Frequency-resolved pump-probe for ultrashort pulse characterization

Baltuška, A.; Pshenichnikov, M.S.; Kane, D.J.

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the pump spectrum with random phase added and convergence was obtained after less than 100 iterations of the MATLAB retrieval program. Figure 2 shows the measured and reconstructed intensity autocorrelation of the pump pulse (a) and the measured and retrieved idler spectrum (b). The algorithm correctly retrieved the idler bandwidth and the pump autocorrelation profile and, as expected, shows both pulses to be dominated by positive linear chirp (Figures 2(c) and (d)). Analysis of the trace marginals confirmed that bandwidth of the crystal was adequate for this measurement and this was consistent with phasematching acceptance-bandwidth calculations. We will present further details of the results summarized here and will discuss extensions of the technique to longer mid-infrared wavelengths.

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CFE3 **8:30 am**

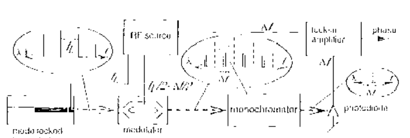
Chirp investigation of monolithic mode locked laser diode pulses with a spectral domain interference method

M. Kwakernaak, R. Schreieck, A. Neiger, D. Erni, H. Jackel, E. Gini,* Hans Melchior,* *Electronics Lab., Swiss Federal Inst. of Tech. Zurich, Gloriastrasse 35, 8092 Zurich, Switzerland; E-mail: kwakernaak@ife.ee.ethz.ch*

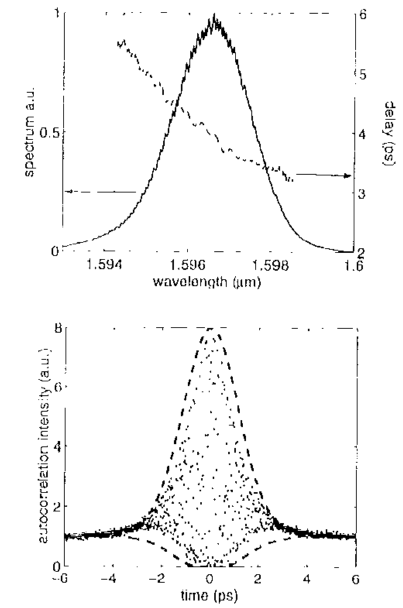
The knowledge of the phase of mode locked semiconductor laser pulses is of prime importance since applications in optical telecommunications require chirp free, transform limited pulses. Pulse phase measurements have attracted considerable interest and have been applied to external cavity mode locked laser diodes.[1] We extend an interferometric setup proposed by[2] to a highly sensitive and real-time method and apply it for the first time to pulses from a monolithic hybrid mode locked laser diode (MLLD).

The bulk active layer rib InGaAsP MLLD with a 1000 μm long amplifier and a 20 μm long saturable absorber section is monolithically integrated with a passive waveguide section extending the cavity to 4 mm. The MLLD is hybridly mode locked by modulating the absorber with a sine signal at frequency f_L = 10.2 GHz.

The phase of the pulses is measured with the setup shown in Fig. 1. Amplitude modulation of the pulse train generates two replicas in the optical spectrum: one up-shifted and one down-shifted by the modulation frequency



CFE3 **Fig. 1.** Setup for phase measurements on mode locked laser diodes.



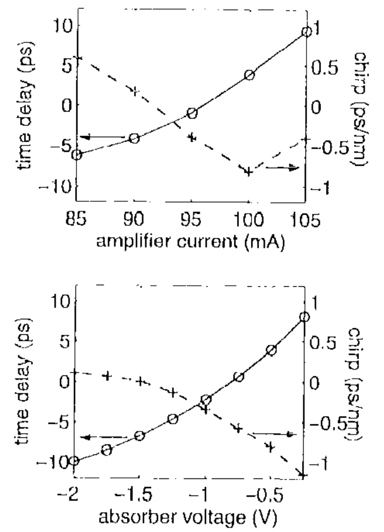
CFE3 **Fig. 2.** Left: Pulse spectrum (solid) and time delay (dashed). Right: Measured interferometric autocorrelation trace (dots) and envelope of the interferometric autocorrelation derived from spectral interference measurements (dashed).

$f_{mod} = (f_L - \Delta f)/2$. The upper and the lower product of two neighboring fundamental lines end up separated by the offset frequency ΔF (100 kHz). Such a pair is selected with a monochromator and produces the beat signal $I_{pd} \propto A_{k+1}A_k cos(2\pi\Delta ft + \phi_{k+1} - \phi_k)$ in the detector. A_k and ϕ_k are the amplitude and phase of the k-th optical spectral component. A two channel lock-in amplifier at the reference frequency Δf detects the beat signal phase $(\phi_{k+1} - \phi_k)$ which is directly related to the relative delay of the spectral components $\tau_{d_{k+1,k}} = (\phi_{k+1} - \phi_k)/(2\pi f_L) + \tau_0$ to the drive signal. τ_0 is a constant offset. There is no second harmonic generation, the complete setup is all in fibers without moving parts and no retrieval algorithms are required resulting in a very sensitive, extremely stable and fast (<2s) method.

