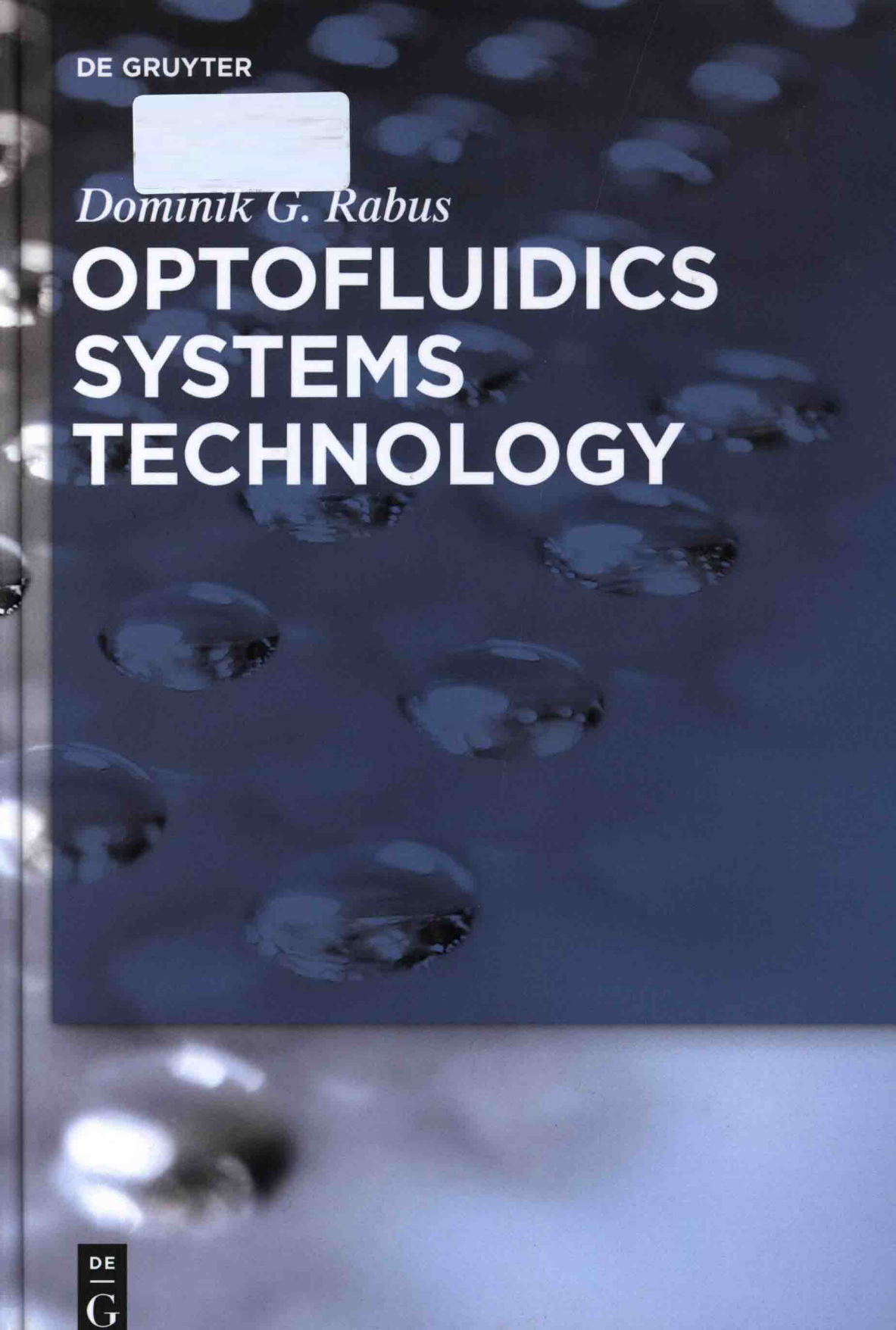

DE GRUYTER
Dominik G. Rabus
OPTOFLUIDICS SYSTEMS TECHNOLOGY
DE G

Dominik G. Rabus

Optofluidics Systems Technology

常州大学山书馆
藏书章

DE GRUYTER

Author
Dr. Dominik G. Rabus
Ahornstr. 47
74670 Forchtenberg
Germany
book@optofluidik.de
www.optofluidik.de

