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External cavity enhancement of picosecond pulses with 28,000 cavity finesse

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We report on the first demonstration, to the best of our knowledge, of the locking of a Fabry–Perot cavity with a finesse of 28,000 in the pulsed regime. The system is based on a stable picosecond oscillator, an ultrastable cavity with high-reflection mirrors, and an all-numerical feedback system that allows efficient and independent control of the repetition rate and the pulse to pulse carrier-to-envelop phase drift (CEP). We show that the carrier to envelop phase can have a dramatic effect even for pulses with hundreds of cycles. Moreover, we have succeeded in unambiguously measuring the CEP of a 2 ps pulse train. Finally, we discuss the potential of our findings to reach the MW average power level stored in an external cavity enhancement architecture. © 2013 Optical Society of America

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1. Introduction

High-quality-factor optical resonators [1] have led to numerous applications since its early development by Fabry and Perot. In the case of a light source with sufficient bandwidth, such resonators provide, under vacuum, an optical spectrum consisting of an equally spaced series of narrow spectral lines referred to as a frequency comb. This technology has a number of important applications mainly dedicated to metrology [2] and exploiting the actual comb structure. These passive resonators are also used as light storage cavities in which a laser beam is injected and if stringent requirements are met, the oscillating light inside the cavity can be passively enhanced with respect to the incoming beam. The enhancement

results from the coherent addition of the incoming field and the circulating field. In the case of a pulsed beam originating from a modelocked oscillator for instance, external cavity enhancement is also referred to as pulse stacking. For example, setting a nonlinear crystal at the focus of an injected cavity will allow us to efficiently frequency double an initially weak laser beam. Similarly, exchanging the crystal with a gas jet and operating with femtosecond pulses will generate a beam of XUV light whose spectrum conserves the driving laser comb structure [3,4]. Alternatively, a high-energy electron beam can be focused to collide with the cavity photon beam thus producing energy up-shifted photons (in the x- or γ -ray domain) through Compton backscattering [5,6]. Intracavity pulse characteristics are a function of the cavity finesse. To start with the extreme, a standalone cavity with a finesse of 10 million has been measured in a whispering gallery mode solid resonator [7]. When

injected in the pulsed regime, commonly used finessees are of the order of 3000–6000 [3,8]. External cavity enhancement in the pulsed regime requires a low phase noise laser (with optional amplifiers) with dynamical actuators, a highly stable cavity frame, high-reflection mirrors, and a locking feedback loop [9]. Achieving enhancement implies locking the repetition rate of the incoming laser beam f_{rep} to the free spectral range of the cavity together with the offset frequency f_o [10]. Monitoring f_o for an accurate control is usually achieved through f -to- $2f$ interferences which is very well adapted to ultrashort femtosecond pulses but fails in the picosecond regime. Moreover, the number of optical cycles within an infrared ps pulse being two to three orders of magnitude higher compared to few cycles pulses, the carrier-to-envelope phase (CEP) is not expected to yield noticeable effects. However, locking a very high finesse Fabry–Perot resonator should alter this temporal interpretation as, even for ps pulses, the resonator eigenmodes consist of a comb of extremely narrow frequency lines whose matching with the incident laser comb is highly sensitive to f_o .

In this paper, we report for the first time, to the best of our knowledge, the stable control and operation of a long cavity with a finesse of 28,000 in the picosecond regime. We also discuss and provide experimental evidence of a strong CEP effect even for pulses lasting thousands of cycles. Additionally, we demonstrate the direct measurement of the average pulse-to-pulse change of CEP $\Delta\phi_{\text{ce}}$, i.e., the CEP drift of a train of picosecond pulses. Cavity enhancement of ps pulses to a very high level is of major importance for applications requiring high-flux x rays or γ rays through inverse Compton scattering [6,11]. Finally, cavity-enhanced power scalability to the MW average power is discussed.

2. Theoretical Background

A finite-length optical cavity is only resonant with discrete light frequencies. In vacuum and omitting the mirror coating dispersion, the longitudinal eigenmodes will therefore consist of a set of equally spaced spectral lines resembling a comb of frequencies. Optical cavities are either passive, and referred to as Fabry–Perot cavities (FPC), or active when they include an optical gain material thus making up a laser. The frequency comb originating from a pulsed laser source is defined within its limited bandwidth by [10]: $\nu_n = n f_{\text{rep}} + f_o = (n + \Delta\phi_{\text{ce}}/(2\pi)) f_{\text{rep}}$. The comb extends around the laser central frequency. Locking the laser to the FPC involves matching each single tooth of the laser beam comb to the FPC resonant frequencies [12]. Partial matching will result in a limited coupling efficiency.

