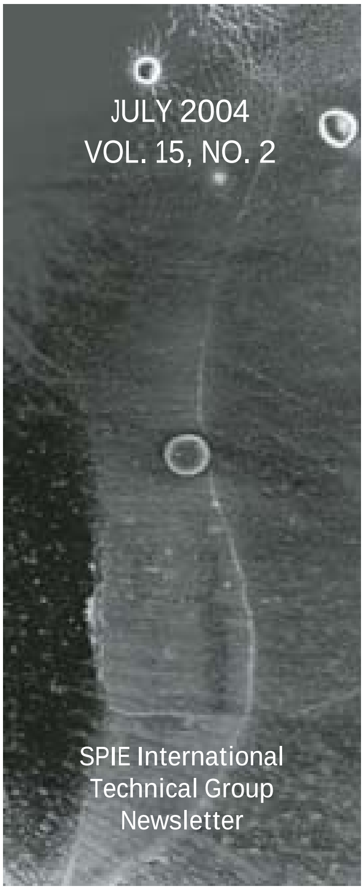
OPTICS IN INFORMATION SYSTEMS



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Special Issue on:

Information processing applications of femtosecond technology

Guest Editor
Shaya Fainman, University of California at San Diego

Time-reversal 3D imaging using broadband terahertz pulses

The most common ways to generate and receive broadband terahertz waves involve femtosecond laser pulses illuminating either photoconductive antennas[1] or electro-optic crystals.[2] Conventional terahertz imaging systems are similar to confocal optical microscopes, where the transmitter and receiver are focused at the same location. The focal spot of the focusing optics determines the pixel size of the reconstructed image. An image is built up in a pixel-by-pixel fashion by mechanically scanning the object.

Stealing a technique used in medical ultrasound scanners, an alternative terahertz imaging system uses an array of transmitters and receivers. The array can be steered and focused by appropriately timing the operation of each array element. The lack of moving parts can substantially reduce data-acquisition times, a critical requirement for real-time imaging applications. A promising image reconstruction technique is time-reversal imaging,[1] which has successfully reconstructed three-dimensional (3D) objects.[3] This is basically an echo-ranging technique: as shown in Figure 1(a), a transmitted pulse is incident on the object of interest, where the scattered fields are detected by an array of receivers. Image reconstruction is performed by numerically backpropagating the received signals using the time-reversed Rayleigh-Sommerfeld diffraction integral, as shown in Figure 1(b). Note that all the points in the entire field of view are reconstructed using the same set of received signals.

Ideally, an array of transmitters and receivers are used to perform time-reversal imaging. However, the lack of availability of such an array forces us to rely on synthetic-aperture techniques. A single transmitter and receiver are used to synthesize a highly-populated array by firing the transmitter multiple times while mechanically scanning the receiver between firings. Once all the signals have been collected, the image reconstruction algorithm treats the data set as if it were acquired by an actual array.

The proof-of-concept imaging setup is shown in Figure 2(a). At its heart are fiber-coupled photoconductive transmitter and receiver modules:[4] the fiber-coupling permits arbitrary placement of the modules for synthetic aperture imaging. We used an object consisting of aluminum-foil letters spell-

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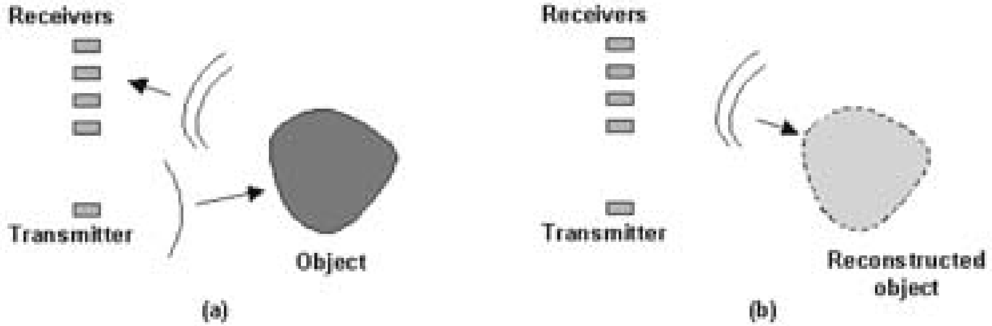

Figure 1. Basic steps for time-reversal imaging: (a) detect scattered fields at various locations; and (b) numerically back-propagate the signals to reconstruct the object.

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Real-time spatial-temporal wave mixing with cascaded second-order nonlinearities

Ultrashort laser pulses are used extensively in the scientific community in diverse fields such as quantum control of molecular and atomic systems, multi-photon microscopy, terahertz pulse generation, frequency comb generation, laser machining, and ultrafast fiber communications. In support of these applications, methods for pulse shaping and characterization have been developed simultaneously. However, pulse-shaping techniques are adaptable on slow time scales, while many pulse-characterization techniques rely on multiple laser pulses to obtain an ultrashort waveform. In the last few years, we have developed real-time optical processors that use nonlinear mixing of two or three input waves originating from spatial- and temporal-information-bearing channels. These processors perform real-time optical signal processing that can be applied to the synthesis, processing, and detection of ultrafast waveforms.

Our real-time optical signal processors are based on the information exchange that takes place in the spatial Fourier plane of the classic 4F optical setup, with diffraction gratings placed at the input and output planes of the temporal channels. The mechanism for this exchange is three- and four-wave mixing via a $\chi^{(2)}$ nonlinear crystal. A cascaded second-order nonlinearity technique is used for four-wave mixing within the crystal: this is a frequency-sum-, followed by a frequency-difference-, generation process satisfying the type-II non-collinear phase matching condition. By employing wave mixing in nonlinear crystals, the information exchange occurs instantaneously. Furthermore, by processing in the Fourier domain within the optical setup, a finite temporal window is simultaneously processed, enabling single-shot information exchange between spatial and temporal channels.