ISBN 978-3-11-033602-3
e-ISBN (PDF) 978-3-11-035021-0
e-ISBN (EPUB) 978-3-11-038416-1
Set-ISBN 978-3-11-037450-6

Library of Congress Cataloging-in-Publication Data
A CIP catalog record for this book has been applied for at the Library of Congress.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

© 2014 Walter de Gruyter GmbH, Berlin/Boston
Cover image: Bürkert Fluid Control Systems, Ingelfingen, Germany
Typesetting: PTP-Berlin, Protago-TEX-Production GmbH, Berlin
Printing and binding: CPI books GmbH, Leck
♾ Printed on acid-free paper
Printed in Germany

www.degruyter.com

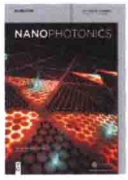
Dominik G. Rabus

Optofluidics Systems Technology

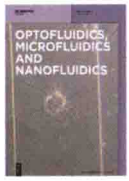
Also of Interest

Advanced Optical Technologies
Michael Pfeffer (Editor in Chief), 6 issues per year
ISSN 2192-8584

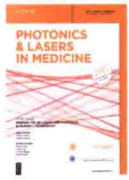
Biomedical Engineering / Biomedizinische Technik
Olaf Dössel (Editor in Chief), 6 issues per year
ISSN 1862-278X



Nanophotonics
Dennis Couwenberg (Publishing Editor), 6 issues per year
ISSN 2192-8614



Optofluidics, Microfluidics and Nanofluidics
Dominik G. Rabus (Editor in Chief), 1 issue per year
ISSN 2300-7435



Photonics & Lasers in Medicine
Frank Frank, Lothar Lilge, Carsten M. Philipp,
Ronald Skroda (Editors in Chief.),
4 issues per year
ISSN 2193-0643

此为试读,需要完整PDF请访问: www.ertongbook.com

To Regina, Anouk and Tizian

Foreword

The decision to write this book was fairly easily made when I realized that there was no real summary of the work in which I have been involved for the last ten years: working on polymer photonics, fluidics, biology, systems in what is nowadays known as Optofluidics Systems Technology.

Finding the time to write this book was on the other hand a challenging task, as one can imagine. Gathering information from former colleagues, students, contacting collaborators and searching my hard drives was the daily business.

Finding a publisher was again easy, as my former colleague and good friend Christian Karnutsch approached me one day and told me of the opportunity at DeGruyter. All puzzle pieces came together and I would like to thank both Christian Karnutsch for his inspirations and discussions and DeGruyter for taking this book into its repertoire.

This book is interdisciplinary in nature bridging the gap from material science, to Photonics to Fluidics to Biology, focusing on the system aspect to integrate these disciplines to create what I call "true Optofluidic Systems". The idea of this book is to provide a basic understanding of the interdisciplinary topics covered and to give the reader further guidance, if in-depth knowledge is required. A "further reading" section at the end of each chapter lists my personal selection of books from the literature.

This work would not have been possible without the help, motivation and research and development of several people whom I was lucky to have called colleagues and friends over the last ten years.

The origin of the true polymer platform was at Karlsruhe in 2003. My special thanks go to Patric Henzi, with whom I had the pleasure of starting and developing the integrated polymer waveguide platform at the Institute for Microstructure Technology (IMT) at Karlsruhe Institute of Technology. His groundbreaking developments have enabled what is now known today as the DUV platform.

During the last ten years, several people have worked on this platform and I would like to start by thanking my KIT collaborators Martin Punke, Yasuhisha Ichihashi, Steffen Mozer, Matthias Bruendel, Alexander Welle, Juergen Mohr, Volker Saile, Uli Lemmer and the permanent staff of IMT for providing the solid groundwork of this platform.

Further, I would like to thank R. Adam Seger and Michael Isaacson with whom I had the pleasure of working together on the Biology side of the DUV polymer platform at the University of California Santa Cruz.