The spectrum and the directly measured relative spectral time delay τ_d of the MLLD pulses at 100 mA and 0.5 V amplifier current and absorber bias, respectively are shown in Fig. 2 (left). Fig. 2 (right) compares the interferometric autocorrelation trace directly measured to a trace calculated from the inverse Fourier transform of the measurement on the left (intensity correlation width: 3.1 ps). The mismatch in the wings of the autocorrelation trace is due to pulse shape fluctuations.

Fig. 3 shows the relative time delay τ_d of the average pulse energy to the drive signal and the linear part of the chirp $(\partial\tau_d/\partial\lambda)$ at different amplifier currents and absorber voltages. Increasing the amplifier current and decreasing the reverse absorber voltage turns the pulses from blue into red chirped and delays the pulse. We explain this dependence, supported by simulations, by the increase of the absorber saturation and thus stronger shaping of the leading edge at higher pulse energies.

In summary we have analyzed a monolithic



CFE3 **Fig. 3.** Relative pulse position (solid) and chirp (dashed). The absorber bias and amplifier current is fixed at 0.5 V (left) and 100 mA (right) respectively.

bulk InGaAsP MLLD which produces pulses with low chirp of both signs depending on the bias conditions and achieved chirp free pulses. We measured the spectral phase with an interference technique which proved to be well suited for low power, fiber based systems where an electrical reference is available.

**Swiss Federal Inst. of Tech. Zurich, Switzerland*

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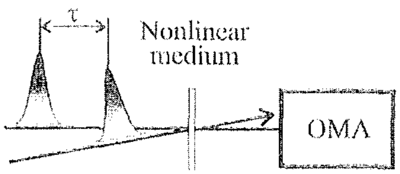
CFE4 **8:45 am**

Frequency-resolved pump-probe for ultrashort pulse characterization

A. Baltuška, M.S. Pshenichnikov, D.A. Wiersma, D.J. Kane,* *Ultrafast Laser and Spectroscopy Lab., Univ. of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands; E-mail: A.Baltuska@chem.rug.nl*

In recent years, frequency-resolved optical gating (FROG) technique has been widely applied for ultrashort pulse characterization.[1] A number of outstanding qualities such as experimental simplicity, uniqueness of the retrieved amplitude and phase, and independent data checks make FROG an invaluable tool in ultrafast spectroscopy.

Most varieties of the FROG technique utilize homodyne detection that requires appreciable pulse intensity. This demand may not be met in many spectroscopic experiments, where the high transition dipole moment and thermal load on the sample impose the power limitations. Another consequence of the ho-



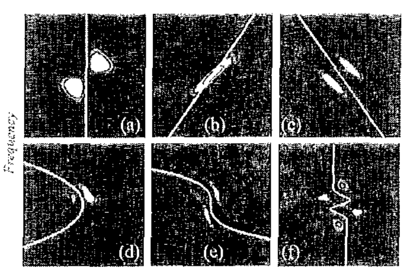
CFE4 **Fig. 1.** Schematic of frequency-resolved pump-probe technique.

modyne detection is that the FROG signal is none-negative and the presence of noise background on experimental traces negatively influences the precision of amplitude-phase retrieval.[2] It has been shown[3] that optically heterodyne-detected (OHD) FROG has a number of advantages over homodyne-based FROG schemes.

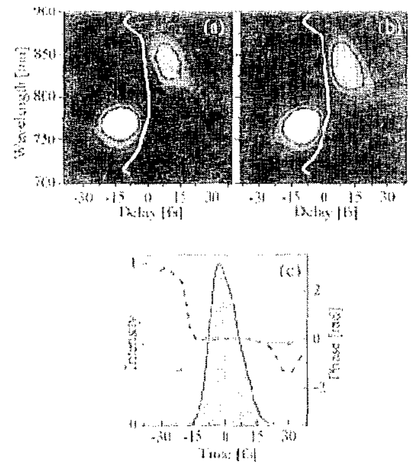
In this contribution we introduce a new member of the FROG family: frequency-resolved pump-probe (FRPP). Unlike OHD FROG,[3] which requires additional polarizers, FRPP employs unmodified pump-probe geometry widely used in ultrafast spectroscopic experiments. Furthermore, a FRPP trace carries both positive and negative values, which should substantially improve the noise stability of the retrieval procedure. Additionally, for the vast majority of experiments in the liquid phase, which involve the use of transparent solvents with fast electronic response, FRPP pulse characterization can be conducted on bare solvent prior to introducing the sample molecules into it. Since not even a change of nonlinear medium is involved, one can be assured that the learned pulse parameters are retained in the spectroscopic measurements that follow. We demonstrate the application of the novel FRPP technique to characterization of 15-fs pulses generated by a Ti:sapphire oscillator.

