ECE 503: Ultrafast Optics | # Syllabus | **Spring Semester 2020**

Instructor: Randy A. Bartels

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Office Hours: by appointment

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Lecture: Tu/Th, 2:00-3:15am: B2 Engineering

Text:

Ultrafast Optics, A.M. Weiner, Wiely, 2009. & Notes provided.

Background: Electromagnetics

HW Policy: No extensions. Graded only if *legible* (as judged by grader).

Course Description: Ultrafast optical science has had a dramatic impact on a vast array of technological disciplines. An ultrafast laser is one that generates laser pulses shorter than 100 fs in duration. The theory and understanding of propagation of broad bandwidth optical signals is essential for the design of high throughput optical communications systems. However, the applicability of ultrashort pulse technology spans areas ranging from studying basic processes in semiconductors and devices, watching and controlling the formation and breaking of chemical bonds, nonlinear frequency conversion for new light sources that span three decades of the electromagnetic spectrum, medical imaging, among others. This course will introduce the principles of ultrafast optics, including the basic theory behind ultrashort pulse generation, amplification, propagation, shaping, and measurement. Some application areas from the recent literature will also be covered, partly in lecture. Our goal will be to start with an introductory knowledge of optics and bring you to a point where you can understand the current research literature on each subject.

Grading: Homework, 35%; Exams, 35%; Final Project, 30%

Book References:

1. *Ultrashort Laser Pulse Phenomenon: Fundamentals, Techniques, and Applications on a Femtosecond Time Scale,* 2$^{\text{nd}}$ *edition*, J. -C. Diels and W. Rudolph, Academic, 2006.

2. *Femtosecond Optical Frequency Comb: Principle, Operation, and Applications*, Jun Ye and Steven T. Cundiff (Ed.), Kluwer Academic Publishers / Springer, 2004.
3. *Optics of Femtosecond Laser Pulses*, S.A. Akhmanov, V.A. Vysloukh, and A.S. Chirkin, American Institute of Physics, 1992.
4. *Lasers*, A.E. Siegman, University Science Books, Mill Valley, 1986.
5. *Nonlinear Fiber Optics*, G.P. Agrawal, Academic, 1995.
6. *Frequency Resolved Optical Gating: The measurement of ultrashort laser pulses*, R. Trebino, Kluwer Academic Publishers, 2002.
7. *Few-Cycle Laser Pulse Generation and Its Applications*, F.X. Kartner (ed.), Springer, 2004.
8. *Ultrafast Lasers Technology and Applications*, M.E. Fermann, A. Galvanauskas, and G. Sucha (eds.), Marcel Dekker, 2003.
9. *Compact Sources of Ultrashort Laser Pulses*, I.N. Duling (ed.), Cambridge, 1995.
10. *Femtosecond Laser Pulses* , C. Rulliere (ed.), Springer, 2002.
11. *Ultrashort Laser Pulses and Applications*, W. Kaiser (ed.), Springer, 1993.

Topics and Schedule:

1. Introduction to Ultrafast Optics.
2. Brief review of electromagnetics.
3. Formal descriptions of ultrafast laser pusles: (time domain, frequency domain and Fourier relations, pulse chirp, time-frequency representations).
4. Linear pulse propagation: (dispersive propagation of Gaussian pulses, general theory of dispersive propagation, material dispersion, dispersion characterization).
5. Coherence Theory: Linear Optics of Broadband Light: (coherence time and measurement, models of coherent and incoherent light, Fourier transform spectroscopy, coherence functions and Wiener-Kinchine Theorem, spatial coherence).
6. Ultrafast pulse interaction with matter
7. Characterization of short pulses: (intensity autocorrelation, FROG and related techniques).
8. Ultrafast pulses in resonant optical systems
9. Diffraction of ultrafast pulses

10. Manipulation of ultrafast pulses: (dispersive optical components: gratings, prisms, lenses etc., phase manipulation and pulse shaping, including space-time analogies, time lenses, and spectral holography).

11. Nonlinear pulse propagation: (propagation in nonlinear dispersive systems b. optical fibers, pulse compression, soliton transmission, parabolic pulses & similaritons, propagation through saturable absorption and gain media, beyond the slowly-varying envelope approximation: self-focusing and space-time coupling).

12. Ultrashort Pulse Generation: Laser Mode-Locking: (review of cavity and atomic rate equations, cw laser theory, active mode-locking: AM and FM theories, loss modulation (e.g. AO ML Nd:YAG), gain modulation (e.g. sync-pumped dye), passive mode-locking: master equation theory, fast and slow saturable absorbers, carrier-envelope phase locking and frequency combs).

13. Chirped Pulse Amplification: (theory, implementation, Nd:glass and Ti:sapphire amplifiers, OPCPA, Ultrafast fiber lasers and amplifiers).

14. Extreme light generation: (high harmonic generation, attosecond pulse generation).

15. Ultrafast Optoelectronics: (the photoconductive switch, electro-optic and photoconductive sampling, Terahertz beams and propagation of single-cycle electromagnetic radiation).

16. Experimental Techniques for High Time Resolution (sampling concepts, pump-probe techniques and time-resolved spectroscopy).

17. Experimental techniques using short pulses.

Homework:

The homework is an essential part of the course. You should attempt all problems yourself, but feel free to argue with your colleagues about them. (Simply copying each other's solutions is, however, counterproductive for all parties and is not acceptable.

By the way, a few of the problems will be numerical, not involving heavy computation, but more in the way of modeling pulse propagation through various dispersive elements, so you will need to use your favorite math package (e.g., Mathcad, Maple, Matlab, Mathematica, IDL, etc.)