Here, the effects of the chromatic dispersion of the mirror coating is neglected as the optical spectrum bandwidth is narrow (FWHM = 0.34 nm) [13]. All teeth can then be efficiently coupled. We further experimentally checked this point by comparing the incident and transmitted laser beam spectrum.

Whenever the cavity is locked to the incident laser ($f_{\text{rep}} = \nu_{\text{FSR}}$ and $f_{\text{ceo}} = 0$), it will behave as a photon storage resonator leading to enhanced power inside the cavity as compared to the incident beam. The intracavity power enhancement is defined as $G = F/\pi$ if two identical mirrors of reflection coefficient R are used and where $F \approx \pi\sqrt{R}/(1-R)$ is the finesse. The mirror transmission is defined by $T = 1 - R - A$, where A embodies the scattering and absorption losses.

3. Experimental Setup

Our experimental setup (Fig. 1) consists of a low phase-noise bulk oscillator, a rigid high-finesse Fabry–Perot cavity which is used as a reference for the laser beam frequency stabilization, a feedback system, and an independent $\Delta\phi_{\text{ce}}$ measurement device. The laser is a customized commercial Ti:sapphire mode-lock oscillator (MIRA from COHERENT Inc.) optically pumped by a continuous wave green laser beam (6 W VERDI from COHERENT Inc.). It delivers 2 ps (0.34 nm bandwidth) transform-limited hyperbolic secant pulses at a repetition rate of 76.4 MHz. The output coupler is mounted on a stepper motor (SM) allowing only a manually coarse tuning of f_{rep} . The other cavity mirror is mounted on a piezoelectric transducer (PZT).

The 2-mirror FP cavity has two identical concave mirrors with 2 m focal length ($L = 2$ m) and is set in a vacuum chamber to prevent any disturbance from air flow as well as nonlinear effects. The mirrors have been designed to provide a finesse of around 30,000 and thus a potential power enhancement factor

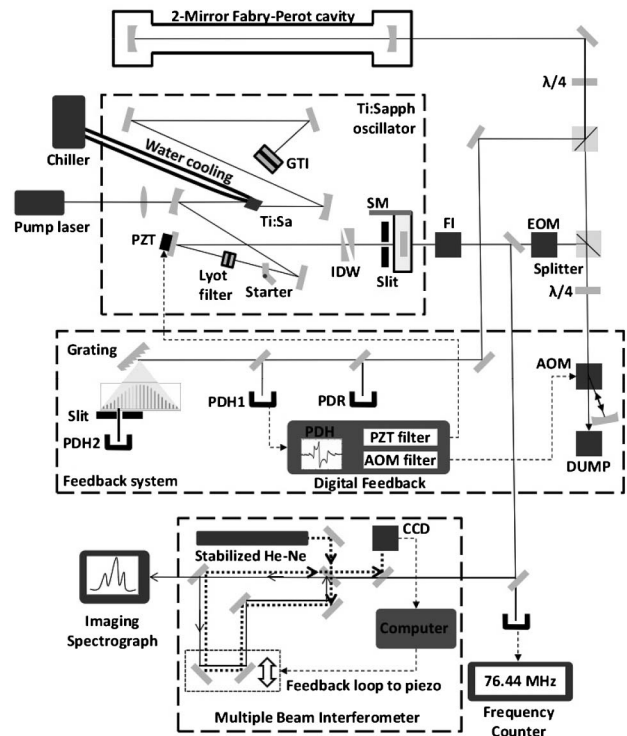


Fig. 1. Sketch of the experimental setup.

approaching 10,000. The coatings have been designed, manufactured, and characterized by us. A detailed analysis of the mirror coatings have revealed scattering losses ranging from 6 to 10 ppm, absorption losses between 1 and 1.5 ppm, and a transmission of $T = 100$ ppm with variations of the order of 1 to 3 ppm.

As locking a laser to a very high finesse FPC requires fine and complex adjustments of several parameters, we have developed a customized digital feedback system [14] based on the Pound–Drever–Hall (PDH) technique [15] to lock the laser oscillator to the FPC. The main advantage of our approach over analog feedback control is the ability to design and modify many signal filters and signal processing by software. The oscillator output beam is first modulated in an electro-optic modulator (EOM) to produce the error signal that is later detected by a photodiode (PDH1). This error signal feeds the PZT and the acousto-optic modulator (AOM) feedback loop. The PZT, which essentially modifies f_{rep} , has a proportional-integral (PI) transfer function (PZT filter) with around 10 kHz of unity gain bandwidth (limited by the first resonances of the PZT). The additional AOM used as a frequency shifter (double pass) with a simple proportional gain (AOM filter) around 100 kHz of unity gain bandwidth (only limited by the global feedback delay response) allows us to reduce the residual noise and stabilize the feedback loop. As its open-loop gain is AC coupled, it has no effect on the long-term variations of $\Delta\phi_{\text{ce}}$. Note that the AOM does not provide any new degree of freedom as it uses the same error signal as the PZT.

