Optical Measurements for Scientists and Engineers

A Practical Guide

With this accessible, introductory guide, you will quickly learn how to use and apply optical spectroscopy and optical microscopy techniques. Focusing on day-to-day implementation and offering practical lab tips throughout, it provides step-by-step instructions on how to select the best technique for a particular application, how to set up and customize new optical systems, and how to analyze optical data. You will gain an intuitive understanding of the full range of standard optical techniques, from fluorescence and Raman spectroscopy to super resolution microscopy, and understand how to navigate around an optics lab, with clear descriptions given of the most common optical components and tools. Including explanations of basic optics and photonics, and easy-to-understand mathematics, this is an invaluable resource for graduate students, instructors, researchers, and professionals who use or teach optical measurements in laboratories.

Arthur McClelland is a Principal Scientist at the Center for Nanoscale Systems at Harvard University. He is a member of the American Chemical Society and the New England Society for Microscopy, and has co-taught Harvard Extension School’s *Introduction to Microscopy* course.

Max Mankin is the Co-Founder and CTO of Modern Electron, USA, and completed his PhD at Harvard University.

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Spectroscopy and Microscopy are two important fields in today's technology. *Optical Measurements for Scientists and Engineers* provides an excellent introduction to these fields with a very practical point of view. The book is very well illustrated and explained; and it limits the number of equations used. Thus *Optical Measurements for Scientists and Engineers* is within the reach of a wide audience. Of course, the emphasis is on optical measurements, which are a critical aspect in applied technology.

José Sasian, *University of Arizona*

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Optical Measurements for Scientists and Engineers

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For Simon, Tobi, and Lisa.
Thanks for being patient while I wrote a book.
A. M.

To my parents and my sister, who by example
taught me the value of hard work and the importance
of passion for one’s pursuits.
M. M.

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Preface

Experiments involving lasers, light, and optics are ubiquitous in virtually every field of experimental science and engineering. Recently, advanced optical characterization techniques have begun to pervade the life sciences and medical fields as more physical scientists are turning their attention to biological questions. There is still a strong "build it yourself" culture in optics and, unfortunately, graduate students and postdocs often find themselves suddenly in charge of a lab full of expensive optics that they are totally unfamiliar with. This book is meant as a crash course "What is that thing?"-type guide, complete with practical tips and tricks to help get optical setups built and collecting data. It focuses on the most common components used in optical spectroscopy and microscopy setups and it is by no means exhaustive. It is, of course, biased by the authors' own experiences in various academic optics labs but it is hoped that it will help the reader feel more comfortable in the lab, dispel some of the incorrect lab lore that is often passed down through the years, and result in better (and easier!) science at the end of the day.

Is this book right for you? We've written the text for biologists, chemists, materials scientists, applied physicists, electrical engineers, and medical professionals, and purposefully limited the theory and the math in favor of diagrams, pictures, tips, tricks, and quick, practical information that will help you get your measurement done without earning a second degree. To understand everything in this book, you'll only need a little algebra and trigonometry, an understanding of 45 and 90 degree angles, and maybe an introductory chemistry or physics course.

Perhaps you have encountered one of the following scenarios:

- You are asked to "Build a photoluminescence spectroscopy system" but you've never turned on a laser, let alone aligned a laser beam, mirrors, and lenses.
- Total internal reflectance microscopy sounds just perfect for characterizing your cells, but you don't know what such a microscope looks like or which vendors to buy the components from.
- You see a complicated graph in an exciting seminar and everyone is talking about it but you have no idea how to even begin interpreting all of the contour lines and symbols.

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- You find an unlabeled, dirty filter on your laser table and the previous student (who has now graduated, moved 6000 miles away, and started a bakery) hinted some time last year that maybe it's the one that you need for your new measurement. How do you figure out what it is?
- Everyone seems to be speaking another language referring to lots of things in optics lab that just sound like gibberish to you. Can you please hand them the what?!

We, the authors, have experienced situations like these, so we wrote this book thinking about our experiences and state of mind when we first started working with laser tables and optics. A practical guide like this would certainly have saved us from many late nights of bad measurements and frustration with laser alignment. We hope it will be helpful to you and your science.