Another special thank you goes to my colleague Uwe Krug from Buerkert Fluid Control Systems who has provided the material for the chapter on Fluidics. I would like to extend my thanks to all Buerkert colleagues who have contributed to this work in one way or another, especially the contributions from Marko Brammer, Christof Megnin and Thomas Hahn who have brought the system aspect to life.

The system aspect was also the driving force for Faraz Arshad, Johannes Kern, Beate Dutschk, Shirley Ma and Nandini Mungee who have contributed to this book with their bachelor or master theses.

A special thank you goes to Florian Zieker and Elias Knubben of Festo AG & Co. KG for bringing the Festo Optofluidics System to life.

I would also like to thank my collaborators who have provided me with the necessary input from Ocean Optics, Michael Matthews and Nick Barnett, as well as from Hamamatsu, Igor Radivojevic and Reinhold Guth.

A special thank you goes to Herbert Venghaus who has taken the time to read the manuscript and provide valuable feedback on the direction and the focus of this book.

Optofluidics is a growing research area, bridging the gap to Chemistry, Biology and Engineering. This is visible for example in a new Journal on Optofluidics, Microfluidics and Nanofluidics (www.optofluidics.info) as well as a European COST action on Optofluidics.

I would like to take this opportunity to also thank the Optofluidics community for being dynamic and vibrant to drive this field.

Finally I would like to thank the "Waldfeld Kurve" for being a great environment to share and live life, especially Uwe, Ingo, Steffen, Alexander and Nils.

My thank you also goes to Diana and Volker, as well as Lisa and Angelos who have been there when needed and who shared the ups and downs while writing this book.

I would like to end this foreword by citing one of my favorite Chinese sayings:

A path starts by making the first step

List of abbreviations

Δp	pressure drop through valve in MPa
A	cross section
ANSC	American National Standards Committee
ANSI	American National Standards Institute (www.ansi.org)
ASE	amplified spontaneous emission
ASIC	application specific integrated circuit
ASTM	American Society for Testing and Materials
BANSAI	biomedical analysis system with laser light
BCG	bromcresol green
BOD	biological oxygen demand
C	carbon
CA	controlled atmosphere
CFD	computational fluid dynamics
CIE	The International Commission on Illumination (**C**ommission **I**nternationale de l´**E**clairage)
C_J	junction capacitance
CTE	coefficients of thermal expansion
DPSS	diode-pumped solid-state
DUT	device under test
DUV	deep ultraviolet
ECL	external cavity laser
ELSA	electron stretcher accelerator
EMF	electromotive force
eV	electron volts
FRET	fluorescence resonance energy transfer
FTIR	Fourier transform infrared spectroscopy
GRIN	graded index
h	thickness of the material
HA	human albumin
HeNe	helium neon
I_D	diode current
I_L	current generated by incident light
IONAS	Institute for Optofluidics and Nanophotonics
IRS	integrated reverse symmetry
I_S	photodiode reverse saturation current
I_{SC}	short circuit current
J	Joule
k	extinction coefficient / wavenumber / Boltzmann constant
K	Kelvin

k_v	defined volume flow of water in m^3/h
LED	light-emitting diode
M	molecular weight/mass
M′	mass flow in kg/h
MID	magnetic inductive flow
MMI	multimode interference
n	refractive index
N_A	Avogadro's number
NA	numerical aperture
NC	normally closed
n_{eff}	effective refractive index
n_f	refractive index of the film layer of a waveguide
NO	normally open
NTC	negative temperature coefficient
OLED	organic light-emitting diode
p1	absolute pressure at valve inlet in MPa
p2	absolute pressure at valve outlet in MPa
PC	polycarbonate
PDMS	polydimethylesiloxane
PIC	photonic integrated circuit
PLC	polarization controller
PMMA	polymethylmethacrylate
PSD	position sensitive device
psi	pounds per square inch
PTC	positive temperature coefficient
PVA	polyvenylalcohol
q	electron charge
QCM	quartz micro-gravimetry
QD	quantum dot
R	molar refractivity
RI	refractive index
R_m	molar refraction
R_S	series resistance
SMA	shape memory actuator
SMP	shape memory polymer
SPD	spectral power distribution
T	absolute temperature in Kelvin
V′	volume flow in m^3/h (at 0.1 MPa and 20° C)
v_k	specific volume at p ½ in m^3/kg
V_{OC}	open circuit voltage
vph	phase velocity
WKB	Wentzel–Kramers–Brillouin approximation

