Measuring several-cycle 1.5-μm pulses using frequency-resolved optical gating

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Abstract: We demonstrate frequency-resolved optical gating (FROG) for measuring the full intensity and phase of several-optical-cycle 1.5-μm pulses generated from a Kerr-lens mode-locked (KLM) Cr^{4+}:YAG laser. This involves the use of an angle-dithered second-harmonic-generation crystal to achieve the full pulse bandwidth despite the use of a relatively thick nonlinear crystal.

OCIS codes: (320.7080) Ultrafast devices, (320.7100) Ultrafast measurements, (320.7090) Ultrafast lasers

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1. Introduction

Extremely broadband several-optical-cycle pulses near telecommunication wavelengths (~1.5 µm), are in high demand for telecommunications, optical coherence tomography and numerous other applications. Recently, a number of publications have considered the possibility of several-cycle-pulse generation [1-4]. The techniques included Kerr-Lens-mode-locking (KLM) [1,2], as well as SESAM-based mode-locking [3,4]. Both prismless [1,3] and direct diode-pumping [4] have been implemented. Direct diode-pumping opens the way for broad usage of affordable compact low-power oscillators.

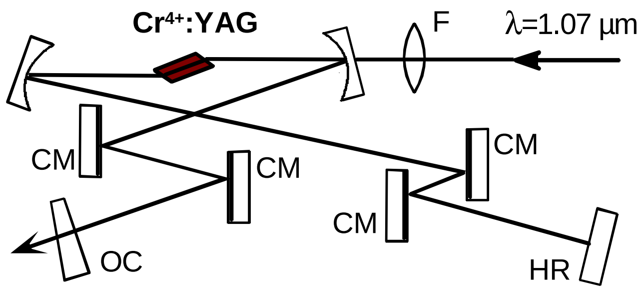

Fig. 1. The Cr^{4+}:YAG laser setup. The mode-locking is achieved by a KLM mechanism with a prismless dispersion compensation. CM: chirped mirrors.

Reliably generating near-infrared pulses requires reliable, accurate, and robust measurement techniques. While it is possible to build an autocorrelator with a proper choice of crystal, especially for shorter pulses, it yields only rough pulse-length information and no pulse phase information. And at such short pulse lengths, spectral and temporal phase information becomes vital [5]. While another method proposed for IR pulse measurements—free-space electro-optic sampling [6]—could provide this information, this method requires a shorter probe pulse, and it also has group velocity mismatch issues.

With the most commonly used intensity-and-phase ultrashort-pulse-measurement method, frequency-resolved optical gating, (FROG) [7], it is now possible to measure pulses on a single shot [5]; over a wide range of wavelengths [5], pulse lengths [8,9], and complexities [10]; and to do so in a manner that is general, robust, accurate, and rigorous. FROG also routinely allows convenient real-time monitoring of ultrashort-pulse intensity and phase. However, FROG has never been tried for such short IR pulses and also with low input power. Thus, in this paper, we engineer a FROG device for this purpose and which combines several recent innovations.

2. 1.55-micron pulse measurements

All pulse-measurement techniques require the use of a nonlinear-optical process, whose phase-matching bandwidth is inversely proportional to the crystal thickness. For very short pulses, very thin second-harmonic-generation (SHG) crystals are usually required. However, we have recently shown that *angle-dithering* a SHG crystal that is otherwise too narrowband

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(that is, too thick) yields a significantly increased effective phase-matching bandwidth in FROG measurements for a given crystal thickness [11]. This is possible because the device phase-matching bandwidth need only exceed that of the pulse over the course of the measurement and not necessarily on every pulse. Because the SHG efficiency scales as the square of the crystal thickness, angle-dithering also yields significantly greater signal strength. This is very important since the nonlinearity of most crystals decreases significantly at IR, where the use of a thicker crystal can compensate for the relatively low nonlinearity. Indeed, this approach works so well that we are able to use a line focus, rather than a point focus, and still achieve sufficient intensity to measure the train of pulses.

While angle-dithering avoids the phase-matching requirement, or equivalently the group-velocity mismatch (GVM) requirement, the SHG crystal cannot, however, be arbitrarily thick in these measurements. The crystal must still have negligible group-velocity dispersion (GVD) to avoid distorting the pulse. This issue is rarely mentioned in pulse-measurement problems because it is automatically satisfied when GVM is made negligible. It becomes an issue when angle-dithering is used due to the removal of the GVM constraint and the relatively thick crystal (here ~1 mm). And it is an issue here, even at the low-dispersion wavelength of 1.5 μm, due to the shortness of the pulse and the resulting large breadth of the spectrum. Fortunately, we find that 1-mm $LiNbO_3$ and $LiIO_3$ crystals yield negligible GVD for pulses as short as a several optical cycles (Fig.2). The rest of our setup is also designed to minimize material dispersion.