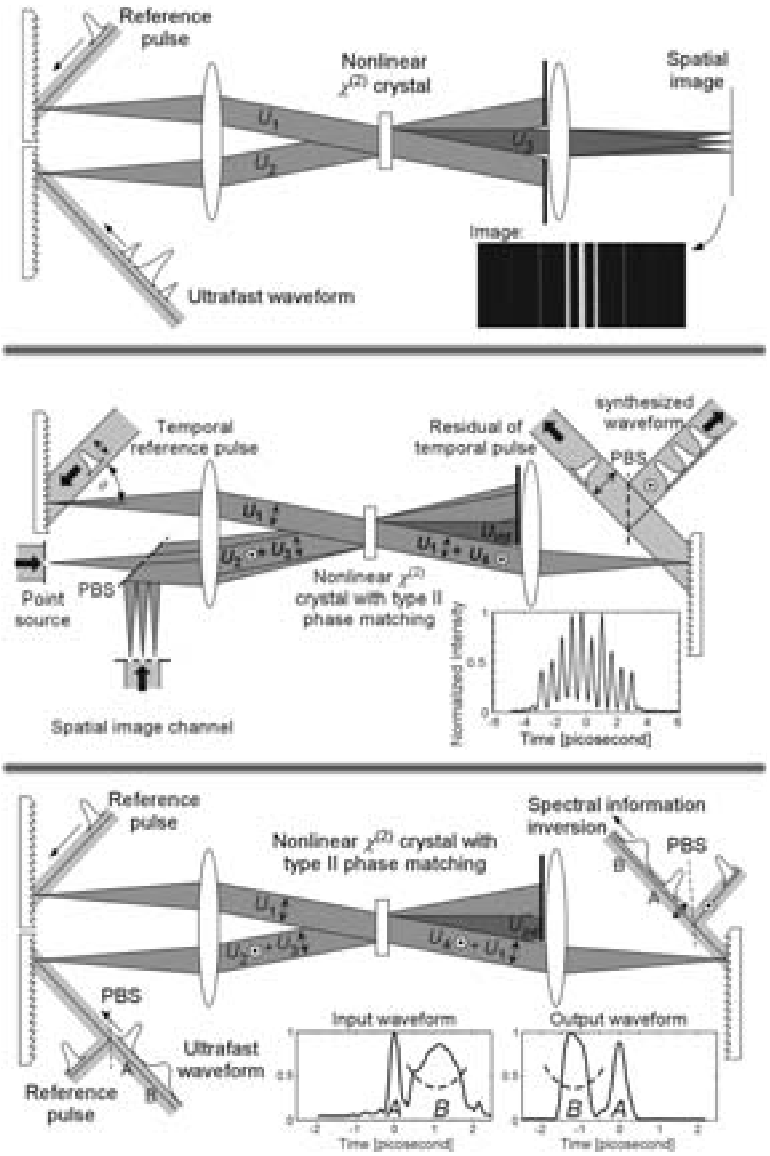

Figure 1. op: Layout of time-to-space processor. Output is a space-scaled image of the input ultrafast waveform. Center: Layout of space-to-time processor. Output is a time-scaled image of the input spatial image. Bottom: Layout of processor of ultrafast waveform. Shown layout performs spatial information inversion of the input ultrafast waveform, achieving time reversal of the waveform's complex envelope.

For detection of ultrafast waveforms, we built a time-to-space mapping processor that mixes two spatially-inverted temporal frequency signals—an ultrafast waveform for characterization and a transform-limited pulse—in a three-wave mixing arrangement.[1] The frequency-sum process between the spectral components of the mutually-inverted spectrally-decomposed waves always add up to a constant optical carrier frequency: the second harmonic of the center frequency of the input ultrashort pulses. The generated quasi-monochromatic spatial signal is spatially Fourier transformed to the output plane. This yields a stationary spatial image that is a scaled replica of the input ultrafast waveform. This is detected by slower electronic means, such as a linear CCD (charge-coupled-device) array that may be matched to the pulse-repetition rate used (top part of Figure 1).

Conversely, we built a space-to-time mapping processor for the generation of arbitrary ultrafast waveforms from an input ultrashort pulse based on a four-wave mixing arrangement.[2] Two spatial signals are introduced to the processor—which consists of an input spatial image and a point source—as a third temporal signal carrying a transform-limited pulse. The resulting output ultrafast waveform is a time-scaled replica of the input spatial image, converting both the amplitude and phase of the spatial image (center, Figure 1). By introducing three temporal information channels to our four-wave mixing processors, real-time optical processing of temporal waveforms is enabled.[3] We have demonstrated time-reversal experiments of an ultrafast waveform based on performing spectral phase conjugation and spectral inversion operations, achieving time reversal of the electrical field and of the complex amplitude waveform, respectively (bottom, Figure 1).

The experiments described above demonstrate the information transfer from an input information-bearing signal (spatial or temporal) to an output information-bearing signal (again, spatial or temporal). However, when several information-bearing signals are intro-

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Device fabrication and information processing with femtosecond laser pulses

Femtosecond technology has been commonplace since the advent of the commercial Ti:Sapphire laser systems, but it is still making a significant impact on a variety of fields. Here we briefly introduce two aspects of that impact in our area: device fabrication and information processing. Femtosecond laser pulses have enabled us to fabricate three-dimensional (3D) photonic device structures in transparent materials such as glass, and perform ultrafast information processing of optical signals beyond the bandwidth of the fastest electronic signals.

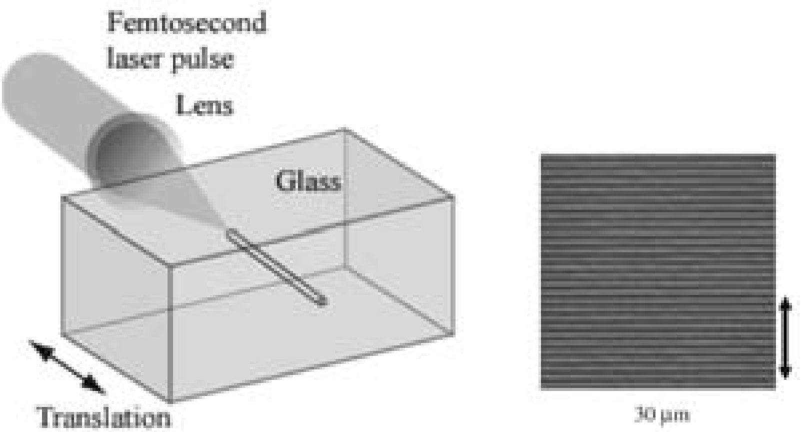

Figure 1. (a) Diagram of the focusing setup used to produce structures in bulk glass using femtosecond laser pulses. (b) Optical images of the volume grating with period 5mm and thickness 150mm.

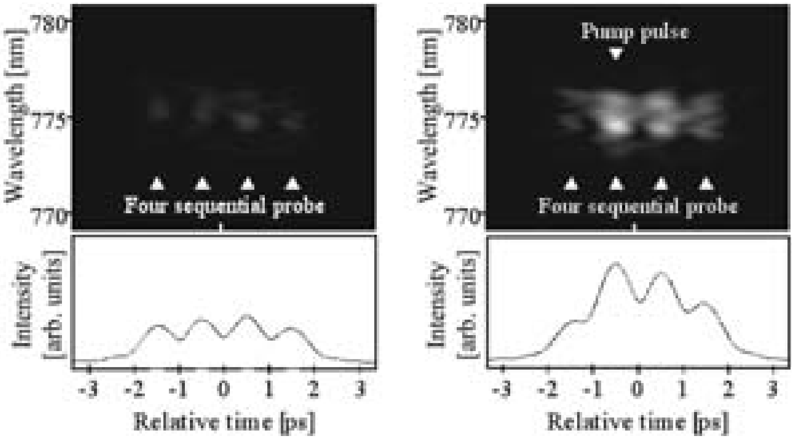

Figure 2. Experimental results showing the measurement of a saturable absorption phenomenon using the optical spectrogram scope: (a) before, and (b) after the incidence of the pump pulse.

