

# Generic Photonic IC Design

Authorlist

2024

© ⓘ ⓘ ⓘ *Handbook of generic photonic IC design*, by the *Eindhoven Hendrik Casimir Institute*, Technische Universiteit Eindhoven, is licensed under a Creative Commons “Attribution-NonCommercial-NoDerivatives 4.0 International” license.

We traced the ownership of all figures used as far as we could. If you are the owner of one of the used figures please contact us.

# Contents

<b>I</b>	<b>An introduction to InP-based generic integration technology</b>	<b>1-1</b>
	MEINT SMIT ET AL.	
1.1	Background . . . . .	1-2
1.1.1	History of Photonic Integration . . . . .	1-2
1.1.2	Generic Photonic Integration Technology . . . . .	1-4
1.1.3	Multi-Project Wafer Runs . . . . .	1-7
1.1.4	Generic Foundry Model . . . . .	1-8
1.2	Generic Integration Process . . . . .	1-10
1.2.1	Epitaxial Growth . . . . .	1-10
1.2.2	Waveguide Etching . . . . .	1-13
1.2.3	Planarization and Passivation . . . . .	1-14
1.2.4	Metallisation and Interconnect . . . . .	1-14
1.3	Building Blocks . . . . .	1-15
1.3.1	Introduction . . . . .	1-15
1.3.2	Basic Building Blocks (BBB) . . . . .	1-15
1.3.3	Composite Building Blocks (CBB) . . . . .	1-18
1.3.4	Basic Technology Blocks (BTB) . . . . .	1-19
1.4	Basic Building Blocks . . . . .	1-20
1.4.1	Passive Waveguide Sections (WG) and Electrical Isolation Sections (EI) . . . . .	1-20
1.4.2	Optical amplifiers (SOA), Photo Detectors (PD) and Saturable Absorbers (SA) . . . . .	1-22
1.4.3	Modulators (ERM, ERMI, TOM, EAM) . . . . .	1-23
1.4.4	Tunable Bragg Reflector Gratings (TBR) . . . . .	1-24
1.4.5	Polarization Rotation Sections (PR) . . . . .	1-24
1.4.6	Spot-Size Converters (SSC) . . . . .	1-25
1.5	Composite Building Blocks . . . . .	1-26
1.5.1	Junctions between Different Waveguides . . . . .	1-27
1.5.2	MMI-components . . . . .	1-28
1.5.2.1	MMI-couplers . . . . .	1-28
1.5.2.2	MMI-filters. . . . .	1-29
1.5.2.3	MMI-reflectors. . . . .	1-29

1.5.3	AWG (De)Multiplexers and Routers. . . . .	1-30
1.5.4	FP-lasers and Ring Lasers . . . . .	1-31
1.5.5	DBR and DFB-lasers . . . . .	1-32
1.5.6	MZI and MI-modulators . . . . .	1-32
1.6	ASPIC Examples . . . . .	1-32
1.6.1	COBRA & SMART Photonics Platform . . . . .	1-33
1.6.2	Oclaro Platform . . . . .	1-35
1.6.3	Fraunhofer HHI Platform . . . . .	1-38
1.7	ASPIC Design Environment . . . . .	1-39
1.7.1	Software Environment . . . . .	1-40
1.7.2	Design Manual . . . . .	1-44
1.7.3	Process Design Kit (PDK) and Component Libraries . . . . .	1-45
1.8	Generic Packaging . . . . .	1-46
1.8.1	A standardized Package. . . . .	1-47
1.8.2	A standardized Chip . . . . .	1-48
1.9	Generic Testing . . . . .	1-49
1.9.1	Wafer Validation . . . . .	1-49
1.9.2	On-Wafer Testing . . . . .	1-49
1.10	Conclusions . . . . .	1-51

## I Physics and Technology

<b>2</b>	<b>Guided Wave Propagation</b>	<b>2-1</b>
	<small>MEINT SMIT, XAVER LEIJTENS</small>	
2.1	Introduction . . . . .	2-1
2.2	Wave propagation in free space . . . . .	2-2
2.2.1	The plane wave . . . . .	2-2
2.2.2	Interference . . . . .	2-5
2.2.3	Fourier optics . . . . .	2-7
2.2.4	Beam Propagation Method (BPM) . . . . .	2-9
2.2.5	Gaussian beam . . . . .	2-12
2.2.6	Gaussian approximation of beams and modes . . . . .	2-14
2.2.7	Diffraction limited imaging . . . . .	2-15
2.3	Wave propagation in two-layer media . . . . .	2-17
2.3.1	Polarization in layered structures . . . . .	2-17
2.3.2	Reflection and refraction . . . . .	2-19
2.4	Wave propagation in three-layer waveguides . . . . .	2-24
2.4.1	Basic concepts of waveguiding . . . . .	2-24
2.4.2	Slab guide . . . . .	2-27
2.4.3	Slab modes (two-dimensional optical waveguide modes) . . . . .	2-30
2.4.4	Dispersion relation . . . . .	2-31
2.4.5	Effective index . . . . .	2-35