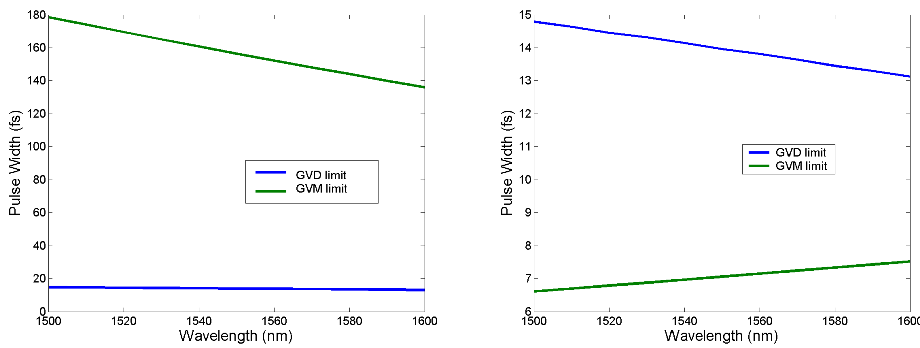

Fig.2. The theoretical shortest pulses satisfying the limits imposed by GVD and GVM, for a 1-mm-thick $LiNbO_3$ crystal for an undithered crystal (left) and for a dithered crystal with a 10^o scan range (right). Note that angle dithering relaxes phase-matching-bandwidth constraint, leaving the GVD constraint unchanged.

Recall that all FROG devices involve splitting the beam into two identical beamlets, which must then overlap in space and time in a nonlinear crystal whose SHG signal is then spectrally resolved vs. relative beamlet delay. Our setup also exploits the simplicity of single-shot FROG [5]. As single-shot FROG maps delay onto transverse position, two beamlets must overlap in time and in space at a line focus, rather than a point focus. We used a reflective telescope to first expand the beam for larger delay range. We also used a Fresnel biprism for beam splitting and crossing, which was first introduced in the GRENOUILLE [12] technique. The Fresnel biprism eliminates the beam splitter and beam-recombining optics and automatically ensures the temporal and spatial overlap between the two beamlets. To obtain the line focus on the nonlinear crystal, we used a cylindrical mirror. The SHG crystal is mounted on a resonant scanner for angle dithering. The nonlinear signal is then mapped onto the slit of a spectrometer, with a CCD camera at its output plane. The whole setup has only one transmissive element, the relatively thin Fresnel biprism (only 1.3 mm of fused silica), before the nonlinear crystal (dispersion after the crystal is irrelevant).

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An additional advantage of this setup is that, since it maps delay onto position, like all other single-shot FROG devices, it also measures spatial chirp [13]. And since it uses a Fresnel biprism to do so, it also measures pulse-front tilt [14].

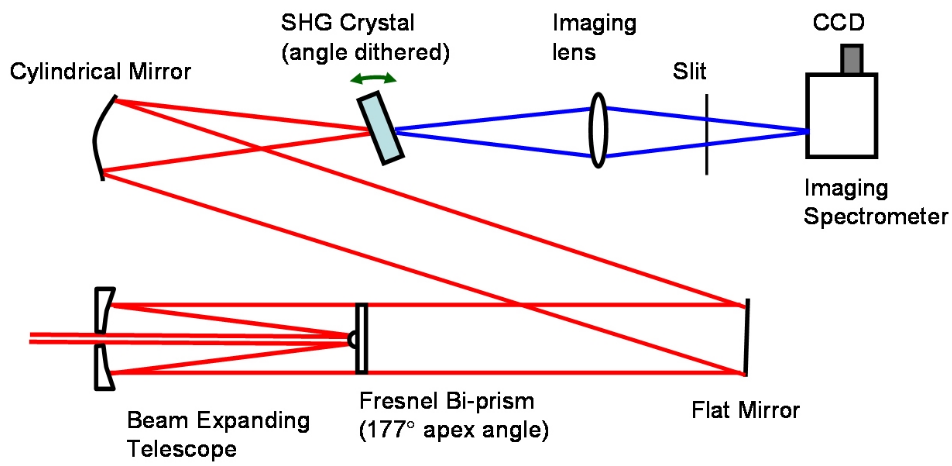

Fig. 3. Angle-dithered SHG FROG geometry. Note that this setup employs all reflective optics except for the Fresnel biprism (1.3 mm of fused silica) before the nonlinear crystal, minimizing the material dispersion. This diagram shows a Cassegrain telescope for beam expansion; but we have also used a simple slightly off-axis reflective telescope (without the hole).