ZLMT	Zentrum für Labormedizin, Mikrobiologie und Transfusionsmedizin
α	flow coefficient
α_e	polarizability of electrons
ε_0	dielectric constant
λ	wavelength
ρ	density in kg/m^{3}at 0.1 MPa and 20 °C)
ρ_1	density of the gas upstream of valve
ψ	outflow function (function of pressure ratio p2/p1)

此为试读,需要完整PDF请访问: www.ertongbook.com

Contents

1 Introduction

Over the past decade, key technologies like biology, microfluidics and photonics have begun to merge with each other. The result was visible in the advent of biophotonics and Optofluidics. Biophotonics has become an established technology creating new ideas and ways of understanding the principles of for example cellular behavior. This merger has helped to open new doors to fundamental research and to rethink the way "biology" has functioned before. Similar breakthroughs have been reported recently on the newly established merger between photonics and fluidics – Optofluidics – which again brought new ideas to life.

This book takes the merging of technologies a step further in showing the way to integrate biology, fluidics and optics. In this book, the merger of technologies is key and program at the same time because new ideas which result in devices are only possible with the combination of the appropriate technologies. Biology, microfluidics and photonics are vast research areas and to cover all aspects of these three key technologies would go beyond the scope of this work.

Therefore, in order to narrow down the spectrum of possible research topics to be covered in this book, the focus lies on the integration and system aspect of future micro- and nanosystems. When dealing with micro- and nanosystems, the next question is on which material. The three key technologies described in this book require a basis, a platform, an enabling "meeting point" for biology, photonics and fluidics. Materials well suited for serving all of these fields are polymers.

Polymers are favorable substrates for biophotonic devices due to their biocompatibility, the fabrication flexibility they offer and their low cost [58, 147]. Polymers also have the advantage of acting as sensitive layers for proteins and cells, which is a prerequisite for the optimization of chemical and biochemical sensors [161].

Integrated micro- and nanosystems for the determination of the characteristics and the behavior of living cells have attracted a lot of attention lately. For decades technical limitations have forced biologists to record the behavior not of individual proteins in single or few cells, but of populations of proteins in thousands or even millions of cells. Given the complexity of the cellular mechanisms, the result was an average idealized description of cellular behavior. To understand these complex cellular mechanisms, it is necessary to determine how individual parts are integrated in space and time to form complex cellular functions and to measure multiple variables of living cells in real time. Integrated biophotonic devices are among the most promising systems for fulfilling this task.

One of the key topics addressed in this book describes the research focus towards a platform which is able to culture and pattern live single cells for a sufficient period of time, enable the integration of optical evanescent field enhanced photonic devices, and provide means to integrate electronic readout and other photonic components

like photodiodes and light sources. This is realized by a combination of engineering nanofabrication and biological methods forming a cross discipline approach.

Over the past few years, there has been an increasing demand and interest both scientifically and technologically for small and portable analytical tools, the so-called Lab-on-Chip systems, for present and future applications in areas such as medicine, food, environment and public security [66, 125]. The ultimate goal has been to integrate as many analytical functions as possible into a single device and research has been undertaken by universities, research institutes and companies all over the world [10]. At the heart of this effort is the non-invasive analysis of isolated cell populations or even single cells. There is a great need to understand the basic cellular mechanisms and yield information unaffected by average measurements. In addition, several cellular signaling pathways act in a timescale of few seconds and there is a need for real time monitoring with similar time resolution.

Fluorescence from designed sensors and probes is the major information channel for obtaining information from living cells to different functional stimuli [185]. There are two major approaches for introducing these sensors and probes without impairing the cell's viability: by using cell-permeable dyes for operation in cytoplasm and labelling cell organelles, and by using cell-impermeable dyes for labelling the cell membrane. This membrane contains a variety of receptor and transporter proteins that modulate the cellular function and serve chemical and electrochemical communication between the cells. Different metabolites and drugs change the surface properties of this membrane.

