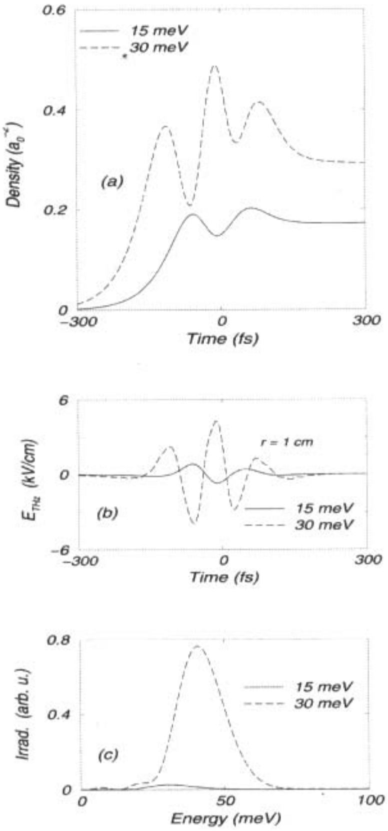

Hughes Figure 1. (a) Temporal variation of carrier pulse-induced carrier density in units of inverse Bohr radius squared; excitation is at the 1*s* exciton resonance. The peak amplitude of the pulse is 15 meV (solid curve) and 30 meV (dashed curve). **(b)** Emitted THzfield versus time for the 15 meV and 30 meV pulses at *r* = 1 cm from the excitation spot. **(c)** Irradiance of the emitted THz spectra corresponding to **(b)**.

play of optical and THz transients, moreover, provides a unique window for simultaneously studying inter- and intra-band carrier dynamics in semiconductor heterostructures. Applications with the semiconductor laser[1] include gain modulation and all-optical ultrafast switching rates of around 500 gigabit/sec—a useful prerequisite for the next generation of broad-bandwidth optical communications networks and the inevitable *gigabit Internet.* More fundamental applications encompass coherent control of electronic wavepackets,[2] nanotechnology, and quantum computing. In short: the cry for reliable THz emitters can be heard throughout the globe. However, apart from expensive free-electron lasers, a common limitation to the generation of THz transients in the laboratory is the lack of tunable sources.

The successful advancement in short-pulse laser techniques and excellent semiconductors samples led to a breakthrough in the last year by the clear observation of self-induced transmission (SIT) in bulk semiconductors[3] and multiple Rabi floppping in quantum wells (QWs).[4] Rabi flopping is a well known coherent effect in atomic systems but has long been considered to be the *Holy Grail* to the *ultrafast* semiconductor community—who are more than ever driven by the pursuit to understand the differences and similarities between the semiconductor and atomic systems resonantly excited by laser pulses. Very recently we have devised a new method[5] that exploits Rabi-flopping-induced density oscillations in a weakly-DC-biased QW to realize very intense (~kV's/cm), tunable terahertz transients. In our scheme, extreme— *tailored*—tunability is achieved by simply varying the area of the input optical pulse. We employ a 150 fs FWHM irradiance pulse. For a weakly-biased QW we assume $d = 0.8\ e$Å(corresponding bias field ~ 10–100 V/cm), and calculate the emitted field at r = 1 cm. We assume the validity of the slowly varying envelope approximation (which is not always valid, see Reference 6), and compute the semiconductor Bloch equations including all the relevant scattering mechanisms.

Figure 1a shows the excitation-induced density for the QW optically excited at the 1*s* exciton resonance using the input Rabi energies of 15 meV and 30 meV (pulse irradiance: ~ GW/cm^2), respectively. The curves display the conduction band-valence band Rabi flopping[3,4] (complete inversion is not possible due to Coulomb processes). Material parameters correspond to $In_xGa_{1-x}As/GaAs$ QW's and agree well with the experimental observations. In Figure 1b we show the emitted THz field versus time corresponding to the density oscillations in Figure 1a. Each transient is approximately 500 fs in duration (due to dephasing) and undergoes a series of polarity changes. In the EM spectra (Figure 1c), clear peaks in the THz regime are seen. For larger areas, more Rabi flops occur[3,5] that subsequenly lead to THz emission with larger frequencies. We note that current techniques employing sub-ps optical pulses for THz-generation are usually limited to about the 1–3 THz regime at best. Our selected examples here easily go to the 10s-of-THz regime with the added bonus of much larger fields. Futhermore they do not suffer from any bandwidth limitations (c.f. optical rectification techniques). These studies are motivated in part because of recent dramatic advances in high-speed, hybrid lightwave-THz photonic applications.

Acknowledgments

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Ultrafast Lasers

Real-Time Optical Pulse Characterization Using SPIDER

Matthew E. Anderson, Timothy M. Shuman, Chris Iaconis and Ian A. Walmsley

The recent advances in ultrafast lasers have mandated a change in the techniques used to measure them. It is no longer sufficient to measure merely the spectrum or the auto-correlation of an ultrafast laser pulse; a more complete picture is required, and this involves determining the phase of the time-varying optical field. The ability to rapidly change the shape of the pulse is a key technology for a variety of new applications, from quantum control to nonlinear optics. Complementary to this is the ability to rapidly characterize the field so that it is possible to understand the physical effects of different pulse shapes. Recently, we have reported a powerful new tool for doing just that. The technique is called Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER)[1] and the new implementation provides feedback in real time[2] for either manual or computer-based control of the pulse shape.

