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Self-referenced optical frequency comb based on low-noise Yb:CALGO femtosecond laser system

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Summary. — We report on the design, realization and characterization of a compact optical-frequency-comb operating in the wavelength range from 670 to 1500 nm, based on a diode-pumped low-noise Yb:CALGO amplified ultrafast laser system. Both the carrier envelope offset and repetition rate frequencies are phase-locked to reference synthesizers providing a long-term fractional frequency stability of 7×10^{-13} at 100 s integration time.

1. – Introduction

Optical frequency combs, originally developed in 1999 for optical frequency metrology, have found a variety of applications over the past decade, ranging from fundamental physics to astronomy, from broadband spectroscopy to environmental and biological sciences as well as from quantum optics sensing to microscopy and hyper-spectral imaging [1]. For this reason, the development of compact and extremely high-performance comb sources is an ever-evolving topic. Among the different technological implementations [1], solid-state laser combs are still demonstrating excellent performance with high flexibility of comb repetition rate, power scalability, and compactness similar to that of the more common fiber combs [2-4].

In this paper, we report on a fully stabilized Yb:$CaGdAlO_4$ (Yb:CALGO) frequency comb operating in the wavelength spectral region from 670 to 1500 nm showing low-noise phase performance combined with power scalability up to watt level or even higher.

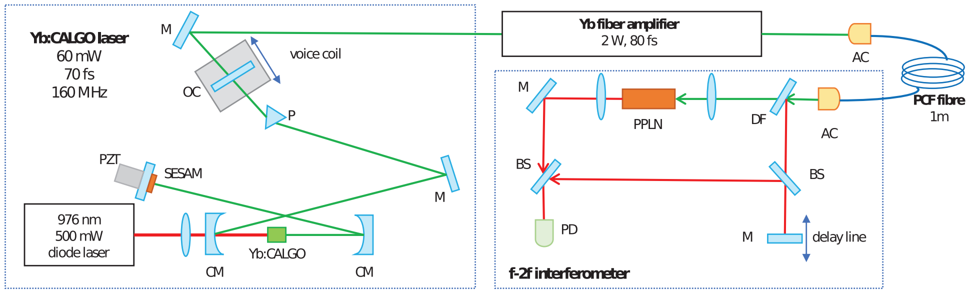

Fig. 1. – Yb:CALGO optical frequency comb setup. AC: aspheric collimator. BS: beam splitter. DF: dichroic filter. M: mirror. OC: output coupler. P: fused silica prism. PCF: photonics crystal fiber. Pd: fast photodetector. PPLN: periodically poled lithium niobate crystal. PZT: piezoelectric transducer.

2. – Yb:CALGO optical frequency comb

Figure 1 shows the scheme of the Yb:CALGO frequency comb constituted by a low-energy SESAM (semiconductor saturable absorption mirror) mode-locked Yb:CALGO oscillator, a Yb-doped fiber amplifier, a supercontinumm generation stage, and an f-to-$2f$ interferometer for the carrier envelope frequency detection. The SESAM mode-locked Yb:CALGO generates pulse trains at 1045 nm with a maximum average power of 60 mW, pulse duration of 70 fs, and a tunable repetition frequency in the range from 155 to 165 MHz. The 2 mm thick 5%-at Yb:CALGO crystal (a-cut) is pumped along the π-polarization by a single-transverse mode fiber diode laser (Lumics, SN0958003) delivering a maximum output power of 500 mW at a central wavelength of 976 nm. The laser resonator consists of a dichroic curved mirror with a radius of curvature (ROC) of 50 mm (highly transmitting at the pump wavelength and highly reflective at the lasing wavelength), a high-reflectivity (HR) 150 mm ROC curved mirror, a SESAM, an HR plane folding mirror, and an output coupler (OC) with 1.6% transmission. The SESAM is mounted on a piezoelectric transducer (PZT) driven by a high-voltage amplifier (HVA) for fine cavity length control (stabilization of the pulse repetition frequency). Intracavity group delay dispersion compensation is obtained by a single fused-silica prism configuration [5]. The OC is mounted on a voice coil linear stage with a large stroke of 20 mm, which turns out in a coarse tuning of both the pulse repetition and carrier envelope offset frequencies. The output of the mode-locked Yb:CALGO laser is coupled through an optical isolator to a low-noise Yb-doped fiber amplifier to increase the pulse peak power for efficient supercontinuum (SC) generation. The amplifier consists of 1.8 m long large mode area, polarization maintaining, Yb-doped fiber cladding pumped by two fiber-coupled diode lasers, each emitting 2.5 W at 976 nm in a 50 μm core diameter. At the active fiber output the amplified pulses are temporally compressed by using a pair of holographic transmission gratings (800 grooves/mm). The maximum average power at the compressor output is 1 W with a minimum pulse duration of $\sim$90 fs, corresponding to a maximum peak power of $\sim$70 kW. The amplified pulses are then coupled with a 50% efficiency into a 1 m long photonic crystal fiber (PCF) with a zero dispersion wavelength of 975 nm for SC spectrum generation (NKT-SC-3.7-975). Figure 2(a) shows the SC spectrum covering a full frequency octave from 650 nm to 1500 nm with an average output power of 160 mW.