Fabrication of 3D photonic devices

When femtosecond laser pulses are focused inside bulk transparent materials, the intensity in the focal volume can become high enough to cause nonlinear absorption, which leads to localized modification in the focal volume while leaving the surface unaffected. By altering the refractive index, we have demonstrated 3D micromachining of glass to produce waveguides, couplers, gratings, binary-data storage, lenses, and channels (see Figure 1).[1] The most important feature of this technique is its ability to integrate 3D optical or photonic devices inside transparent materials: sequential direct writing of individual devices can produce, for instance, a 3D photonic signal-processing system. Although the approach lacks the speed necessary for mass production at the scale of conventional lithographic processes, the added value of 3D integration—difficult to achieve by other means—is significant.

Filamentation of femtosecond laser pulses—which occurs due to a balance between the Kerr self-focusing of the laser pulse and the defocusing effect of the high-intensity plasma generated in the self-focal region—induces a permanent refractive-index change in silica glass. We have realized 3D directional couplers using this technique.[1] The devices consisted of three waveguides: one 2mm-long and straight, the other two curved but connected to straight sections. We showed that spectra of these devices are different at the output than the input because the coupling properties are dependent on wavelength.[2] We also created volume gratings in bulk silica glass: we stacked 60 layers with a sample displacement of 3mm. Figure 1(b) shows an optical image of the fabricated grating. The maximum diffraction efficiency, 74.8 % ,was obtained with the HeNe laser beam when the grating was fabricated with a period of $3\mu m$.[3]

Ultra-fast processing using multi-dimensional time-space conversion

System architecture is also critical for improving ultrafast information processing systems. As the ultrashort pulse looks set to become the means of data exchange in the next generation of information technology, it is increasingly important to be able to synthesize arbitrary ultrashort waveforms: this is not possible using current electronic technologies. One promising approach is the substitution of ultrafast processing in the time domain and parallel processing in the space domain. Based on this concept, a novel time-space conversion technique has been proposed to exchange time and wavelength for two-dimensional spatial variables.[4,5] Generally, the time-frequency transform is used for the analysis of time-varying spectra and is based on correlation, which is straightforward to implement optically using conventional optical information processing techniques and bulk devices and systems. Such techniques can also be applied to fields such as ultrafast measurement for the analysis of photochemical reactions and ultrafast processing for the next generation of communication systems.

As a representative example of the application of the proposed time-space conversion technique, here we will consider the measurement of an ultrafast photochemical reaction. The method used is that of the optical spectrogram scope (OSS):[6] Figure 2 shows a saturable absorbtion phenomenon recorded using the setup. To achieve single-shot (rather than iterative) measurement, we adopted the use of pump and sequential multi-probe pulses. We measure the saturation recovery of the absorp-

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Beyond observation: microscopy with ultrashort laser pulses to probe and manipulate cortical vasculature

Understanding the microscopic details of cortical blood supply is fundamental both to clinical progress in the treatment of stroke and neurovascular disease, and to building a more comprehensive interpretation of blood-flow-based brain-imaging techniques, such as functional magnetic resonance imaging. We have developed several novel ultrashort-laser-pulse-based methodologies that allow us to map microvascular morphology, probe blood-flow dynamics, query the oxidation state of hemoglobin, and induce and monitor microvascular disruption. Here, we provide a brief overview of this ongoing work.

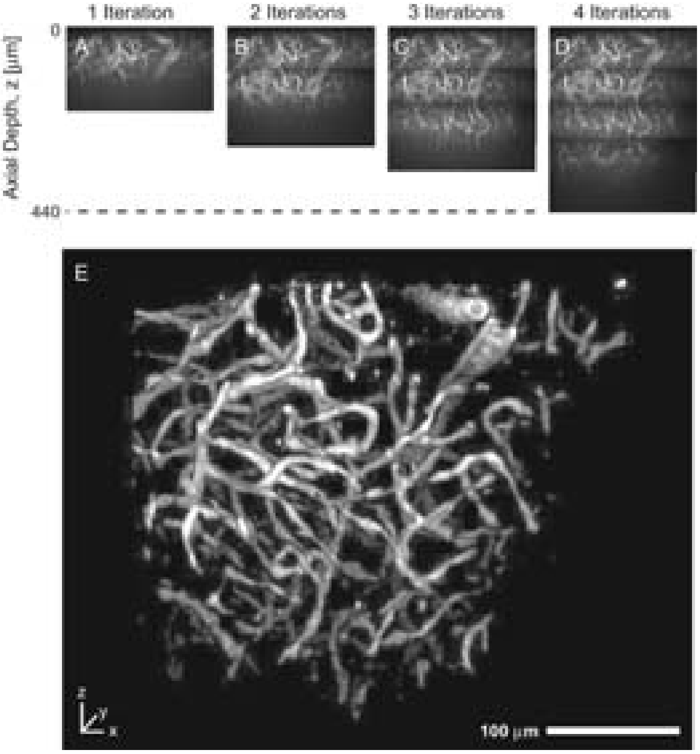

Figure 1. All-optical histological processing. A to D: Serial reconstruction of vasculature in a block of neocortex in a cyan-fluorescent-protein-labeled transgenic mouse. E: Volume rendering of labeled vasculature.[1]

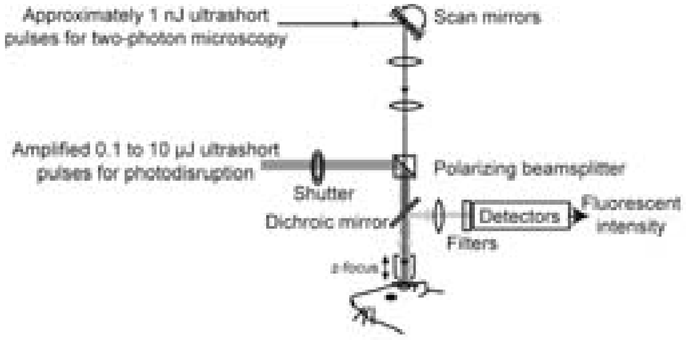

Figure 2. Schematic of the microscope for in vivo *two-photon imaging and multi-photon ablation.*