3. Experiment

We used a KLM Cr^{4+}:YAG laser (Fig. 1) yielding pulses with approximately 110 nm of bandwidth near 1.55 μm [3], producing pulses with 50 mW of average power at a 100 MHz repetition rate. We also used chirped mirrors in the cavity for dispersion compensation, suppressing the third-order dispersion [3]. The output pulses were measured with the angle-dithered SHG FROG (Fig. 3). In our FROG setup, we used a 1-mm $LiIO_3$ crystal, mounted on an EOPC SC40 type scanner, oscillating at 30 Hz with an amplitude of about 10°. The pulses were split and combined using a 177^0 apex angle Fresnel biprism, which ensured both spatial and temporal overlap, without any additional alignment. A 10-mm cylindrical mirror was used to obtain a line focus along the delay axis, as per the usual single-shot FROG geometry [5]. Here, “single-shot” refers to the mapping of delay onto position by crossing at a line focus, allowing the potential measurement of a single pulse. However, our measurement here is “multi-shot” in the sense that it is not of a single pulse, but averaged over a number of identical pulses. The resulting SHG signal was imaged onto the slit of Acton SpectraPro150 spectrometer. The spectrometer output was recorded by a Sony XC-ES50 CCD camera and Spiricon SP-LTA video capture card, and the intensity and phase retrieved from the resulting FROG traces using the Femtosoft SHG FROG code.

The total group-delay dispersion of our device was only 1.6 as/nm, so that a 37-fs 1.55-μm flat-phase Gaussian pulse would increase to 37.2 by the time it reached the center of the crystal. And, although the crystal phase-matching bandwidth was 39 nm, the range of phase-matched wavelengths was 500 nm with the crystal angle-dithering.

Figure 4 shows the measured and retrieved FROG traces, as well as the retrieved and independently measured spectra, all of which are in very good agreement with each other. The measured pulses are 37.1 fs long (FWHM) and have nearly Gaussian intensity envelope with only a few tenths of a radian of phase distortion. Our measurements thus show that the chirped mirrors sufficiently compensate for the cubic phase and do not introduce significant higher-order phase distortions into the pulse.

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Also, our measurements reveal a minimum of spatial chirp in the pulses (spatial chirp is revealed by a shear in the otherwise symmetrical trace, and no evidence of shear is present). Specifically, we can place an upper bound of 0.42 µm/nm for the pulse spatial chirp. Pulse-front tilt can also be measured using our set-up (it is indicated by a displacement of the trace along the delay axis). At the time of the measurement, however, the device was not calibrated for pulse-front tilt (the zero-delay position was not recorded), so a numerical evaluation of pulse-front tilt could not be made.

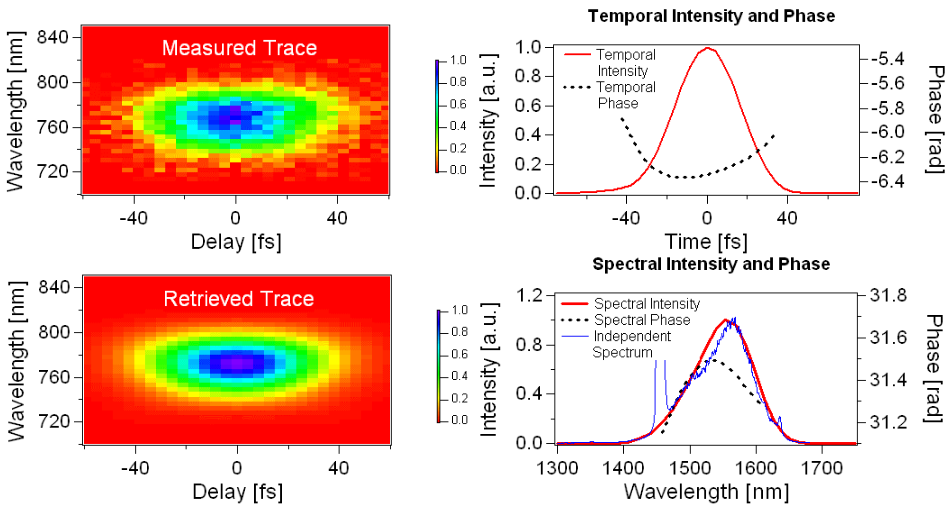

Fig. 4. FROG measurements of full intensity and phase of Cr4+:YAG laser. The retrieved pulse width is 37.1 fs (FWHM). The spike in the independently measured spectrum is the continuous-wave (CW) component oscillating in a higher transverse mode. FROG is designed not to see this spike due to its ultrafast gating and small range of delays.