The output beam is finally injected in the FPC after spatial shaping to match the transverse fundamental mode of the cavity. As discussed below, even in the case of a ps pulse with a very large number of cycles, the CEP has a major influence on the coupling efficiency. In order to measure and better control the drift, we have installed an independent diagnostic able to accurately retrieve the $\Delta\phi_{\text{ce}}$. The conventional techniques commonly used to record it such as f -to- $2f$ interferometry cannot be used in our context as generating an octave-spanning supercontinuum from a transform-limited ps pulse results in a loss of spectral coherence preventing the observation of the beating expected between f and $2f$ [16]. Instead, we have used an all-linear optical method based on a multiple-beam interferometer (MBI) for the real-time measurement of the $\Delta\phi_{\text{ce}}$ (see Fig. 1), since it does not have any bandwidth requirements [17]. The path length of the MBI closely matched the repetition rate of the oscillator and the output beam was directed into a high-resolution spectrograph. Since the delay between the subsequent pulses of the train is small, they interfere spectrally at the output of the MBI. With the use of a spectrograph, we uniquely recover $\Delta\phi_{\text{ce}}$ from the position of the spectral interference fringes. Note here that during this experiment, we have demonstrated for the first time, to

the best of our knowledge, the direct measurement of $\Delta\phi_{\text{ce}}$ of ps pulses.

4. Data Analysis

Once the laser oscillator was locked to the cavity, we simultaneously measured $\Delta\phi_{\text{ce}}$ and the signal reflected by the cavity (PDR in Fig. 1) as well as another independent error signal, unused in the feedback loop at the moment. The latter signal is read out by a photodiode on the reflected beam after diffraction on a grating (PDH2) and demodulated by the PDH technique as PDH1. We choose to measure and analyze the reflected signal PDR because it contains information on both the cavity finesse and the cavity-laser beam coupling. The coupling efficiency is of major importance for the applications described in the introduction since it provides the amount of incident laser beam power fed into the cavity and further passively amplifies once the system is locked. A correlation analysis between these signals and the measured $\Delta\phi_{\text{ce}}$ variations have revealed a correlation factor of the order of 85%–90%. While performing measurements, the system was operated either in the free-running mode or with a controlled slow variation of $\Delta\phi_{\text{ce}}$. Three means were used to slowly change $\Delta\phi_{\text{ce}}$: the pump laser beam power (directly from the laser controller), the laser crystal temperature (via the water cooling temperature), and an isochronic double wedge (IDW) [18] (see Fig. 1). Although the different controls exhibit very similar behaviors, the laser pump power provides the smoothest control with the least laser/FPC delocking. The measured data are binned after a simple unbiased data cleaning procedure and the error bars are defined by the variance within the bins. We found the power variations of the oscillator to lie below the percent level during the measurements. A fine scan of $\Delta\phi_{\text{ce}}$ over $\approx 2\pi$ rad is achieved by varying the laser pump power with small steps. The control drift of $\Delta\phi_{\text{ce}}$ is recorded with our MBI setup and plotted as a function of time in the top graph of Fig. 2. The corresponding reflected power is shown in the middle graph of Fig. 2 with errors bars. Note here that varying the cavity mirror parameters (losses and reflectivity mismatch) within their measured deviations, leads to negligible fluctuations compared to the actual error bars. Finally, the independent error signal PDH2 is plotted in the bottom graph. As expected, when $\Delta\phi_{\text{ce}}$ deviates from 0, the reflected power increases (up to a maximum value of around 70% in the present case) while it reaches a minimum value of 21% for $\Delta\phi_{\text{ce}} = 0$. Accordingly, the error signal PDH2 vanishes at the zero values of $\Delta\phi_{\text{ce}}$. The minimal reflectivity of only 21% (79% transmission) is attributed to several factors such as incident beam geometrical mismatch and mirror reflectivity mismatch. This parameter is rarely mentioned in publications related to laser beam cavity locking. In [8], 50%–65% is reported but for much higher laser beam powers and for a more complex cavity geometry.