Fundamental quantitative questions regarding brain architecture—such as the cortical volume dedicated to blood supply or the co-distribution of microvasculature and neuron cell bodies—are extremely difficult to address with standard histological techniques. We have pioneered an all-optical approach to histology that mitigates many of the difficulties of conventional methods (patent pending).[1,2] Volumetric histological data is obtained iteratively by the alternate acquisition of successive optical sections through a depth of ~100 µm and photo-ablation of the previously-imaged tissue. Our images are collected using a Ti:Sapphire-oscillator-based two-photon laser-scanning microscope.[3,4] Ablation makes use of a Ti:Sapphire multi-pass amplifier based on the design of Murnane and Kapteyn[5], with ~100fs pulses at 800nm and 1-10µJ energies. We can cut fixed and fresh tissue with ~1µm tolerance and minimal collateral damage. Figure 1 shows a volume of fluorescently-tagged cortical vasculature which has been reconstructed using this iterative all-optical approach. This project involves colleagues at the University of California at San Diego (UCSD, Roger Tsien Laboratory), the Colorado School of Mines (Jeffrey Squier), and Science Applications International Corporation (Augustin Ifarraguerri and Beverly Thompson).

Dynamic blood-flow measurements can be made *in vivo* in rodents prepared with a window in the animal's skull.[6] Our two-photon microscope, shown schematically in Figure 2, can be used to image vasculature and blood flow in single vessels in neocortex.[7] Red blood cells stand out as dark spots against fluorescently-labeled plasma, and their flow velocity can be measured in real time (Figure 3). This approach has been used by us[8,9] and others[10] to quantify changes in blood flow driven by sensory stimulation.

In addition to enabling three-dimensional optical sectioning, nonlinear microscopy has the potential advantage of providing intrinsic functional images. In collaboration with our colleagues in Colorado, we are investigating the nonlinear optical properties of hemoglobin as a means of determining its ligand-binding state concomitant with optical sectioning. In the first measurements of its kind, we found that oxygenated, deoxygenated, and carboxylated hemoglobin solutions have significantly different third-harmonic spectral features in the 770-1000nm wavelength range.[11] We have also begun measuring two-photon absorption cross-sections in hemoglobin and other non-fluorescent bio-molecules

Lastly, we have launched a series of investigations into the blood-flow changes that result from vascular insult. This work is motivated by suggestions that the highly-interconnected cortical vascular network is robust to multiple blockages.[12] We induce intravascular clotting in microvessels without the application of any exogenous agents through the use of focused, amplified, 800nm laser pulses (patent pending).[13,14] Since the absorption of ultrashort pulses in the vessel lumen is a highly nonlinear process, localized damage can be produced up to ~500µm below the surface of the brain. Adjusting the energy of the amplified laser pulses between 1µJ and 5µJ allows us to create a range of vascular insults ranging in severity from blood plasma extravasation—i.e. small hemorrhages and ischemic clots—to gross hemorrhages (Figure 4). Concurrent two-photon imaging allows us to monitor the consequences of accumulated vascular defects.

For the case of single-point ischemic clots in surface vessels, related work has shown a re-establishment of flow at the first downstream branch point due to a flow reversal in one of the branches.[15,16] Although the re-established flow is, on average, at 50% of its initial flux, this is likely to be sufficient to maintain tissue oxygenation at physiologically-viable levels.

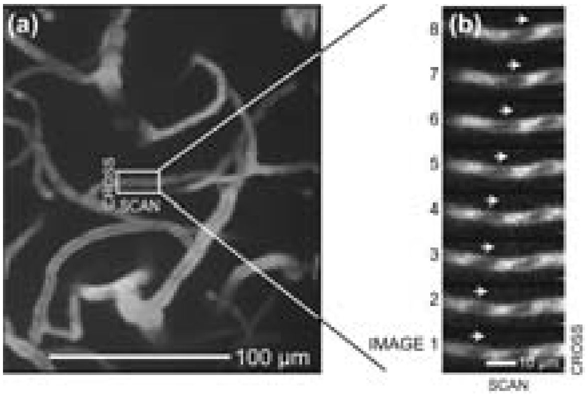

Figure 3. Two-photon in vivo *imaging of cortical blood flow. A: Submicron-resolution images of blood flow. B: Time series depicting the transit of a red blood cell against the fluorescently-labeled plasma.*[9]

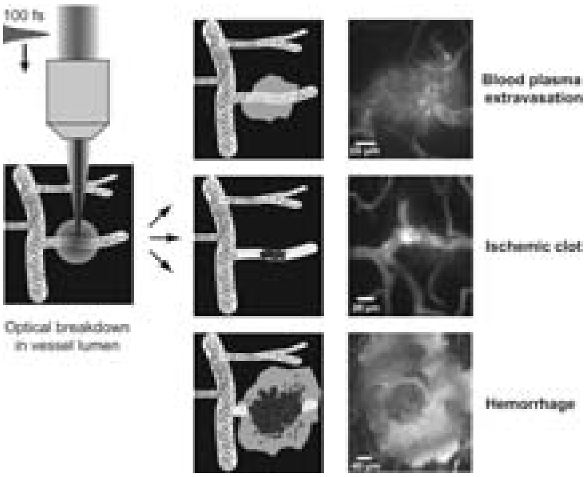

Figure 4. Schematic and two-photon images of vascular disruption induced by ultrashort laser pulses. Photo-disruption is initiated by focusing amplified ultrashort pulses into the target vessel. Subsequent dynamics result in the formation of three types of vascular injury.[13]

This work involves colleagues at UCSD (Patrick Lyden Laboratory) and Vanderbilt University (Ford Ebner).

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Femtosecond-pulse processing: applications to optical communications and radio-frequency photonics

In the Ultrafast Optics and Optical Fiber Communications Laboratory at Purdue University, our research focuses on femtosecond Fourier-optical techniques for processing ultrahigh-speed, broadband optical signals. Our research aims to develop new and sophisticated signal manipulation techniques within the context of ultrafast optics, and to apply these techniques to problems in ultrahigh-speed communications and radio-frequency photonics. In the following I will touch briefly on three representative activities within my laboratory: sensing and compensation of wideband polarization-mode dispersion, optical code-division multiple-access communications, and photonic synthesis of arbitrary radio-frequency electrical waveforms.