SPIDER is a self-referencing technique based on spectral shearing interferometry (Figure 1). The input pulse (not shown) is split into three pulses: a pulse pair (replicas of the incident pulse) and a highly chirped (stretched) pulse. These are upconverted in a nonlinear crystal to give two spectrally sheared pulses (each pulse has a different center frequency). The spectrometer then yields an interferogram which contains information about the phase of the optical pulse (which dictates the positions of the interferogram's peaks and valleys). The spectral phase of the pulse can be extracted by simple non-iterative linear operations (Fourier transforms and filters). The simplicity of the inversion algorithm allows the input pulsed electric field, either as a function of frequency or time, to be reconstructed. The inversion algorithm is a direct, non-iterative algorithm that has excellent immunity to noise (a S/N ratio of four will return a phase profile accurate to $\pi/10$).

The straightforward experimental implementation of SPIDER, together with the sensitivity of interferometric measurement, make it quite versatile, robust, and easy to use. For example it has been used to characterize pulses from a cw modelocked laser oscillator, with pulses as short as 6 fs,[3] as well as on high and low repetition rate amplifiers.[2,4] In the latter configuration single shot pulse reconstruction with update rates of 10 Hz have been demonstrated[4] which makes it possible to measure the statistical properties of the laser system.

Moreover, because the input data consists of a one-dimensional array of real numbers, the inversion algorithm returns complete pulse shape information (amplitude and phase in either the frequency or time domain) at an update rate of 20 Hz,[2] surpassing previous efforts by nearly an order of magnitude. An important feature of this result, however, is that it was obtained with standard laboratory equipment. The algorithm is programmed entirely in LabView code, running on a 266 MHz PC. Higher update rates can be easily envisioned using compiled code and dedicated processors. This new device, together with parallel developments in spectrographic pulse shape measurement,[5] indicate that time resolved measurements are entering a new era of utility.

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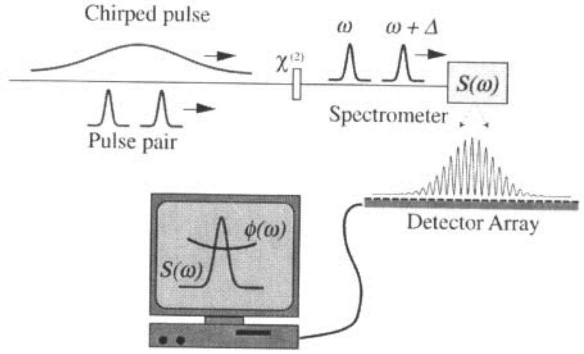

Anderson Figure 1. Components of real-time SPIDER including nonlinear crystal, spectrometer, photodiode array, and computer.

A Femtosecond Ti:Sapphire Laser with GHz Repetition Rate

A. Bartels, T. Dekorsy and H. Kurz

The invention of solid-state femtosecond lasers, the Ti:sapphire laser based on Kerr-lens modelocking,[1] had probably the deepest impact on the development of ultrafast spectroscopy and nonlinear optics within the last decade. Since the era of ultrafast physics based on femtosecond dye lasers in the 1980s, the solid-state systems have lead to an enormous expansion of the whole field. The Ti:sapphire laser is now the workhorse of nonlinear optics, e.g., for pumping OPOs, seeding amplifiers, generating the shortest optical pulses, time resolved spectroscopy, etc. Working in the field of ultrafast semiconductor phenomena, we figured out that a femtosecond oscillator with a significantly higher repetition rate than the available systems working around 100 MHz would bring great benefits for spectroscopic applications. A repetition rate in the GHz range allows achievement of a better signal-to-noise ratio while—at the same average power— the carrier excitation densities can be kept very low, which is of prime importance for experiments where carrier-carrier scattering plays a crucial role. But also in other applications, like two-photon microscopy or THz spectroscopy, a higher repetition rate could be very advantageous to increase the yield of the detectable fluorescence and the signal-to-noise ratio, respectively. A further key aspect of GHz repetition rate lasers is their compactness, which allows the integration of the laser directly into the application.

We developed an ultracompact Ti:sapphire ring laser operating at repetition rates of 1 GHz to 4 GHz. These repetition rates correspond to cavity lengths between 30 cm and 7.4 cm, resulting in a footprint size of below 100cm^2 only.[2] A key issue for shrinking the resonator length is a group-velocity dispersion control that does not require a minimum geometrical cavity length like prismatic elements, with which the highest repetition rate achieved was 1 GHz.[3] Dispersive mirrors, like Gires-Tornouis interferometer mirrors or chirped mirrors,[4] have