2.4.6	Normalized approach of mode properties . . . . .	2-39
2.4.7	Mode properties . . . . .	2-41
2.4.8	Gaussian approximation of modes. . . . .	2-43
2.4.9	Power carried by a mode. . . . .	2-44
2.4.10	Phase and group velocity, group index . . . . .	2-46
2.5	Wave propagation in three-dimensional waveguides . . . . .	2-49
2.5.1	Effective Index Method (EIM) . . . . .	2-49
2.5.2	EIM accuracy in a standard waveguide . . . . .	2-51
2.5.3	Mode nomenclature . . . . .	2-53
2.6	Wave propagation in multi-layer and active waveguides . . . . .	2-53
2.6.1	System mode theory . . . . .	2-54
2.6.2	Coupled mode theory . . . . .	2-55
2.6.3	Waveguides with absorption or gain . . . . .	2-58
2.6.4	Curved waveguides . . . . .	2-62
2.7	Beam coupling . . . . .	2-66
2.8	Appendices . . . . .	2-69
2A	Derivation of the Gaussian beam formula . . . . .	2-69
2B	Derivation of the normalized dispersion relation . . . . .	2-69
2E	Group index . . . . .	2-70
2C	Derivation of the Effective Index Method . . . . .	2-71
2D	The transfer matrix approach . . . . .	2-72
<b>3</b>	<b>Semiconductor Physics (Draft)</b>	<b>3-1</b>
	DAAN LENSTRA, WITH CONTRIBUTIONS FROM MEINT SMIT	
3.1	Introduction . . . . .	3-1
3.2	Semiconductor crystal structure . . . . .	3-1
3.2.1	Crystal structure. . . . .	3-1
3.2.2	Miller Indices . . . . .	3-3
3.3	Band structure, Schrödinger equation and Fermi-Dirac distribution . . . . .	3-6
3.4	Doped semiconductors . . . . .	3-14
3.5	The pn-junction . . . . .	3-16
3.5.1	Zero applied bias . . . . .	3-16
3.5.2	Space charge width in the junction area . . . . .	3-18
3.5.3	Reverse applied bias, junction capacitance and reverse current . . . . .	3-20
3.5.4	Forward applied bias: the pn-junction diode . . . . .	3-24
3.6	Quantum-well double heterostructures . . . . .	3-24
3.7	Electro-optic effects . . . . .	3-28
3.8	Light emission and absorption in semiconductor devices . . . . .	3-28
3.8.1	Optical absorption . . . . .	3-28
3.8.2	Photodetectors . . . . .	3-30
3.8.3	Light emission . . . . .	3-33
3.9	Stimulated emission and amplification . . . . .	3-36