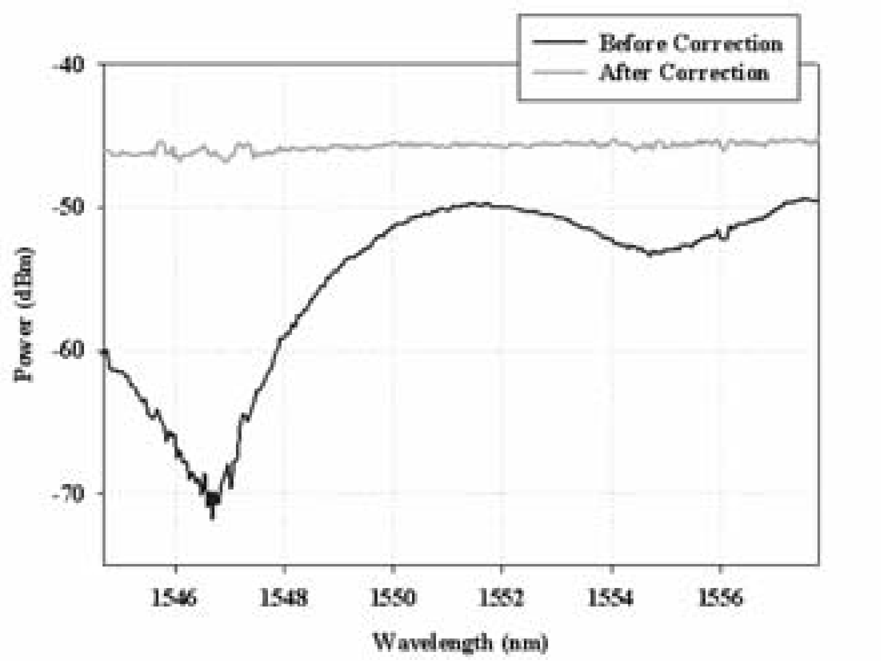

Figure 1. Data demonstrating wavelength-by-wavelength correction of the frequency-dependent state of polarization. Transmission through a linear polarizer shows deep frequency-dependent fades before correction but is nearly flat afterwards.

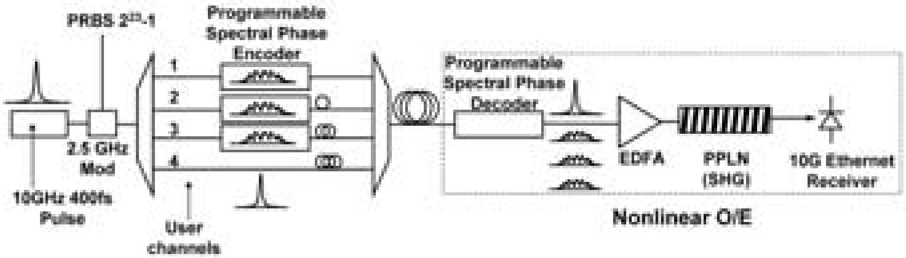

Figure 2. Testbed configuration for four-user O-CMDA system experiments at 2.5Gb/s.

Dispersion compensation

Polarization mode dispersion (PMD) is a major issue in high-speed optical-fiber communications, especially at bit rates of 40Gb/s and above.[1] Arising from small random birefringences in fibers, this effect leads to complicated wavelength-dependent polarization scrambling and polarization- and wavelength-dependent delays. The result is to increase error rates. In our research, our goal is to exploit and extend ultrafast optical-pulse-shaping technology[2] to compensate for PMD of wide-band optical signals in parallel: both on a wavelength-by-wavelength basis and under computer control. This should improve on current approaches: these usually allow only for compensation of first-order PMD for a single wavelength, and do not apply to situations with wide-band optical signals where the distortion caused by PMD varies substantially across the optical bandwidth.

To date, we have made two key achievements related to this project. First, by using a novel liquid crystal-modulator-array configuration, we have demonstrated the first use of an optical pulse shaper for wavelength-by-wavelength polarization compensation.[3] In particular, we were able to take an input field with strongly wavelength-dependent polarization and restore it to a nearly wavelength-independent linear polarization—see Figure 1. This can significantly reduce penalties associated with polarization-dependent loss of optical components, and is the first step towards full compensation of the coupled wavelength-dependent polarization and delay variations arising from wideband PMD.

Second, we have demonstrated a novel wavelength-parallel polarization sensor which can measure the complete state of polarization of 256 wavelength components in parallel: all, potentially, in under 1ms.[4] This substantially improves upon conventional, single-channeled commercial polarimeters and should be sufficient for use in a feedback control loop for PMD compensation.

Intensity discrimination

Optical code-division multiple-access (O-CDMA) is a form of communication in which different users—whose signals may be overlapped both in time and frequency—share a common medium. Multiple-access is achieved by assigning different, minimally-interfering code sequences to different CDMA transmitters. The optical implementation of this technology is receiving increasing attention due to its potential for enhanced information security, simplified and decentralized network control, and increased flexibility and granularity for provisioning bandwidth.

In our approach to O-CDMA,[5] a pulse shaper encodes input ultrashort pulses with a pseudo-random spectral phase code that time-spreads the pulses into lower-intensity noise-like signals. In the receiver, data corresponding to a desired user is separated from multi-access interference via a matched filtering (decoding) operation, also implemented using a pulse shaper. The result is that properly decoded signals are converted back to the original pulse-like signals, while improperly decoded signals remain low-intensity, noise-like, temporallybroad waveforms. Since the energy in properly- and improperly-decoded signals is similar—and since the temporal duration of even improperly-decoded signals is on the order of the bit period or below—both will appear identical to an electronic receiver band-limited to the data rate. We therefore use a nonlinear optical-intensity discriminator based on second-harmonic generation in a fiber-coupled periodically-poled lithium niobate waveguide (provided through a collaboration with Stanford University). This converts an ultrafast intensity contrast into a pulse-energy contrast recognizable by a band-limited receiver.

Figure 2 shows a schematic layout of our recent system demonstration, in which we were able to achieve operation of four simultaneous users at 2.5Gb/s with full O-CDMA interference suppression without the need for synchronous optical gating or ultrafast electronics.[6] Bit-error rates were below 10^{-11}. A key point is that operation at ~0.5mW per user was possible using the nonlinear discriminator: from one to several orders of magnitude lower than previous experiments based on nonlinear fiber optics. Such low-power nonlinear processing will be very important for scaling to higher numbers of simultaneous users at power budgets compatible with practical fiber-optic systems.