The schematic of the FRPP arrangement is presented in Fig. 1. Two replicas of the input pulse, delayed by the time τ, are crossed in medium with instantaneous 3rd-order nonlinearity. Behind the medium, one of the beams is detected by an OMA that registers the FRPP signal related to both pulses (e.g., employing a lock-in or synchronous detection).[4]

$$S_{FRPP}(\Omega, \tau) = \mathrm{Im}\lfloor E^*(\Omega)\, E_s(\Omega, \tau)\rfloor \quad (1)$$



CFE4 **Fig. 2.** Examples of FRPP traces: spectrum-limited pulse (a), quadratic positive (b) and negative (c); cubic negative (d); quartic negative (e) spectral phases and self-phase modulation case (f). White curves, drawn along the respective group delays, demonstrate the intuitiveness of HD FROG technique. The amplitude of the traces changes from negative (white color) to positive (black color) values.



CFE4 **Fig. 3.** Experimental (a) and reconstructed (b) FRPP traces for a pulse the intensity and phase of which are shown in (c). The gray scale in (a), (b) is identical to that in Fig. 2. White line marks the recovered group delay.

where $E(\Omega)$ denotes the pulse spectrum, and the signal generated due to nonlinear interaction, is given by

$$E_s(\Omega, \tau) = i \int |E(t+\tau)|^2 E(t) e^{i\Omega t} dt \quad (2)$$

Figure 2 presents several examples of FRPP traces of different pulses. As it is usually the case for the $\chi^{(3)}$-based techniques, the traces in general are not symmetric around $\tau = 0$ and therefore the direction of time flow is unambiguously determined. Furthermore, the FRPP traces are highly intuitive: a curve drawn along crests and valleys follows the group delay (white curves in Fig. 2). In particular, the trace corresponding to a spectral-limited pulse, consists of four distinct quadrants with well-defined boundaries (Fig. 2a). Vice versa, the latter can serve as a sensitive indication of high compression quality.

The essential feature of the FROG technique is the ability to check experimental data via the so-called marginals. FRPP is no exception in this respect. The peculiarity of FRPP lies in the fact that both temporal and spectral marginals are equal to zero. The time marginal indicates whether spectral filtering has occurred in recording the FRPP trace, while the frequency marginal is an extremely sensitive tool to verify the instantaneous nature of the nonlinearity.

Figure 3 shows the experimental and reconstructed FRPP traces obtained from a 100-μm water sample. The temporal intensity and phase of ~15-fs pulses used in the experiments are given in Fig. 3c. Since the overall water response is extremely fast and dominated by electronic hyper-polarizability,[5] it is well justified to treat the nonlinearity as instantaneous. As can be judged from Fig. 3, the reconstructed FRPP trace reproduces fairly well the essential features of the experimental pattern.

*Southwest Sciences, Inc., USA; E-mail: djkane@swsciences.com

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CFE5 **9:00 am**

Carrier-phase measurement of sub-harmonic optical pulses

Y. Kobayashi, K. Torizuka, *Electrotechnical Lab., 1-1-4 Umezono, Tsukuba, 305-8568 Japan; E-mail: yohei@etl.go.jp*

Recently, it has made possible to obtain pulse width within two-optical-cycles using Ti: sapphire lasers. In this region, a carrier phase is important for the phase sensitivity of nonlinear-optical interaction.[1] A sub-femtosecond pulse train generation by a Fourier synthesis of subharmonics has been proposed.[2] In this case, carrier phase shift between different wavelengths has to be controlled when the pulsed lights are superposed.

In this report, we have developed sub-harmonic generator by using the femtosecond OPO and observed phase relation between three pulses. Wavelengths of the pump, signal and the idler are 850 nm (3ω), 1275 nm (2ω) and 2550 nm (ω), respectively by using $KTiOPO_4$ (KTP) with $\theta = 71.5$-deg. phase-matching angle. Two pulses, second harmonic of the signal and sum-frequency between the pump and the idler, are generated from the KTP at the same time with same wavelength (4ω: 638 nm) and their phases are transferred from the signal and the idler, respectively. Then the phase relationship between the pump, signal and the idler can be observed by measuring the beat signal of these two pulses without extra frequency conversion.

Experimental setup is shown in Fig. 1. The pump is a 1.2 W, 50-fs, Ti:sapphire laser in a 72-MHz train. The OPO cavity is linear, group-velocity-dispersion compensated by two-chirped mirrors. The OPO produces as much as 80 mW of power in the signal with the pulse duration of about 40 fs, and produces 70 mW of power in the idler branch. Two red lights (4ω) are collimated by a lens and are taken apart from the pump or the idler by a prism and detected by a photo-multiplier (PM) and analyzed by a spectrum analyzer.

Figure 2 (a) shows the beat signal of the red lights changing the OPO cavity lengths. The stable peaks around 72 MHz represent the repetition rate (F). The measured beat frequency (f) varies in accordance with f = −Δl/λs × F,