3.9.1 Stimulated emission . . . . .	3-36
3.9.2 Semiconductor Optical Amplifier . . . . .	3-39
3.10 Quantum Wells . . . . .	3-39
3.11 Quantum Dots . . . . .	3-39
3.12 Appendices . . . . .	3-39
<b>4 Fabrication Technology</b>	<b>4-1</b>
YUQING JIAO, JEROEN BOLK, HUUB AMBROSIUS, AMER BASSAL, KLEMENS JANIAK	
4.1 The generic process flow . . . . .	4-2
4.1.1 Epitaxial (re)growth . . . . .	4-2
4.1.2 Waveguide etching . . . . .	4-4
4.1.3 Contact opening . . . . .	4-8
4.1.4 Contact and interconnect metallization . . . . .	4-8
4.1.5 Electroplating . . . . .	4-9
4.2 The generic process flow of HHI . . . . .	4-11
4.2.1 Gain stack epitaxy . . . . .	4-11
4.2.2 Modulator stack regrowth and grating formation . . . . .	4-12
4.2.3 Passive and active WG formation . . . . .	4-14
4.2.4 Passive and PD stack regrowth, contacts and PD formation . . . . .	4-14
4.2.5 Contact formation and metallization . . . . .	4-15
4.3 Introduction to clean room environment . . . . .	4-16
4.4 Substrate and wafer cleaning . . . . .	4-18
4.5 Introduction to vacuum . . . . .	4-18
4.5.1 Concept of vacuum . . . . .	4-18
4.5.2 Boiling point and vapour pressure . . . . .	4-20
4.5.3 Vacuum pumps . . . . .	4-20
4.6 Substrates and epitaxial growth . . . . .	4-21
4.6.1 Substrates . . . . .	4-21
4.6.2 Substrate growth techniques . . . . .	4-21
4.6.3 Characteristics of substrates . . . . .	4-23
4.7 Epitaxial growth . . . . .	4-24
4.7.1 Vegard's law . . . . .	4-24
4.7.2 MOVPE . . . . .	4-26
4.7.3 MBE . . . . .	4-27
4.7.4 Characterization of epitaxy quality . . . . .	4-29
4.8 Optical Lithography . . . . .	4-30
4.8.1 Introduction . . . . .	4-30
4.8.2 Contact and proximity lithography . . . . .	4-31
4.8.3 Projection lithography . . . . .	4-33
4.8.4 Evolution of wavelength . . . . .	4-36
4.8.5 Masks . . . . .	4-37
4.8.6 Photoresists . . . . .	4-38

4.8.7	Lithography procedure . . . . .	4-40
4.8.8	Mask overlay . . . . .	4-41
4.8.9	Lithography for InP PICs: solutions and challenges . . . . .	4-43
4.9	Electron-beam lithography . . . . .	4-45
4.10	Deposition techniques . . . . .	4-47
4.10.1	Plasma Processes . . . . .	4-47
4.10.2	Plasma Enhanced Chemical Vapour Deposition . . . . .	4-47
4.10.3	Evaporation . . . . .	4-51
4.10.4	Metal lift-off . . . . .	4-51
4.10.5	Sputtering . . . . .	4-51
4.11	Etching techniques . . . . .	4-53
4.11.1	Wet etching . . . . .	4-53
4.11.2	Reactive ion etching . . . . .	4-55
4.12	Planarization . . . . .	4-61
4.13	Rapid Thermal Processing . . . . .	4-61
4.14	Backend Processing . . . . .	4-63
4.14.1	Cleaving and dicing . . . . .	4-63
4.14.2	Facet coating . . . . .	4-64
<b>5</b>	<b>Simulation Methods (Draft)</b>	<b>5-1</b>
	<small>DOMINIC GALLAGHER, MEINT SMIT</small>	
5.1	Numerical Methods . . . . .	5-1
5.1.1	Introduction . . . . .	5-1
5.1.2	Passive Component Modelling . . . . .	5-2
5.1.2.1	Finite Element Frequency Domain Methods (FEFD) . . . . .	5-4
5.1.2.2	The Finite Difference Time Domain Method (FDTD) . . . . .	5-5
5.1.2.3	The Finite Element Time Domain Method (FETD) . . . . .	5-8
5.1.2.4	Eigenmode Expansion Methods (EME) . . . . .	5-10
5.1.2.5	The Beam Propagation Method (BPM) . . . . .	5-12
5.1.2.6	Electromagnetic Simulators – Domains of Competence . . . . .	5-13
5.1.3	Circuit Modelling . . . . .	5-13
5.1.3.1	Frequency-domain Circuit Simulators . . . . .	5-15
5.1.3.2	Time-domain Circuit Simulators . . . . .	5-15
5.2	Computation Examples . . . . .	5-18
5.2.1	Mode and field properties . . . . .	5-18
5.2.1.1	Propagation constant and effective index in a slab guide. . . . .	5-19
5.2.1.2	Effective indices in a 2d waveguides. . . . .	5-20
5.2.1.3	Mode profiles in semiconductor waveguides. . . . .	5-21
5.2.1.4	Mode profiles in asynchronous coupled waveguides. . . . .	5-22
5.2.1.5	Mode profiles and propagation loss in lossy waveguides. . . . .	5-23
5.2.1.6	Propagation loss in curved waveguides. . . . .	5-24
5.2.1.7	Confinement factor . . . . .	5-25