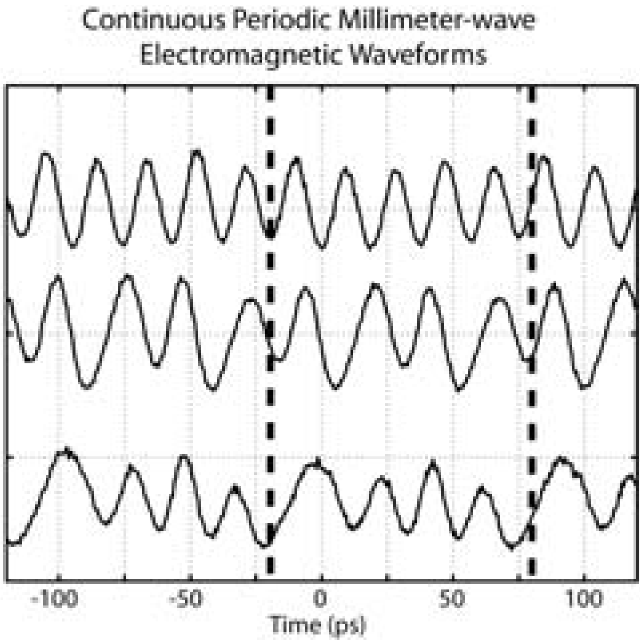

Figure 3. Generation of continuous, periodic, ultra-wideband electrical waveforms. Top: Continuous 50GHz waveform. Middle: Waveform with abrupt binary-phase modulations. Bottom: Frequency-modulation waveform showing abrupt switching between 50GHz and 25GHz.

Waveform synthesis

Finally, we are exploiting femtosecond pulse-shaping technology for cycle-by-cycle synthesis of arbitrary radio-frequency electrical waveforms.[7,8] Commercial electronic arbitrary-waveform-generation instrumentation is currently limited to ~1GHz. In our research we use pulse shaping to create optical signals with user-controlled intensity profiles over time apertures from ~100ps to several nanoseconds and then convert these signals into current waveforms using a fast photodetector. Examples of our results are shown in Figure 3.[7] A mode-locked fiber laser with a 10GHz repetition rate passes through a pulse shaper to produce various pulse sequences repeating at the 10GHz laser frequency. Optical-to-electronic conversion results in the generation of continuous, periodic, ultra-wideband signals with various phase or frequency modulations. These results are the first of their kind in this frequency range. This technology may open new opportunities for electronic countermeasures, pulsed radar, and ultra-wideband wireless communications at frequencies from the gigaHertz to tens-of-gigaHertz range.

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Ultrafast optics in classical and quantum information processing

Ultrashort optical pulses are the information-carrying entities in the current, and will be in future, generations of telecommunications systems. Although it is generally the presence or absence of energy in a given time slot that specifies the bit value, the ability to measure in detail the waveform of the pulses themselves is crucial to understanding the properties of the systems that encode data on the pulses and the optical transfer function of the systems through which the pulses propagate. This information is vital in developing strategies to overcome current capacity limitations.

A quite different technology for optical communications is based on quantum mechanics. This technology, quantum information processing, employs unique properties of quantum systems to achieve communication and computation tasks that cannot be achieved classically. For instance, this approach promises both increased capacit,y via improved coding, and truly secure communications. Ultrafast optical pulses can also play an important role in the preparation of the appropriate quantum states of light that are required in quantum communications entangled photon pairs, for example:

Here we outline research in our group that impacts both classical and quantum technologies for information processing.

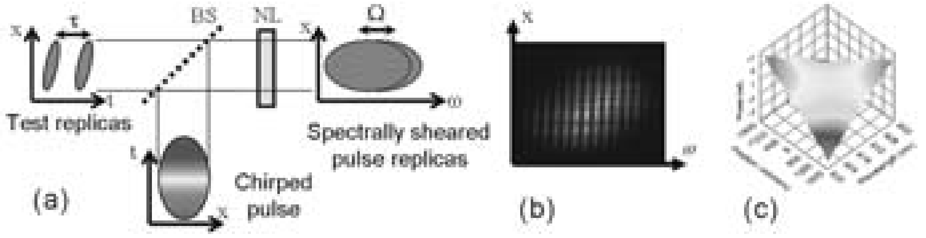

Figure 1. Generation of spectral shear in a space-time spectral-phase interferometer for direct electric-field reconstruction—SPIDER—with (a) a resulting spatial resolved spectral interferogram, and (b) the reconstructed spatio-spectral phase of a test pulse with space-time coupling.

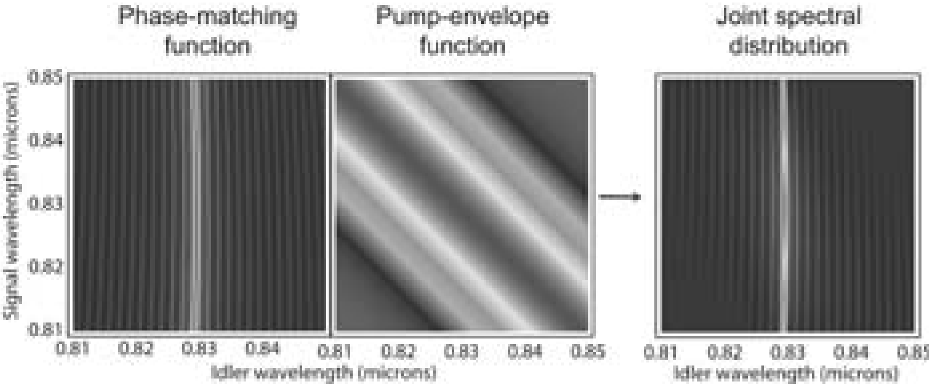

Figure 2. Shown is a parametric down-conversion (PDC) source with engineered spectral properties such that all spectral correlations between signal and idler photon are eliminated.

Ultrafast metrology for classical pulsed fields

Spectral phase interferometry for direct electric-field reconstruction (SPIDER) is an accurate, precise, reliable, and rapid self-referencing interferometric method for measuring the complete temporal intensity and phase of ultrashort optical pulses. It involves the measurement of the spectral interferogram between a pair of spectrally-sheared replicas of the input pulse. A direct (non-iterative) inversion of the interferogram unambiguously reconstructs the spectral amplitude and phase.[1] In the past few years, numerous variations of the original SPIDER concept have been realized and multiple modifications to the original apparatus and algorithm implemented. These have enabled complex pulses in a variety of wavelength ranges to be measured.

In just one example, a modified SPIDER (M-SPIDER) has been used to characterize 3.4fs pulses produced in an argon-filled hollow fiber.[2] The rapid reconstruction algorithm allowed the optimal pulse to be generated by controlling the shape of the pump pulse in real time. At the post-deadline session of the 2004 Conference on Lasers and Electro-Optics, the same group reported the measurement of 2.8fs transform-limited optical pulses, the shortest pulses in the visible region characterized to date.

