“If you haven’t measured it, you haven’t made it.”

Wayne Knox

To Linda Leigh, whose love and enthusiasm made this work—and everything else—possible.

Frequency-Resolved Optical Gating:
The Measurement of Ultrashort Laser Pulses

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0. Read Me!

I don't know about you, but whenever I try to read a scientific book for more than a few minutes, I fall asleep. Scientific writing is dull. Indeed, scientists have a well-deserved reputation for being dull people who write dull books for other dull scientists.

I hate this.

So in writing and editing this book, I've tried something different. I've tried, not only to teach you the science of ultrashort-laser-pulse measurement, but also to convey to you the excitement and fun I've experienced in learning and discovering these ideas. For example, when I heard about the idea of phase retrieval, I dropped everything I'd been doing and spent an entire week in the library reading everything I could find on this amazing topic. So I've tried to convey that enthusiasm to you whenever possible. I've also tried to use some writing techniques that make reading a novel fun. For example, you may notice some recurring themes and direct addresses. (Lucky for you I don't know anything about symbolism.) And I've just written whatever I've felt like writing in places and not bothered to edit it out. Fortunately, the wonderful folks at Kluwer Academic Publishers have encouraged this. I've had a lot of fun writing this book, and I hope this means that you'll have some fun reading it.

But that's not all that makes this book different from the other scientific books on your shelf. I've included a CD that's full of cool full-color stuff for you to play with and lecture from.

The CD contains the FROG software (for the PC and Mac) that retrieves pulses from traces. This software is fun to play with even if you haven't set up a FROG; you can have it try theoretical (or experimental) traces and watch it work. Ken DeLong and Marco Krumbuegel (the authors of this software and both former post-docs in my group) sell this software for a few hundred dollars, so they've disabled the 'save' functions on these free versions. Please buy a copy from their companies (Femtosoft or MakTech) if you plan to do anything serious with it. They're nice guys who aren't making much money from this endeavor; they're mostly doing it for the benefit of humankind.

The CD also contains five hours of full-color PowerPoint lectures (for the PC and Mac) that I give to my Ultrafast Optics class on ultrashort pulses and their measurement. So if you're teaching such a class, you just saved 200 hours of lecture preparation time when you bought this book! Indeed, I'm hoping that my supplying these polished files might persuade you to make the transition to high-tech teaching. Gone are the days when the most important attribute of a professor was his pen-

manship on the blackboard. Why don't all textbooks do this? I don't know. Okay, it might have something to do with those 200 hours it took to create them. Nevertheless, I think they should. Supplying prepared lectures along with a textbook could free up some time for teachers to actually improve the lectures, help students, do research, or maybe just relax.

And there's yet a third innovation in this book. I've written a couple of hundred pages, but the life of a professor is a busy one, and I don't have time to write about everything I'd like included this book. So I've asked several other scientists to supply chapters on important relevant subjects on which they're the world's leading experts. In this way, we can cover everything, but still get this book to you in a reasonable amount of time. The result is that this is not a single-author book, but it's also not an edited book of independent chapters; it's a hybrid. Whatever works. I've tried to edit the style of these additional chapters to better match mine, but my style is sufficiently weird that I exhibited some restraint here to avoid irritating these wonderful folks who were kind enough to provide chapters.

The result is that roughly the first half of the book—which I mainly wrote—is more general, simpler, more informal, and about right for an advanced undergrad or a first- or second-year grad student, who's just learning about the fascinating world of ultrafast optics and who'd like to know the basic concepts of ultrashort pulses and their measurement. The second half—by the additional authors—is more specialized, more advanced, more formal, and about right for an older grad student or researcher who has to worry about the details of a specific pulse-measurement project. The book is so long that, if you start it your first year in grad school, you'll probably not get through it until a few years later when you're about to graduate, so things may work out just right.

Coincidentally, that's about the same time scale over which the research described in this book occurred. Only a decade ago, it wasn't possible to measure an ultrashort pulse. Autocorrelators provided a rough measure, but that was about it. FROG emerged in 1991, and it's changed the way ultrafast scientists think about their lasers and helped to provide an understanding of these lasers that has led to ever-shorter pulses.

This book is mainly about FROG, which has allowed us to measure an ultrashort laser pulse's complete intensity and phase vs. time and to do it very well and in a very general way. But it also discusses in some detail autocorrelators, partly for historical reasons, but also because an autocorrelator is a key component of a FROG. There's also some discussion of spectrometers for the same reasons. We also cover spectral interferometry (SI) because it nicely complements FROG: it's extremely sensitive (FROG isn't); it's linear (FROG is nonlinear); it requires a well-characterized reference pulse, and FROG, which doesn't, is the best way to obtain one.

Some people have asked me about including other methods, which (in my completely unbiased opinion…) are less well known, less general, less accurate, and more complex. Actually, that *was* my original plan, but I realized that all such methods are used by at most a few groups (usually just the group that invented it) for highly specialized purposes, and they already know about them. Typically, these methods are prohibitively complex: they often begin with a FROG, and then add numerous additional components—including such complex devices as interferometers and pulse stretchers!—seriously complicating an already nontrivial measurement. One involves an interferometer within an interferometer! (If you know someone who's using such a method, ask him which device he re-aligns when his pulse isn't short enough, the laser or the measurement device. I'll bet it's the latter…) Since these other methods are not in general use, there are only a few papers on each of them, and it's easy to do a quick literature search and read everything there is to know about them; a book on them is unnecessary. Many of them don't actually work or only work on a limited class of pulses—a fact that might not be evident from the papers—so consider yourself warned!

Also, FROG isn't just one technique; it's a class of powerful techniques, each with many variations. In addition, there are many clever things you can do with FROG that you can't do with other methods. For example, FROG has reliable independent checks on the measurement, something not present in any other method. These independent checks are very important because the corollary to Wayne's quotation on the first page of this book is that "If you measured it badly, you probably made it badly, too." Which suggests the following joke:

Question: What's a poorly measured 5-femtosecond pulse?
Answer: A 10-femtosecond pulse.

FROG can even measure the most complex ultrashort pulses ever generated (with a time-bandwidth product in excess of 1000); this is about three orders of magnitude more complex than the most complex pulse ever measured with any other method. Even its alleged weaknesses are in fact advantages: FROG's relatively slow (few-second) iterative algorithm makes it much more versatile than any other method. And its overdetermination of the pulse allows such niceties as automatically calculated error bars and the correction for systematic error. More than 300 scientific papers describe FROG and its variations, features, and applications. And, as you can see, just covering FROG has required more than 400 pages—and we had to leave lots of stuff out! In the final analysis, I'd rather do one or two things well than a bunch badly.

In fact, if you feel that I've omitted something—like a reference to a paper—let me know, and I'll include it in the next edition. Keeping

up with the literature—even just the FROG literature!—is becoming harder and harder everyday, so I'd appreciate the help.

Finally, when a professor writes a book, the folks who really pay the price are his grad students, who, as a result, are neglected so badly that their graduations can be delayed by as much as a year or more. I'm sensitive to this issue, so I've carefully avoided doing that. In view of the fact that scientists are even duller public speakers than they are writers, I took a different approach, and here's the resulting disclaimer:

> No graduate-student careers were harmed in the writing of this book. I wrote my share while pretending to take notes during dull conference talks when the rest of the audience—and in some cases the speaker—were asleep.

Rick Trebino
Georgia Research Alliance-Eminent Scholar
Chair of Ultrafast Optical Physics

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