5.2.2	Properties of passive devices . . . . .	5-26
5.2.2.1	Waveguide tapers . . . . .	5-26
5.2.2.2	Y-junctions. . . . .	5-28
5.2.3	Field coupling and reflection . . . . .	5-30
5.2.3.1	Transmission and reflection of a star coupler . . . . .	5-30
5.2.3.2	Coupling efficiency with field overlap integral . . . . .	5-32
5.2.3.3	Coupling between straight and curves waveguides . . . . .	5-33
5.2.3.4	Optical Properties of active devices . . . . .	5-34
5.2.4	Electric fields and current densities . . . . .	5-34
5.3	Simulation Tools . . . . .	5-35
5.3.1	VPIphotonics Design Automation . . . . .	5-35
5.3.1.1	Photonic Integrated Circuits Design . . . . .	5-35
5.3.1.2	Foundry-specific and custom PDK libraries . . . . .	5-36
<b>6</b>	<b>Design Tools (Missing)</b>	<b>6-1</b>
<b>7</b>	<b>Measurement (Missing)</b>	<b>7-1</b>
<b>8</b>	<b>Test, Assembly and Packaging (Missing)</b>	<b>8-1</b>
 <b>II Basic Building Blocks</b>		
<b>9</b>	<b>Passive waveguides</b>	<b>9-1</b>
	<small>XAVEER LEIJTENS ET AL.</small>	
9.1	Waveguide structure in the TU/e process . . . . .	9-1
<b>10</b>	<b>Waveguide junctions (Missing)</b>	<b>10-1</b>
	<small>XAVEER LEIJTENS ET AL.</small>	
<b>11</b>	<b>Polarization Rotators and Converters (Draft)</b>	<b>11-1</b>
	<small>JOS VAN DER TOL</small>	
11.1	Polarization effects in PICs . . . . .	11-1
11.2	Polarization conversion . . . . .	11-3
11.3	Waveguide birefringence . . . . .	11-5
11.4	Sloped sidewall polarization converter . . . . .	11-6
11.4.1	Principle . . . . .	11-6
11.4.2	Modeling . . . . .	11-7
11.4.3	Fabrication . . . . .	11-11
11.5	Tolerance analysis of the Polarization Converter . . . . .	11-12
11.5.1	Theory . . . . .	11-12
11.5.2	Simulations . . . . .	11-12
11.5.3	The Double-Section Polarization Converter . . . . .	11-14
11.6	Summary and Conclusions . . . . .	11-18
11.7	Appendices . . . . .	11-19



<b>12 Waveguide Gratings (Missing)</b>	<b>12-1</b>
<b>13 Waveguide Terminations (Missing)</b>	<b>13-1</b>
<b>14 Semiconductor Optical Amplifiers (In preparation)</b>	<b>14-1</b>
<b>15 Detectors (In preparation)</b>	<b>15-1</b>
15.1 Photodetectors . . . . .	15-2
15.2 Photodetector structure . . . . .	15-2
15.3 Photodetectors geometry . . . . .	15-4
15.4 Figures of merit . . . . .	15-5
15.4.1 Dark current . . . . .	15-5
15.4.2 Responsivity \label{sec:figures_of_merit_responsivity} . . . . .	15-6
15.4.3 Linearity . . . . .	15-6
15.4.4 High-frequency response . . . . .	15-7
<b>16 Saturable Absorbers (Missing)</b>	<b>16-1</b>
<b>17 Modulators (In preparation)</b>	<b>17-1</b>
<b>18 RF Waveguides (Missing)</b>	<b>18-1</b>
 <b>III Composite Building Blocks</b>	
<b>19 Multi-Mode Interference Devices</b>	<b>19-1</b>
<small>XAVEER LEIJTENS AND MEINT SMIT</small>	
19.1 Introduction . . . . .	19-1
19.2 Multi-Mode Interference (MMI) and Self Imaging . . . . .	19-1
19.3 Analysis of the imaging mechanism . . . . .	19-2
19.3.1 Full image. . . . .	19-4
19.3.2 Mirrored Image . . . . .	19-5
19.3.3 3-dB coupler. . . . .	19-6
19.3.4 Restricted interference: symmetric excitation. . . . .	19-7
19.3.5 Restricted interference: paired interference. . . . .	19-8
19.4 MMI-couplers . . . . .	19-9
19.4.1 Optimization of access waveguide width. . . . .	19-9
19.4.2 Design for low reflection. . . . .	19-10
19.5 MMI-filters. . . . .	19-11
19.6 MMI-reflectors. . . . .	19-11
19.7 Description of available PDK modules . . . . .	19-11
<b>20 Directional Couplers (Draft)</b>	<b>20-1</b>
20.1 Introduction . . . . .	20-1
20.2 Synchronous couplers . . . . .	20-1
20.3 Asynchronous couplers . . . . .	20-3