For application to communications systems, spectral-shearing interferometry can be implemented using linear optics. In conventional SPIDER, for example, nonlinear frequency mixing between a chirped pulse and two time-delayed replicas of the characterized pulse are used to obtain the spectral shear. However, use of a linear nonstationary modulator increases the sensitivity of the technique dramatically. Recently, such a scheme has been demonstrated for telecommunications wavelengths and pulse durations in an all-fiber-compatible configuration.[3]

It is also possible to go beyond conventional spectral phase characterization and measure the complete spatio-temporal field distribution of an ultrashort pulse using SPIDER. Since it uses a one-dimensional data set to construct a one-dimensional field, the additional degree of freedom on an imaging detector can be used to extract spatial phase information with no prior assumptions about the form of space-time coupling. By combining spatial- and spectral-shearing interferometry, the electric field as a function of time and one transverse spatial coordinate can be obtained from a single two-dimensional interferogram.[4] It is straightforward to extend this approach to two spatial dimensions and time. Such characterization of space-time fields has important implications for dynamical imaging and microscopy.

Ultrafast optics for preparing pure-state photonic wavepackets

Ultrashort laser pulses with temporal, spectral, and spatial properties that are tailored for quantum information-processing applications may be used for generating photon pairs by means of spontaneous parametric down-conversion (PDC). This process produces distinguishable photon pairs via a non-linear $\chi^{(2)}$–process in which a pump photon is split into a signal and idler photon at roughly half the pump frequency. PDC has now become an established technology for the generation of quantum-correlated, or so called entangled, photon-pair states as well as for the conditional preparation of single photons. Thus it has been used as the primary source of non-classical radiation in many recent experiments, e.g. quantum teleportation,[5] entanglement swapping[6] and quantum cryptography.[7] The concept of linear optical quantum computation[8] exploits interferences of multiple pure single-photon states in linear optical networks, in conjunction with conditional state-preparation steps such that the detection of auxiliary photons indicates successful operation.

We are developing parametric down-conversion sources optimized for quantum networks: these require the concatenation of multiple input states, the interference of different channels, and advanced single-photon detection. For the concatenation of multiple sources it is essential that we are able to synchronize the generation events, which we ensure by pumping with ultrashort pulse trains. To achieve high probabilities of simultaneous generation events, we need high source brightness. For the implementations of interactions between different channels we have to ensure classical interference as well as quantum interference, which is characterized by photon bunching for pure single-photon states. The classical interference visibility depends on the mode matching between the channels of the network. Here we have to consider all degrees of freedom of the photons: namely their polarization, spatial, and spectral properties. Quantum interference necessitates modal indistinguishability, and thus purity, of conditionally-prepared single photons, which implies that the photon pairs have decorrelated spectral and spatial properties.

Finally, in order to measure the photons, we need efficient and photon-number-resolving detectors with single-photon sensitivity, which we implemented recently.[9] Our waveguided source,[10] pumped by femtosecond pulses, combines timing with spatial and spectral control and exhibits an extraordinary source brightness of 8.5×10^5 counts/s for each milliWatt of power supplied, and a directly observed detection efficiency of 51%.

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Real-time spatial-temporal wave mixing with cascaded second-order nonlinearities

Continues from page 2.

duced to our processors, more interesting information exchange takes place. In general, in a four-wave mixing arrangement in the spatial Fourier domain, the resultant wave will be proportional to the convolution and correlation of the three input signals.[4] As an example, we used two information-bearing spatial images as input signals to the processor, together with a transform-limited pulse. The output signal in this case consisted of the correlation of the two images imparted onto an ultrafast waveform. When two rectangular functions were used as the input signal, the correlation function was an ultrafast triangular-shaped waveform. When two identical pseudo-random masks were used, a sharp spike and background noise were exhibited in the temporal waveform of the correlation function.

We typically employed a 2mm-thick beta-barium borate (BBO) crystal as the nonlinear wave mixing medium in our experiments. By processing in the spatial Fourier plane, where the temporal-information-bearing channels are spatially dispersed and consequently quasi-monochromatic, the limitation of temporal walkoff of ultrashort pulses is mitigated. The information conversion efficiency can therefore be very high, as demonstrated in our record-holding, time-to-space conversion experiment with information conversion efficiency exceeding 100%.[5] Thus, we demonstrated ultrafast waveform synthesis, processing, and detection using our real-time spatial-temporal wave mixing in nonlinear crystals and with high resolution and efficiency.

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Time-reversal 3D imaging using broadband terahertz pulses

Continues from cover.

ing *CUOS* (for Center for Ultrafast Optical Science) attached to a high-density polyethylene substrate. Each letter is approximately 12mm tall and 3mm wide with a linewidth of 1mm. Steps of 1.5mm deep, machined into the substrate, place each letter at a different depth. As shown in Figure 2(b), 10 concentric rings are combined to form an annular imaging aperture. A weighted sum of the images reconstructed from each of these produces the final image.

The reconstructed image planes containing the letters *C, U, O,* and *S* are shown in Figure 3(a-d), respectively. Each image covers a 25×25mm field of view, and all are displayed over the same linear grayscale where white (black) represents positive (negative) field amplitude and mid-gray corresponds to zero. Each letter is clearly reconstructed, demonstrating image planes can be distinguished along the z-axis. However, in each image in Figure 3, faint patches of white and black are visible in regions that are not part of the letters: these reconstruction artifacts are due to scattered waves from out-of-plane objects.[3] A more highly-filled two-dimensional (2D) array, ideally a fully-populated grid, would be required to suppress these artifacts.

Plenty of work lies ahead in developing a terahertz imaging system analogous to medical ultrasound scanners: two major obstacles are parallel detection and signal-to-noise ratio (SNR). Although 3D imaging is possible with synthetic-aperture techniques, the parallel-detection capability of a physical array is necessary for real-time acquisition. A promising approach uses a CCD (charge-coupled device) camera as a 2D array in an electro-optic-based terahertz-imaging system.[2] Even with parallel detection, complete temporal waveforms must be acquired faster than 33ms to satisfy video frame rates. Such short data acquisition times put a high premium on SNR, making it crucial to develop more efficient transmitters and sensitive detectors.

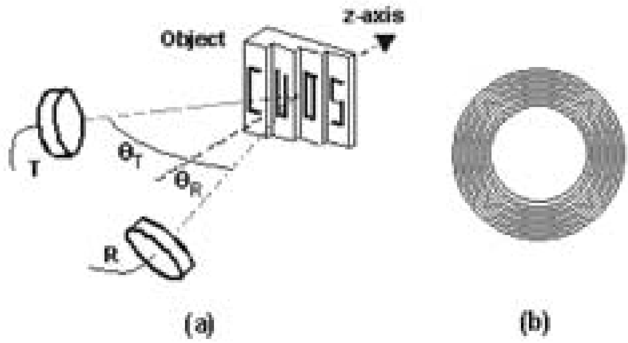

Figure 2. Experimental setups for time-reversal imaging: (a) reflection imaging configuration and (b) annular synthetic aperture.