We performed another set of measurements, this time with the laser slightly modified. Specifically, we used fused-silica prisms in the cavity for dispersion compensation, in combination with the chirped mirrors. In this case, the intracavity dispersion had a significant positive third-order component, due to the material dispersion of both YAG and fused silica. Then we measured the output pulses with our FROG. Figure 5 shows the measured and retrieved FROG traces, as well as retrieved and independently measured spectrum, again, all of which are in very good agreement with each other. The measured pulse width was about 25% longer, 46.6 fs (FWHM). However, unlike the chirped mirror case, these pulses had also visible third- and higher-order phase distortions. In addition, side-bands appear in the spectrum, as expected in systems with large higher-order dispersion [15]. These spectral spikes do not appear in the FROG measurement because they correspond to very slow and weak components and persist for much longer times than the delay range scanned.

These measurements also reveal a minimum of spatial chirp. Specifically, for this longer pulse, we can place an upper bound of 0.09 µm/nm for the pulse spatial chirp.

The above measurements were performed using a relatively powerful 50 mW of average power. In order to find the applicability of our FROG system for monitoring very low-power oscillators, we used neutral density filters to attenuate the beam. We were able to measure pulses as weak as 5 mW (average power), at the repetition rate of 100 MHz. If even lower-power operation is desired, the experimentally simple Fresnel biprism/cylindrical lens/line focus that we used could be replaced a more traditional (somewhat more complex) beam-splitter and spherical focus to increase the intensity at the SHG crystal. We estimate that this approach could measure a 100 MHz pulse train of several-cycle IR pulses of as little as a few tens of µW. Our estimations also show that our low-dispersion device could measure 1.55-µm pulses as short as 20 fs without introducing significant pulse distortion. This corresponds to a

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1.55-µm pulse only four cycles long. For shorter pulses, a thinner crystal and a “Fresnel bi-mirror” would further decrease the dispersion, allowing the accurate measurement of few-cycle pulses.

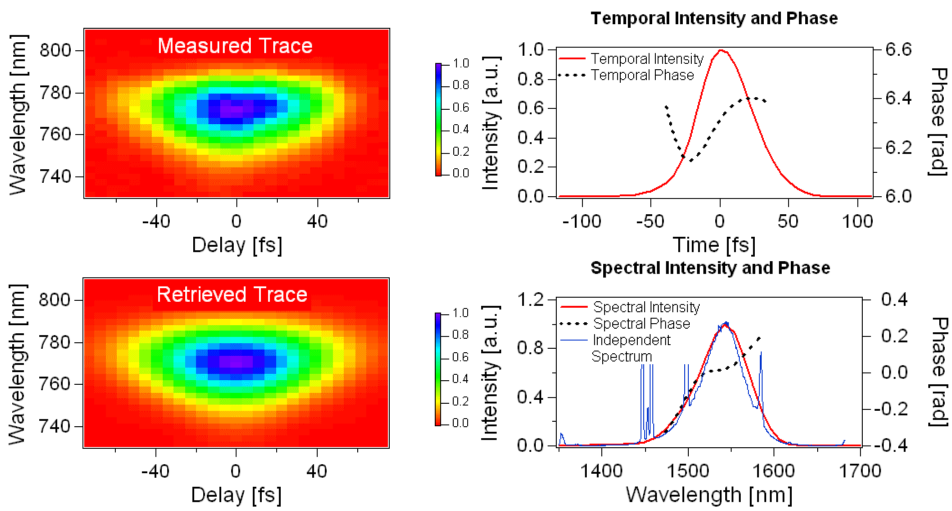

Fig. 5 FROG measurements of the intensity and phase of Cr4+:YAG laser output pulses. The retrieved pulse width is 46.6fs (FWHM). The narrow spikes in the independently measured spectrum are the cw component and sidebands originating from the higher-order dispersion inside the cavity.

4. Conclusions

We have measured the full intensity and phase of ~40-fs, 1.55-µm pulses from a Cr^{4+}:YAG laser using angle-dithered SHG FROG. Our measurements show that, by using a relatively thick crystal and angle dithering, FROG can be extended well into the infrared even for several-cycle pulse measurements, and can be used as a monitoring tool with very low-input power.

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