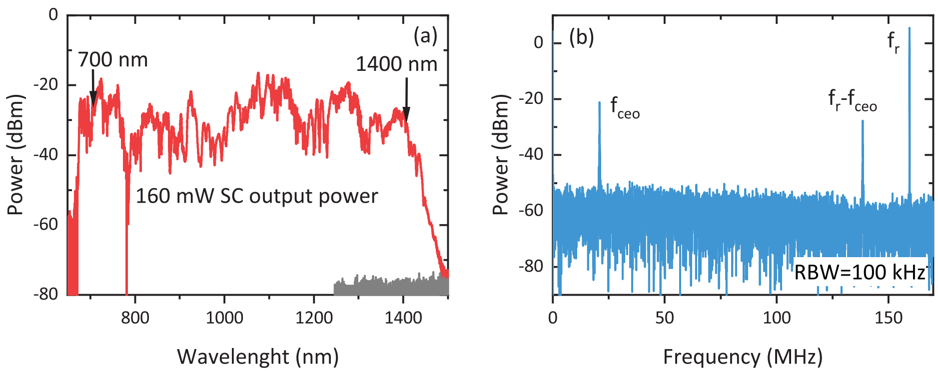

Fig. 2. – (a) Octave spanning SC spectrum at the output of the PCF recorded with a resolution bandwidth of 0.1 nm (the gray curve represents the instrument noise floor). (b) RF spectrum of the signal at the output of the f-to-$2f$ interferometer showing the beat note at the CEO frequency of $\sim$21 MHz with a SNR of higher than 30 dB in 100 kHz resolution bandwidth.

For the detection of the CEO frequency, the SC radiation is coupled into a f-to-$2f$ interferometer (see fig. 1) constituted by a low-pass dichroic filter transmitting wavelength longer than $\sim$1000 nm and reflecting a wavelength shorter than $\sim$1000 nm, a 10 mm long periodically poled lithium niobate crystal for quasi-phase matched second harmonic generation at 700 nm (15.1 μm poling period), and an adjustable delay line. The SC fundamental and SHG components at 700 nm are then combined using a beam splitter, filtered with a reflection grating, and detected by a fast Si-photodiode. Figure 2(b) shows the CEO beat note recorded at the output of the f-to-$2f$ interferometer with an SNR of $\sim$35 dB in a resolution bandwidth of 25 kHz. The sharpness of the CEO signal is a clear evidence of the low-noise properties of the Yb:CALGO fiber-amplified comb. Both CEO and repetition rate frequencies are then actively stabilized against RF synthesizers, referenced to a rubidium RF standard (fractional frequency accuracy of 10^{-12}), using two opto-electronics phase-locked-loop (PLL) schemes acting on the Yb:CALGO pump diode for CEO stabilization and on the Yb:CALGO cavity length for the stabilization of the repetition frequency. In particular, we measured the amplitude and phase (fig. 3(a)) of the transfer function of the CEO frequency with respect to the Yb:CALGO pump diode current, which is characterized by a -3 dB bandwidth of $\sim$1 kHz. This cutoff frequency arises from a first-order low-pass filter behavior originating from the effective upper-state lifetime and the photon lifetime of the mode-locked Yb:CALGO cavity, because the diode pump power can be modulated with up to 300 kHz without significant amplitude change.

Figure 3(b) reports the overlapping Allan deviation, $\sigma_y(\tau)$ where τ is the integration time, of the CEO (green triangles) and repetition rate (red triangles) frequencies, respectively, in full-locking conditions. The contribution of the stabilized CEO, characterized by a white frequency noise law, $\sigma_y(\tau) = 5 \times 10^{-14} \cdot \tau^{-1/2}$, is more than two orders of magnitude lower than the measured repetition frequency stability. The contribution of the repetition frequency stability, at the level of $\sigma_y(\tau) = 6 \times 10^{-12} \cdot \tau^{-1/2}$, is somewhat partly limited by the finite resolution of the adopted electronic counter (dashed black curve in black dots in fig. 3). For integration times as long as 100 s, the overall fractional stability of the Yb:CALGO comb is at a level of 7×10^{-13}, which corresponds to the stability of the Rb reference clock.

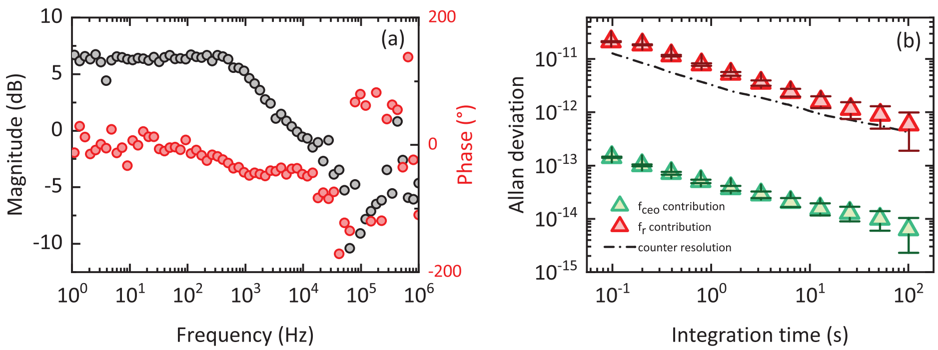

Fig. 3. – (a) Transfer functions of the CEO frequency with respect to the Yb:CALGO pump diode current. (b) Allan deviation versus integration time when the Yb:CALGO comb is stabilized against the RF reference. The dashed line represents the electronic counter fractional frequency resolution.

3. – Conclusion

A self-referenced frequency comb based on a compact Yb:CALGO ultrafast laser system covering the spectral range from 650 to 1500 nm is reported. A long-term frequency stability at the level of 7×10^{-13} (at 100 s integration time) is demonstrated, limited by the performance of the synthesizer used for comb stabilization, making the Yb:CALGO frequency comb a versatile tool for frequency metrology and high-resolution spectroscopy.

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