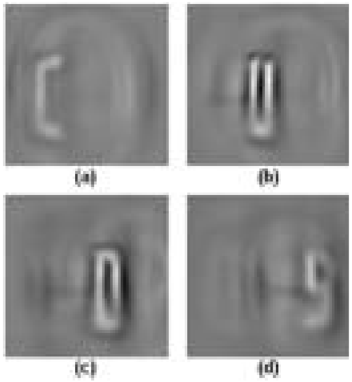

Figure 3. Reconstructed image planes for (a) C, (b) U, (c) O, and (d) S.

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Device fabrication and information processing with femtosecond laser pulses

Continues from page 3.

tion spectrum of an organic dye IR-140 (5,5'-dichloro-11-diphenylamine-3,3'-diethyl-10,12-ethylenethiatricarbocyanine-perchlorate). From Figure 2, we can see the apparent transitional change of the absorption spectrum after incidence of a pump pulse.

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Holographic capture of femtosecond pulse

Continues from page 12.

weak trail, but in this case it is negative phase change. We attribute this to a plasma trail that forms as a result of multi-photon absorption.

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Holographic capture of femtosecond pulse propagation through liquids

We present a technique for capturing a short holographic movie of femtosecond- (fs-) pulse propagation with 150fs time resolution. Our method uses a pulse from a femtosecond laser to record a time-sequence of four on-axis holograms on a CCD camera,[1] and has been applied to the comparison of pulse propagation in water and carbon disulfide (CS_2).

There is considerable interest in the propagation of short pulses through liquids.[2,3] Water and CS_2 are examples of materials with relatively weak and strong nonlinearities, respectively. A nonlinear index change in the material due to the Kerr effect introduces a phase change in the pulse traversing the material, while absorption and scattering cause amplitude changes. Our holographic camera allows us to capture a sequence of snapshots of the pulse propagation in a single-shot experiment, while preserving amplitude and phase information. The time resolution and the frame rate are limited only by the duration of the pulses. The use of holography allows us to spatially multiplex several images on a single frame of a CCD camera. The amplitude and phase of the probe pulses after traversing the material can be digitally reconstructed with a spatial resolution of 40μm.

In the experimental setup, a single pulse from a Ti:sapphire laser system (150fs pulse width, 2mJ maximum energy) is used to capture four snapshots of its own propagation (Figure 1). The pulse is first split in two—pump and probe pulses—and the former is focused inside a glass cuvette filled with either water or CS_2. The probe is further split into four using an array of mirrors that introduce an adjustable time delay between the pulses. The angle between the pump and the probe is fixed at 30° outside the glass container, and an angle of 1.4° is introduced between the probe pulses so that they overlap in the region of interest and then spatially separate. A delay line is used to temporally overlap the pump and probe pulses, to record four spatially-multiplexed on-axis (Gabor) holograms[4] on a single frame of the CCD camera. The holograms are then digitally reconstructed to recover the amplitude and phase of the probes.

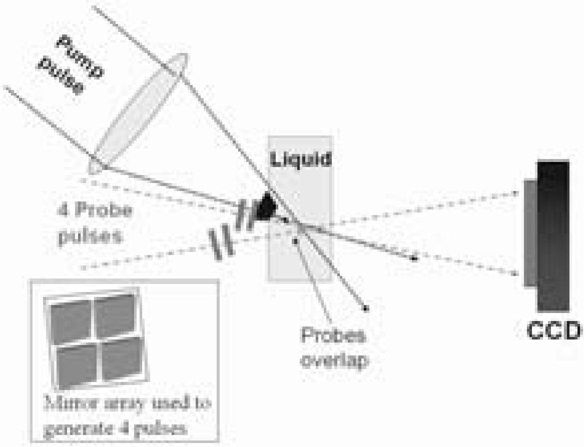

Figure 1. Experimental setup to record a holographic movie. Four probe pulses are generated using a mirror array (see inset), while a pump pulse is focused in the material. The probe pulses travel at different angles (exaggerated in the figure) such that they overlap in the region of interest and are spatially separated on the CCD camera.

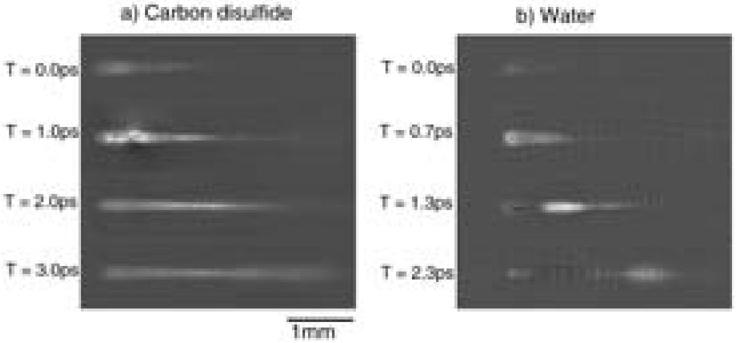

Figure 2. Holographic phase reconstructions of femtosecond pulse propagation: a) in CS2; and b) in water. The maximum phase changes are 3rad and 1rad respectively. The time delay between the holograms is indicated in the figure. Each image is 4mm (horizontal) by 1mm (vertical).

A pump pulse with 50mJ energy was focused inside a glass cuvette filled with CS_2. In Figure 2(a) we see the reconstructed phase change for four different time snapshots: 0, 1, 2 and 3 picoseconds (ps). Water has a weaker nonlinear response so the pulse energy was increased to 300μJ. Figure 2(b) shows the reconstructed phase change for time delays of 0ps, 0.7ps, 1.3ps and 2.3ps. The propagation speed is different in the two cases because CS_2 has a higher index of refraction (n=1.63). In the first image, the probe pulse interacts only with the leading edge of the pulse, so a weak signal is recorded. The second and third holograms capture the pulse before the focal point, while the fourth one captures the pulse after the focal point. The Kerr effect in CS_2 has both instantaneous and non-instantaneous contributions, so as the pulse traverses the liquid it leaves a trace of index change. Using longer time delays between the pump and probes, we measured a decay time constant of the non-instantaneous index change of 1.7ps, in agreement with the values reported in the literature.[5] The nonlinear index change in water is much faster than the duration of the pulse, so instead of a trace we get a direct snapshot of it. The maximum phase change was 3rad for CS_2 and 1rad for water, which correspond to index changes of 10^{-3} and 3×10^{-4}, respectively. Note that, even though the pulse energy was five times higher in the water, the index change in CS_2 was greater. The phase reconstruction in water also shows a

Continues on page 10.

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