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Single optical cycle laser pulse in the visible and near-infrared spectral range

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Abstract. Since the inception of the laser, pulse duration has been continuously decreased by the use of a variety of techniques: Q-switching, mode-locking, and pulse compression. We would like to present a new technique based on the addition of laser sub-harmonic, ALS, that allows the production of a single-cycle pulse with single-femtosecond pulse duration. This simple technique takes advantage of the recent progress made in the generation of a few optical cycles and in optical parametric amplification.

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Combining femtosecond pulses is a promising way to generate monocycle pulses. By either interferometrically combining spectra [1], or by a nonlinear induced phase modulation pulse combination [2], engineering of monocycle pulses is theoretically possible.

We are presenting the results of a theoretical study on the generation of single-cycle pulses of single-femtosecond duration based on addition of laser sub-harmonics, ALS. We show that, by using as few as six sub-harmonics produced in three optical parametric amplifiers and the fundamental pulse, single-cycle pulses with good contrast could be obtained. The requirements are that the initial pulse duration of the fundamental must be of the order of the period of the sub-harmonics and that the sub-harmonic number is sufficient to generate a single-cycle pulse. The generation of each sub-harmonic is done by an optical parametric amplifier pumped by the fundamental. All the sub-harmonics are recombined by means of a diffraction grating. This technique has the advantage of being general, efficient, and able to be extended to high energy and ultrahigh intensity.

1 Principle and numerical simulation

Laser pulse duration is linked to the bandwidth the laser can amplify. To generate a 10-fs pulse with a Gaussian spectrum, one needs a bandwidth of $\Delta\nu_0 = 45\,\mathrm{THz}$ or $\Delta\lambda_0 = 94\,\mathrm{nm}$ with $\lambda_0 = 800\,\mathrm{nm}$. Generating a single-cycle pulse with a Gaussian spectrum centered around 800 nm implies a spectrum bandwidth of about 440 THz. No laser system can deliver such a broad band.

An alternative way is to use several phase-locked pulses. By coherently adding spectra from different pulses, we can design a spectrum to generate a single-cycle pulse [1].

Periodically spaced spectra allow one to Fourier synthesize periodically spaced temporal single-cycle pulses. The closest analogy is the Pérot–Fabry relationship between spectrum and temporal propagation of light in the cavity. We propose to add pulses out of laser sub-harmonics (ALS). We then take advantage of the periodically spaced spectrum to generate a short temporal shape.

Equation (1) corresponds to the generated spectrum $\tilde{E}(\omega)$, with $\omega = 2\pi\nu$:

$$\tilde{E}(\omega) \propto \delta(\omega-\omega_0) \otimes \exp\left(-\frac{\Delta t^2\omega^2}{4}\right) \otimes \sum_{n=0}^{N} \delta\left(\omega - n\frac{\omega_0}{M}\right) , \tag{1}$$

with ω_0 the central frequency of the laser pulse, Δt the pulses' duration, M the sub-harmonic number and N the amount of pulses added. The two first terms of (1) correspond to a Gaussian pulse. The last term will give a new shape to the pulse. The associated temporal pulse shape, $E(t)$, is given by:

$$E(t) \propto \cos(\omega_{\mathrm{ave}}t) \exp\left(-\frac{t^2}{\Delta t^2}\right) \frac{\sin\left(\frac{(N+1)\omega_M t}{2}\right)}{\sin\left(\frac{\omega_M t}{2}\right)} , \tag{2}$$

with $\omega_M = \omega_0/M$ and $\omega_{\mathrm{ave}} = (1 - N/2M)\omega_0$.

The third term of (2) gives the new monocycle shape of the pulse. With as few as 6 sub-harmonics, the contrast between the pulse and the background is better than 1% and each pulse corresponds to a single-cycle pulse at the frequency of the fundamental laser pulse. The interval ω_0/M between each spectrum in (1), is determined by the choice of the sub-harmonics used. It has to be compared with $\Delta\omega_0$, the spectral bandwidth of the separated pulses. If $\Delta\omega_0 > \omega_0/M$ or $\Delta t_0 < M/\omega_0$, only one single-cycle pulse is generated.

To illustrate the advantage of adding laser sub-harmonics, we simulate the generation of single-cycle pulses in the visible and near-infrared ranges. In both examples, the laser used

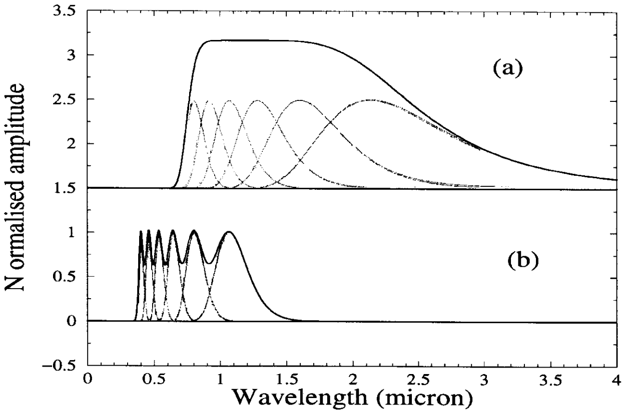

Fig. 1. Pulse spectra composing the overall calculated spectrum for an 800-nm (a) and a 400-nm (b) ALS system