<b>21 Tapers and Spot-Size Converters (Draft)</b>	<b>21-1</b>
<small>MEINT SMIT</small>	
21.1 Waveguide tapers . . . . .	21-1
21.2 Spot-size converters . . . . .	21-5
21.2.1 Additional information on the HHI SSC . . . . .	21-7
21.2.2 Additional information on the SP SSC . . . . .	21-8
<b>22 Y-junctions (Draft)</b>	<b>22-1</b>
22.1 Introduction . . . . .	22-1
22.2 Geometry . . . . .	22-1
22.3 Excess loss and reflection. . . . .	22-2
22.4 Symmetry . . . . .	22-3
22.5 Tree networks. . . . .	22-3
<b>23 Star Couplers (Draft)</b>	<b>23-1</b>
23.1 Introduction . . . . .	23-1
23.2 Coupler geometry and beam shape . . . . .	23-1
23.3 Array coupling loss. . . . .	23-3
23.4 Truncation loss. . . . .	23-5
23.5 Non-uniformity. . . . .	23-6
23.6 Higher order mode excitation. . . . .	23-6
<b>24 Optical Phased Arrays (Missing)</b>	<b>24-1</b>
<b>25 Arrayed Waveguide Gratings (Draft)</b>	<b>25-1</b>
<small>MEINT SMIT, XAVEER LEIJTENS ET AL.</small>	
25.1 Introduction . . . . .	25-1
25.2 Operation Principle and Device Characteristics . . . . .	25-2
25.2.1 Principle . . . . .	25-2
25.2.2 Focusing, Spatial Dispersion and Free Spectral Range . . . . .	25-3
25.2.3 Insertion Loss and Non-uniformity . . . . .	25-4
25.2.4 Bandwidth . . . . .	25-5
25.2.5 Passband Shape . . . . .	25-6
25.2.6 Crosstalk . . . . .	25-7
25.2.7 Wavelength Routing Properties . . . . .	25-8
25.2.8 Configuration-dependent Crosstalk . . . . .	25-8
25.2.9 Polarisation Dependence . . . . .	25-10
25.2.10 Temperature Dependence . . . . .	25-11
25.3 InP-based Devices . . . . .	25-11
25.3.1 Introduction . . . . .	25-11
25.3.2 Fabrication . . . . .	25-12
25.3.3 InP-based AWGs . . . . .	25-13
25.3.4 AWG-based Circuits . . . . .	25-15

25.3.4.1 Multiwavelength Transmitters . . . . .	25-15
25.3.4.2 Multi-wavelength Receivers . . . . .	25-18
25.3.4.3 Channel Selectors and Equalizers . . . . .	25-19
25.3.4.4 Multi-wavelength Add-drop Multiplexers and Cross-connects . . . . .	25-21
25.4 Methods for AWG Characterization . . . . .	25-22
25.4.1 Insertion Loss . . . . .	25-22
25.4.2 Wavelength dependent measurements . . . . .	25-23
25.4.3 Polarisation-dependent Loss . . . . .	25-24
<b>26 Mach-Zehnder Modulators (Missing)</b>	<b>26-1</b>
<b>27 Polarisation Based Components (Missing)</b>	<b>27-1</b>
<b>28 Resonators (Missing)</b>	<b>28-1</b>
<b>29 Lasers (Missing)</b>	<b>29-1</b>
<b>IV Circuits</b>	
<b>30 Worked ASPIC Examples (Missing)</b>	<b>30-1</b>
<b>31 Future Developments (Missing)</b>	<b>31-1</b>
<b>V Appendices</b>	
<b>A Rainbow Color Coding</b>	<b>A-1</b>
<b>B Refractive indices</b>	<b>B-1</b>
B.1 Refractive index definition . . . . .	B-1
B.2 Refractive indices in the C-band (around 1550 nm) . . . . .	B-1
<b>C Standard waveguide structure</b>	<b>C-1</b>
<b>D FIMMWAVE-FIMMPROP Detailed Descriptions</b>	<b>D-1</b>
D.1 Planar Waveguide Taper. . . . .	D-1
D.2 Y-junction . . . . .	D-5
<b>Nomenclature</b>	<b>1</b>
<b>Bibliography</b>	<b>1</b>
<b>Index</b>	<b>16</b>