A homework solution MUST include a full explanation of how the problem is set up, the motivation of steps in the analysis, and an interpretation of the results. The entire point of homework is to explore and think about the material presented in the class AND to be able to communicate your findings. The ability to communicate scientific ideas is of critical importance. Moreover, the emphasis of homework is to analyze each physical situation, interpret that analysis, and communicate the meaning. As a result, the emphasis is NOT on algebraic manipulations. You are encouraged to use Mathematica (and to a MUCH lesser extent other mathematical tools) to write up your solution. All solutions MUST be in a highly simplified form that YOU interpret correctly. Remember: each homework solution should be a short story that includes a reproduction of appropriate diagrams and may require plots of the final solutions you find to explain behaviors.

Some Ultrafast Freeware:

- Lab2 - The virtual Femotlab www.lab2.de/
- Disperse-o-matic from Craig Siders http://siders.creol.ucf.edu/dom/

Websites of Other Courses:

Doug Schumacher at Ohio State University

http://www.physics.ohio-state.edu/ dws/class/880.uf/

Rick Trebino at Georgia Tech.

http://www.physics.gatech.edu/gcuo/UltrafastOptics/

Franz Kartner at MIT

http://ocw.mit.edu/OcwWeb/Electrical-Engineering-and-Computer-Science/6-977Spring-2005/CourseHor

Ultrafast Optics Review Articles

In my opinion, there is no good ultrafast optics textbook. As a result, we will rely on my notes that I will distribute and the ultrafast optics literature. To get Started, please consult the following references:

Dispersion in Ultrafast Optics: A nicely written overview of dispersion and its role in ultrafast optics and propagation [1].

Ultrafast Optics Review: For a recent review of ultrafast optics, see [2].

Ultrafast Source Review: A recent, but somewhat biased, review of ultrafast oscillator source [3].

Ultrafast Amplifier Review: Reviews of ultrafast amplifiers [4, 5].

Phase-stabilized ultrafast sources: Very nice reviews of phase-stabilization in ultrafast lasers [6, 7, 8].

Ultrafast Pulse Shapers: Reviews of ultrafast pulse shapers [9, 10].

Nonlinear Imaging with Ultrafast Pulses: Review of ultrafast microscopy [11].

Ultrafast Nonlinear Propagation in Fibers: A recent review of nonlinear propagation effects in fibers [12].

Ultrafast Coherent Control: A few coherent control reviews [13, 14].

Few-cycle Pulses: A review of few-cycle pulse propagation [15].

Ultrafast Pulse Measurement: Review and article on the two most common measurement techniques [16, 17].

Bibliography

[1] I. Walmsley, L. Waxer, and C. Dorrer, "The role of dispersion in ultrafast optics," Review of Scientific Instruments **72**(1), 1–29 (2001). Part 1.

[2] G. Steinmeyer, "A review of ultrafast optics and optoelectronics," Journal of Optics a-Pure and Applied Optics **5**(1), R1–R15 (2003).

[3] U. Keller, "Ultrafast solid-state lasers," in *Progress in Optics, Vol 46*, vol. 46 of *Progress in Optics*, pp. 1–115 (2004).

[4] S. Backus, C. G. Durfee, M. M. Murnane, and H. C. Kapteyn, "High power ultrafast lasers," Review of Scientific Instruments **69**(3), 1207–1223 (1998).

[5] C. G. Durfee, S. Backus, M. M. Murnane, and H. C. Kapteyn, "Design and implementation of a TW-class high-average power laser system," Ieee Journal of Selected Topics in Quantum Electronics **4**(2), 395–406 (1998).

[6] S. T. Cundiff and J. Ye, "Phase stabilization of mode-locked lasers," Journal of Modern Optics **52**(2-3), 201–219 (2005).

[7] S. T. Cundiff and J. Ye, "Colloquium: Femtosecond optical frequency combs," Reviews of Modern Physics **75**(1), 325–342 (2003).

[8] S. T. Cundiff, "Phase stabilization of ultrashort optical pulses," Journal of Physics D-Applied Physics **35**(8), R43–R59 (2002).

[9] A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," Review of Scientific Instruments **71**(5), 1929–1960 (2000).

[10] A. M. Weiner, "Femtosecond pulse processing," Optical and Quantum Electronics **32**(4-5), 473–487 (2000).

[11] J. Squier and M. Muller, "High resolution nonlinear microscopy: A review of sources and methods for achieving optimal imaging," Review of Scientific Instruments **72**(7), 2855–2867 (2001).

[12] J. Toulouse, "Optical nonlinearities in fibers: Review, recent examples, and systems applications," Journal of Lightwave Technology **23**(11), 3625–3641 (2005).

[13] H. Rabitz, R. de Vivie-Riedle, M. Motzkus, and K. Kompa, "Chemistry - Whither the future of controlling quantum phenomena?" Science **288**(5467), 824–828 (2000).

[14] W. S. Warren, H. Rabitz, and M. Dahleh, "Coherent Control of Quantum Dynamics - the Dream Is Alive," Science **259**(5101), 1581–1589 (1993).

[15] T. Brabec and F. Krausz, "Intense few-cycle laser fields: Frontiers of nonlinear optics," Reviews of Modern Physics **72**(2), 545–591 (2000).

[16] R. Trebino, K. W. DeLong, D. N. Fittinghoff, J. N. Sweetser, M. A. Krumbugel, B. A. Richman, and D. J. Kane, "Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating," Review of Scientific Instruments **68**(9), 3277–3295 (1997).

[17] C. Iaconis and I. A. Walmsley, "Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses," Optics Letters **23**(10), 792–794 (1998).