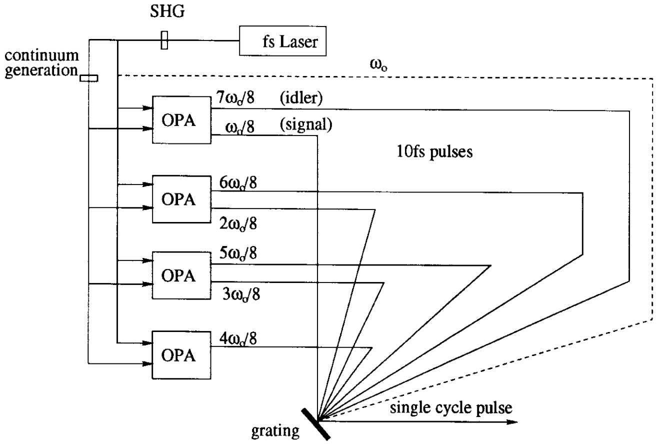

Fig. 3. Proposed experimental setup

is the Ti:sapphire laser with $\lambda_0 = 800$ nm or its first harmonic at $\lambda_0 = 400$ nm. Figure 1 displays the spectrum generated using (1) for the 800-nm and 400-nm ALS setup. In both cases, the sub-harmonic interval $\omega_0/M = \omega_0/8$, and there are just six pulses generated with bandwidth corresponding to 10-fs Gaussian pulses. Both examples can be experimentally generated using optical parametric amplifiers. The calculated pulses out of Fig. 1 spectra are both single cycle (Fig.2). It shows that it is possible to generate a single-cycle pulse in the visible or the near infrared with this ALS technique. The 400-nm ALS pulse on Fig.2 has some remaining lateral pulses. Those low-amplitude pulses are due to a compromising setup. For the feasibility of the system, we choose to generate all the different pulses with 400-nm pumped OPAs. This condition limits the wavelength range available. To get a minimum of six sub-harmonics, we then choose a $\omega_0/8$ interval between them. Unfortunately, this interval gives $\Delta\omega_0 \approx \omega_0/8$ with 10-fs pulses instead of $\Delta\omega_0 > \omega_0/8$.

2 Proposed experimental setup

To generate the periodically spaced pulses, we propose to use optical parametric amplification, which allows the generation of frequency-tunable signal and idler. Pulse duration for signal and idler can be shorter than the pump pulse duration using non-collinear OPAs [3]. This condition allows one to generate ∼ 10-fs pulses adjustable to the sub-harmonic frequencies using a wide range of Ti:sapphire laser pulse durations and energies. This technique allows the ALS generation of intense single-cycle pulses using a high-energy amplified 50-fs laser system. To keep coherence between pulses, each OPA is seeded with a threshold-generated continuum pulse. Using continuum allows one to avoid the loss of coherence due to parametric amplification seeded by noise. As shown in Fig. 3, seven pulses are taken from the signal and idler of four OPAs. It is also possible to add the main laser pulse to the system, if its duration matches the OPA durations.

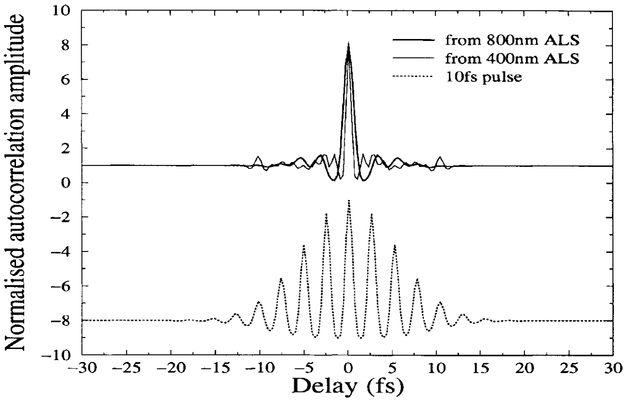

Fig. 2. Calculated interferometric autocorrelation of ALS pulses generated out of 800-nm and 400-nm lasers compared to a 10-fs, 800-nm input pulse

All pulses are collimated together using a grating. We propose to compensate the sub-harmonics angular dispersion on the grating by a zero-dispersion line setup for each sub-harmonic. The sub-harmonics are separately dispersed using gratings that match the recombination grating. Those grating are then imaged on the recombination grating that then put the sub-harmonics all together and also is part of each zero-dispersion line, refer to [3] and references therein.

This system is interferometric, meaning that all seven or eight arms are to be phase locked. To realize that it is sufficient to add a phase-locking electronic system on each arm of the system, refer to [1]. Comparing this technique with the generation of ultrashort pulses using harmonics [1] or high-order harmonics [4], it is easier to keep the coherence between sub-harmonics out of OPAs. Measuring the duration of the pulse is as complicated as generating it. Experimental problems will arise from the phase-matching bandwidth of nonlinear crystals used with autocorrelation techniques and from the dispersion induced by any material on the pulse. But instruments such as SHG FROG can be adapted to measure extremely short pulses [5].

3 Conclusion

We have presented a simple technique to generate single optical cycles in the visible and near infrared by adding laser sub-harmonics. Due to the recent progress with femtosecond OPAs, we propose to use non-collinear optical parametric amplifiers to generate phase-locked 10-fs laser sub-harmonics. This technique can be applied to generate intense single-cycle pulses.

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