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I started experimenting with lasers by making holograms and exploring optics in general at a summer science camp in Morgantown, WV, circa 1993. Thanks to my parents Christine and Steve McClelland for letting me enroll in the science summer camp. Thanks to Judy Werner for doing the thankless job of organizing the summer camp every year, and a special thanks to Sean Lalley for letting a bunch of middle schoolers play with lasers and develop holograms. Lasers in those days were expensive and often somewhat homebuilt. In retrospect, it was an amazing effort on his part to organize the hands-on making of holograms by kids.

In college I was fortunate enough to work in a number of research groups with quite a number of very patient graduate students and postdocs. Thanks to Sava Denev and Professor David Snoke for my first summer research experience in an optics lab at the University of Pittsburgh. Thanks to Vasiliy Fomenko for his infinite patience in teaching me how to realign a Ti:sapphire laser after I had messed it up yet again, and Professor Eric Borguet for giving me the opportunity to do an undergraduate research thesis in his lab in ultrafast optics at the University of Pittsburgh. Thanks to the Applied Physics program at the University of Michigan for support to explore different areas of research. Thanks to Professor Steve Yalisove for time in his group. Thanks to Jie Wang for the patience while teaching me how to realign an OPO/OPA/DFG system for SFG-VS spectroscopy. Thanks to Professor Zhan Chen for overseeing my PhD thesis at the University of Michigan. Thanks to Abdelkrim Benabbas and Professor Paul Champion for my postdoctoral experience at Northeastern University.

Thanks to Eric Martin and Fettah Kosar for hiring me and giving me a chance to grow professionally at the Center for Nanoscale Systems at Harvard University. Thanks especially to Fettah for getting the Introduction to Microscopy course for the Harvard Extension School off the ground, as large sections of this book grew out of lectures and discussions from this course. Thanks to David Bell, Bill Wilson, Greg Lin, and all my other CNS colleagues for their continued support.

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Thanks to all the users of CNS who bring me new scientific challenges to think about every single day.

Thanks to Doug Richardson at the Harvard Center for Biological Imaging for contributing a variety of microscopy images and being a great colleague. I sometimes wish that all my colleagues were Canadian.

Thanks to Jennifer Waters in the Nikon Imaging Center at Harvard Medical School. The Quantitative Imaging course at Cold Spring Harbor Laboratories was a formative two-week experience. Thanks to the New England Society for Microscopy for providing a community of microscopists. Thanks to all the vendors who I have coerced into giving workshops at CNS over the years, especially Philippe Clemenceau for organizing the FLIM and New Approaches in Light Microscopy workshops with me. I learn a lot every time.

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Finally, thanks to my co-author Max Mankin who made the hypothetical idea of writing this book a reality with his infectious enthusiasm.

Arthur McClelland

When I started graduate school, I had never worked in an optics lab before. There were lots of people who helped me learn my way around a laser table.

First, thanks to my co-author Arthur McClelland, who taught me optics, tolerated countless uninformed questions, and humored my suggestion to write a book to help others who wanted to use optical techniques without much of a background in it. Arthur served as a constant resource, inspiration, and friend in using optics for my research.

Second, I owe my PhD adviser Professor Charles M. Lieber a big debt of gratitude for figuratively throwing me in the deep end of the world of optics in one of my first graduate school projects. I learned by doing! Professor Lieber was also generous enough to provide me opportunities to learn from experts in this area, including Professor Ritesh Agarwal at the University of Pennsylvania and his accommodating and patient student Dr. Carlos Aspetti, and Professor Hongjie Dai at Stanford. During that trip to Stanford, I worked with Dr. Guosong Hong for the first time. Guosong patiently tolerated my rudimentary understanding of infrared optics and photonics and very quickly got me up to speed. I'm enormously thankful for the opportunities to learn from experts that I had during this time.

I was also lucky enough at the time to have fantastic mentors and experienced laser jocks to constantly pester with questions. Thank you to my fantastic

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Finally, thank you to all of my friends, colleagues, and family who encouraged me to write this book! Hearing from you about your experiences in optics and photonics labs informed the contents, writing style, and level of detail that we hope will make this a useful manual for everyone out there who needs to use optical characterization for their science, engineering, and analysis.

Max Mankin

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