CWF16 Fig. 1. Spectral transmission of the birefringent filter (solid line) and the corresponding pulse outgoing spectrum after 20 round trips in the regenerative amplifier (mixed line).

CWF16 Fig. 2. Experimental 50 nm and 83 nm FWHM spectra from our regenerative amplifier with a 474 μm thick birefringent plate.

have successfully used this method to amplify femtosecond pulses up to an energy of 1 millijoule. Depending on the adjustment of the filter one can obtain for example, 83 nm square spectra or 50 nm gaussian spectra. Experimentally, one can switch from one spectrum to the other by spinning the birefringent plate around the axis of rotation of its mount. Basically we can tune the laser spectrum shape from a set up where the birefringent filter has no effect on the pulses (axis of the plate parallel to the laser direction of polarization) to a set up that maximizes the phenomenon. The depth of modulation can be adjusted in real time to accommodate for changes in the amplifier small signal gain. Due to its bulk nature, this filter is very stable: once set up the system does not need realignment for days or weeks and it is not sensitive to temperature/air fluctuations.

Extension toward even broader bandwidth and optimization of the spectrum shape for optimum recompression will be discussed at the conference.

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CWF17

Fourier synthesis of 9.6-GHz optical pulse trains with ultralow timing-jitter fluctuation

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Fourier synthesized optical pulse trains whose repetition rate and pulse width are readily controllable are desirable for various applications such as time-resolved measurements and optical communications. Optical pulse syntheses using independent cw lasers have been demonstrated based on a nonlinear phase-locking scheme.¹ Although there is no fundamental limitation on a wider frequency separation or on the laser material, the low conversion efficiency of the nonlinear process for cw lasers and the difficulty in stable operation of homodyne optical phase-locked loop (OPLL) are the problems commonly encountered under this scheme.

Since a very high conversion efficiency of four wave mixing (FWM) in a semiconductor optical amplifier (SOA) has been reported,² it is more convenient to use $\chi^{(3)}$ than $\chi^{(2)}$ in the 1.5- μm range. Also, the FM sideband heterodyne technique had been proven to ensure the stable operation of homodyne OPLL.³ In this report, we demonstrate the synthesis of optical pulse trains based on the nonlinear phase-locking scheme using SOA and the FM sideband heterodyne technique.

Figure 1 shows the experimental setup. We used three independent cw semiconductor la-

CWF17 Fig. 1. Experimental setup for Fourier synthesis.

CWF17 Fig. 2. Temporal waveform of the synthesized pulse train.

sers (L1, L2, and L3) which had grating-extended external-cavities and operated near 1.53 μm . The temporal spectral linewidths of the lasers were less than 100 kHz, while acoustic vibration broadened them to several hundreds of kHz. The outputs from L2 and L3 were introduced into the SOA in order to generate FWM signal. The anti-Stokes component and the output from L1, which was previously phase-modulated, generated beat signal on the photodetector PD1. The output from PD1 was demodulated and fed back to L2 to construct stable homodyne OPLL. The rms phase fluctuation during phase locking was estimated to be 70 mrad. For the synthesis of pulse trains, the outputs from the lasers were directly introduced to the fast photodetector PD2.

Figure 2 shows the temporal waveforms of the synthesized pulse trains. The solid line represents the observed waveform and the dotted line represents the calculated one. As shown in the figure, they are in good agreement. The background originates from the nonuniform frequency response of PD2. The repetition rate was 9.6 GHz, which was limited by the measuring instruments. The timing jitter fluctuation of the pulse train was estimated to be 2.3 fs using the theory⁴ derived for passively mode-locked lasers. The value is one or two orders of magnitude smaller than those of ordinary, passively mode-locked semiconductor lasers. We believe this small timing jitter fluctuation is due to the nature of Fourier synthesis, in which the fluctuation is connected to the linewidth of the individual lasers and is extraneous to the fluctuations related to the mode-locking process.