Microfluidic chips are ideal platforms for housing and handling small numbers of living cells [174]. A large variety of microfluidic systems are available for cell analysis. The cell handling procedure in microfluidic chips follows cell sampling, cell trapping and sorting, cell treatment and cell analysis. Cell trapping and immobilization at predetermined places inside fluidic channels and keeping the cells alive for a long period of time are of fundamental importance.

Polymers have been investigated for a long time for creating photonic waveguides and devices like splitters, couplers and complex photonic integrated circuits. Consequently, the fabrication of optical waveguides on polymeric substrates has the potential to solve a major integration challenge. The focus on polymer processing technologies provides the necessary platform in order to combine biology, fluidics and photonics due to the fact that all three technologies are well established on polymer materials. Using for example well-known polymers like methacrylate- based polymers, opens up the possibility to use readily available micro-nano fabrication tools like lithography, hot embossing or etching technologies. Polymers are available in solid and liquid form, which enables the creation of hybrid polymer devices like, for example, polymer photonic devices on silicon. Polymers can not only serve as the basis of the three mentioned technologies, but can also serve merely as a carrier for other devices on non-polymer substrates like, for example, silicon photodiodes or InP laser sources. This fact is again a major advantage for creating a truly merging material platform.

Optical waveguides are the basic and the most important optical elements that must be integrated into Lab-on-a-Chip Microsystems [157]. So far, there have been many bioanalytical systems that use optical waveguides as their main analytical tool [67, 144]. The most common methods for waveguide fabrication are conventional deposition techniques like chemical vapor deposition, flame hydrolysis deposition and ion exchange on glass substrates.

Various concepts for biosensors based on evanescent field sensing [172] have been demonstrated [25, 34, 82]. Recently it has been shown that living animal cell adhesion and spreading can be monitored online and quantitatively via the interaction of the cells with the evanescent electromagnetic field present at the surface of an optical waveguide [193]. The idea to study living cells in combination with optical waveguides has also been used in connection with optical waveguide lightmode spectroscopy (OWLS) and confocal laser scanning microscopy (CLSM), which provides information about the shape of the cells at the surface [226]. This allows for the correlation between the cell-shape information from CLSM and the cell-surface interaction measurements from OWLS.

The evanescent field in planar waveguide structures does not usually reach more than 300 nm into the cell. Using a reverse symmetry waveguide presented in [95–97], an evanescent field of about 1 μm is obtained, which is sufficient to penetrate into the cell body. The reverse symmetry waveguide uses a cladding material with a higher refractive index than the substrate (here nanoporous silicon), thus enabling the optical mode field in the waveguide to turn around and penetrate the cladding compared to a conventional waveguide design, where the optical mode field decays gradually into the direction of the substrate.

Integrated ring resonator biosensors have attracted attention recently. Their compact size and the resonance effect enable the detection of very small quantities of substances [21, 40, 133, 134, 243]. The combination of these integrated devices with living cells in microfluidic devices is a focus of the Optofluidics community.

Living cells have been attached to optical fibers for realizing biosensors, e.g. [216]. The fiber is immersed in an aqueous media appropriate for cell viability. The response of the cells to small quantities of toxicant can be monitored spectroscopically [146].

Living cells on top of waveguides in a microfluidic chip can potentially give valuable information about cell attachment, spreading and proliferation on solid surfaces. In order to grow living cells on waveguides, the ability to specifically pattern cells has to exist. Until now, surface chemistry controlled cell patterning was performed predominantly on the basis of self-assembled monolayers of substituted thiols on coinage metals [159]. However, polymeric substrates are not suitable or need special pretreatments like metal deposition or hydroxylation in order to be structured by that method. Although different polymers are the abundant material for cell culture substrates, far fewer investigators have used polymers for patterned cell cultures [54, 153]. In [54] conventional photoresist technologies are used to create patterns of oxygen plasma treated regions on polystyrene. Although this multistep protocol is rather time con-

此为试读,需要完整PDF请访问: www.ertongbook.com