “Optical constants of transition metals: Ti, V, Cr, Mn, Fe, Co, Ni, and Pd,” Phys. Rev. B, vol. 9, pp. 5056–5070, June 1974. 1

[3] C. H. Henry, R. A. Logan, F. R. Merritt, and J. Luongo, “The effect of intervalence band

[1] Refractive index values for InP-based semiconducors are taken from [227] and for dielectrics and metals from [228].

absorption on the thermal behavior of InGaAsP lasers," IEEE J. Quantum Electron., vol. 19, pp. 947–952, June 1983.

[4] M. Ordal, L. Long, R. Bell, S. Bell, R. Alexander Jr., and C. Ward, "Optical properties of the metals Al, Co, Cu, Au, Fe, Pb, Ni, Pd, Pt, Ag, Ti, and W in the infrared and far infrared," Appl. Opt., vol. 22, pp. 1099–1119, Apr. 1983.

[5] H. Casey Jr. and P. Carter, "Variation of intervalence band absorption with hole concentration in p-type InP," Appl. Phys. Lett., vol. 44, pp. 82–83, Jan. 1984.

[6] F. Fiedler and A. Schlachetzki, "Optical parameters of InP-based waveguides," Solid State Electron., vol. 30, no. 1, pp. 73–83, 1987.

[7] J. Weber, "Optimization of the carrier-induced effective index change in InGaAsP waveguides-application to tunable Bragg filters," IEEE J. Quantum Electron., vol. 30, pp. 1801–1816, Aug. 1994.

[8] J. Piprek, P. Abraham, and J. E. Bowers, "Self-consistent analysis of high-temperature effects on InGaAsP/InP lasers," in IEEE Int. Symp. on Compound Semiconductors, Berlin, 1999.

[9] J. Taylor and V. Tolstikhin, "Intervalence band absorption in InP and related materials for optoelectronic device modeling," J. Appl. Phys., vol. 87, pp. 1054–1059, Feb. 2000. 2