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CWF18

The effects of chirp on the spectrally resolved two-beam coupling technique

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Characterization of third-order optical nonlinearity ($\chi^{(3)}$) is essential in applications like optical switching and optical communication, etc. The existing methods, however, suffer from either the complexity of the experimental setup (such as four-wave mixing) or the low sensitivity (Z-scan). Recently, with femtosecond laser pulses, Wise *et al.* have demonstrated a simple method to determine refractive, absorptive and Raman-induced $\chi^{(3)}$, based on the spectrally-resolved two-beam coupling (SRTBC) method.¹ The usage of their simple model is, however, limited to transform-limited laser pulses. In this report, we extend the SRTBC method to chirped pulses.

For the electronic and Raman contribution in $\chi^{(3)}$, the total nonlinear response induced by the pump pulse can be described as

$$S(t) = S_E(t) + S_R(t) \\ = \int_0^\infty (n_2^I - i\beta)\delta(t')I_{pu}(t' - t)dt' \\ + \int_0^\infty [R' \sin(\Omega t') \\ + iR'' \cos(\Omega t')]e^{-t'/T_R}I_{pu}(t' - t)dt', \quad (1)$$

where n_2^I is the intensity nonlinear refractive index, β is the two-photon absorption coefficient, R' and R'' are the Raman coefficients, Ω is the Raman frequency, and T_R is the dephasing time of the Raman transition. To extend the SRTBC method to linearly chirped Gaussian pulses, $E_{pu}(t) = E_{pu}^0 \exp(-t^2/\tau^2 + i\omega_0 t + i\beta t^2)$, we have derived a formula for the transient transmittance of the probe beam at a certain detection wavelength ($\lambda_D = 2\pi c/\omega$):

$$\frac{\Delta T}{T}(\Delta t, \delta) = \frac{\Delta T}{T}(\Delta t, \delta)_E + \frac{\Delta T}{T}(\Delta t, \delta)_R, \quad (2)$$

where

$$\frac{\Delta T}{T}(\Delta t, \delta)_E = 2 \left[\frac{(3 + b^2\tau^4)^2 + 4b^2\tau^4}{(9 + b^2\tau^4)^2} \right]^{1/4} \\ \exp(f_E) \exp \left[-\frac{(\Delta t - T_i)^2}{\Gamma^2} \right] \\ \times (2\Delta\Phi_E \sin \Theta_E - q_E \cos \Theta_E) \quad (3)$$

and

$$\frac{\Delta T}{T}(\Delta t, \delta)_R = -\frac{1}{2} \exp(f_R) \exp \left(-\frac{\Delta t}{T_R} \right) \\ \times [(2\Delta\Phi_R + q_R) \exp(g_R) \cos \Theta_R^- - (2\Delta\Phi_R - q_R) \exp(-g_R) \cos \Theta_R^+]. \quad (4)$$

$\delta = \omega - \omega_0$, Δt is the pump-probe time delay, $\Delta\Phi_E = \omega_0 n_2^I I_{pu} L / c$, $q_E = \beta I_{pu}^0 L$, $\Delta\Phi_R = \omega_0 R' I_{pu}^0 L / c$, $q_R = R'' I_{pu}^0 L$, I_{pu}^0 is the peak pump intensity, and L is the interaction length. The associated functions are given by

$$T_i = \frac{\delta b \tau^4}{2(3 + b^2\tau^4)}, \quad \Gamma = \tau \sqrt{\frac{9 + b^2\tau^4}{2(3 + b^2\tau^4)}},$$

$$f_E = \frac{\delta^2 \tau^2}{2(1 + b^2\tau^4)(3 + b^2\tau^4)},$$

$$\Theta_E = \frac{4b}{9 + b^2\tau^4} \left(\Delta t + \frac{3\delta}{4b} \right)^2 - \frac{\delta^2}{4b(1 + b^2\tau^4)} \\ - \frac{1}{2} \tan^{-1} \left(\frac{2b\tau^2}{3 + b^2\tau^4} \right),$$

$$f_R = -\frac{3 + b^2\tau^4}{8(1 + b^2\tau^4)} \Omega^2 \tau^2,$$

$$g_R = \frac{\Omega \delta \tau^2}{2(1 + b^2\tau^4)},$$

CWF18 Fig. 1. (a) The experimental $\Delta T/T$ on fused silica. The solid curve: the linear-chirp fit; the dashed curve: the chirp-free fit. (b) The simulated $\Delta T/T$. The solid curve: the linear-chirp fit.

CWF18 Fig. 2. The simulated $(\Delta T/T)_R$. $\Omega = 419 \text{ cm}^{-1}$, $\tau = 24 \text{ fs}$, $\delta = 9.79 \times 10^{13} \text{ sec}^{-1}$, $R'' = 0$, $T_R = 6 \text{ ps}$. —, $b = 0$; —, $b = 1 \times 10^{27} \text{ sec}^{-2}$; - - -, $b = 1.73 \times 10^{27} \text{ sec}^{-2}$; ···, $b = 3.39 \times 10^{27} \text{ sec}^{-2}$. The arrows indicate the phase relation between these curves.

$$\Theta_R^- = \Omega \Delta t - \frac{b\tau^4}{4(1 + b^2\tau^4)} (\Omega^2 - 2\delta\Omega) \text{ and}$$

$$\Theta_R^+ = \Omega \Delta t + \frac{b\tau^4}{4(1 + b^2\tau^4)} (\Omega^2 + 2\delta\Omega).$$

A 100 fs mode-locked Ti:sapphire laser was used to perform the SRTBC measurements. Figure 1(a) shows the experimental result of fused silica at $\lambda_D = 806.5 \text{ nm}$. Notice that the fitting with the linear-chirp model is much better than that with the chirp-free model. Using the phase obtained from FROG, we calculated the transient based on the two-beam coupling equation [Fig. 1(b)]. The simulation and experimental results are almost identical. We also applied this method to semiconductor-doped glass (RG610), where two-photon absorption also contributes to the signal. The extracted β is comparable to the published

value. Similarly, the same approach was applied to OG550, resulting in $\beta = 6.4 \times 10^{-13} \text{ m/W}$. This is the first optical nonlinearity measurement on this material.

Figure 2 shows the simulated $(\Delta T/T)_R$ by a non-zero R' using Gaussian pulses with different linear chirp values. The phase shift in the modulation feature, the peak amplitude in $(\Delta T/T)_R$ and, therefore, the extraction of R' and R'' are strongly affected by the linear chirp. Finally, due to the sensitivity of the SRTBC method to the chirp, it can potentially serve as a chirp-monitoring system and is much simpler than FROG in calculation and setup.

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CWF19

Generation of optical sub-cycle pulses and full Maxwell-Bloch solitary waves by coherent propagation effects

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Recent advances in ultrafast laser technology have made possible the generation of extremely short and intense pulses with only two optical periods or less than 5 fs in duration in the visible region.¹ Efforts for generation of still shorter pulses is motivated by the possibility to study light-matter interactions under unique conditions as the pulse duration approaches the duration of a single optical cycle. In the present talk we study the propagation of a 5-fs pulse through a layer of a dense medium of two-level systems. As a result we demonstrate the formation of single-cycle and half-cycle pulses in the sub-fs region and novel types of spectral changes during propagation as large blue and red shifts in the transmitted and reflected pulses, respectively, explained by intra-pulse frequency-difference mixing. Solitary pulse propagation phenomena beyond the limits of slowly-varying envelope (SVEA) and rotating-wave approximation (RWA) are illustrated as the formation of full Maxwell-Bloch half-cycle solitons and two-soliton pulses.

We solved the initial problem of the full Maxwell-Bloch equations without SVEA and RWA for different input pulse parameters and medium densities. In general, for an input envelope area $A < \pi$ and the considered medium densities the main part of the pulses is reflected, but with increasing area splitting of the penetrating part accompanied by shortening occurs, in qualitative agreement with results within the SVEA and RWA. However, in detail the pulse evolution dramatically changes for input pulses with a duration of 5 to 10 fs in comparison with standard results and novel transient features arise. In Fig. 1 the reflected, penetrating and transmitted pulses are shown for different medium densities and fixed input peak field strength $E_0 = 1.8 \times 10^9 \text{ V/m}$ corre-