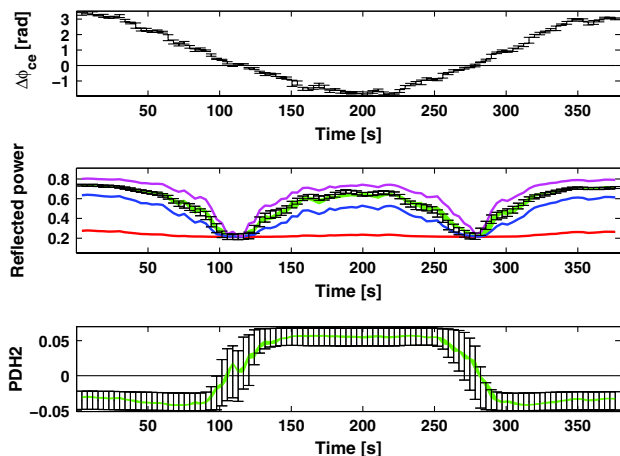


Fig. 2. (Top) Controlled variation of $\Delta\phi_{ce}$ as a function of time measured by the MBI technique. (Center) Reflected power (normalized to one) measured (with error bars), the comb theory for $F = 28,000$ (green), $F = 5000$ (red), $F = 15,000$ (blue), and $F = 45,000$ (pink). (Bottom) PDH2 independent error signal.

A mean-square fit of the frequency comb model [12] is applied to the measured data. The free parameters are a scaling factor and a constant offset. The model shows a remarkable agreement with the measured data for a theoretical finesse of $F = 28,000$ in agreement with the theoretical finesse derived from the mirror reflectivity. Although intuitive, this agreement demonstrates that the frequency comb theory, extensively used to describe a femtosecond mode lock oscillator, also holds in the picosecond regime. Additional predictions with different finesses are also plotted to emphasize the impact of $\Delta\phi_{ce}$ on the transmitted power. Figure 3 displays the cavity enhancement inferred from the data as a function of $\Delta\phi_{ce}$ for the measured values as well as for predicted values with different finesses. A cavity with a finesse of 5000 is barely sensitive to $\Delta\phi_{ce}$ fluctuations thus releasing the need for a feedback loop. As a contrast, a finesse

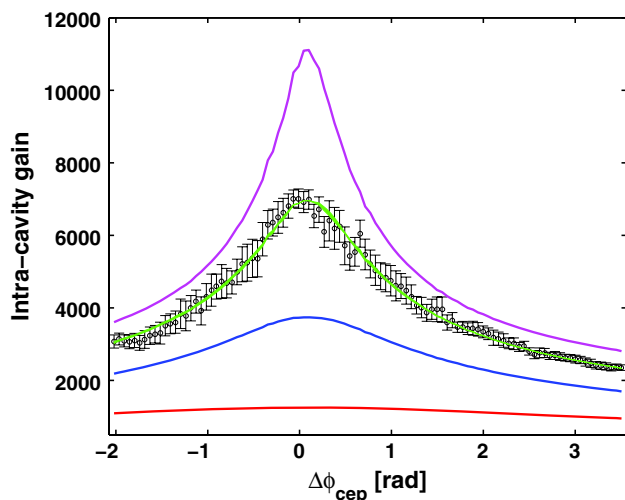


Fig. 3. Effective power enhancement factor inferred from the experimental data as a function of $\Delta\phi_{ce}$ for finesses of 5000 (red), 15,000 (blue), 28,000 (green), and 45,000 (pink).

of 45,000 will result in a sudden drop of the coupled power for small $\Delta\phi_{ce}$ variations. In these conditions, an active control on $\Delta\phi_{ce}$ is achieved by a feedback loop on PDH2. Within our experimental uncertainties, we are thus able to describe and control all the DC variations of the laser/cavity coupling solely by the slow $\Delta\phi_{ce}$ drifts of the picosecond oscillator. As demonstrated here, optimal external enhancement with finesses of the order of 30,000 require a feedback on $\Delta\phi_{ce}$ even in the ps regime. The dual-parameter locking (f_{rep} and $\Delta\phi_{ce}$) has thus allowed us to achieve a recorded effective power enhancement factor of 7,040. For an incident power of 100 mW, the enhanced power inside the cavity reaches 704 W corresponding to pulses of 9.2 μ J. Although reaching such a power with an oscillator and an external cavity looks very attractive, the enormous potential of the present achievement is found in the power scalability. State of the art Ti:sapphire commercial systems are able to provide up to 50 W of average power but implement complex technologies such as cryogenic cooling. At such an average power, the beam quality might be altered as compared to an oscillator and will lead to a weaker coupling efficiency. Another issue occurring in such systems is the slow drift of $\Delta\phi_{ce}$ which could potentially be balanced by our feedback system. Accounting for these limitations, a rough estimate will give an intracavity power of the order of 250 kW. Way more promising is the fiber technology. In fact, amplification of femtosecond pulses at powers in excess of 800 W have recently been demonstrated [19]. Even at this extreme power, the beam quality and stability remain exceptional as compare to bulk systems, a key property for efficient external cavity enhancement. Assuming an improved coupling efficiency and a power enhancement factor of 10,000 (provided no additional phase noise is induced by the amplifiers, especially in the range 1 kHz–1 MHz), one can easily reach an outstanding theoretical intracavity power of more than 5 MW. However, such an average power and circulating intensity will generate deleterious effects preventing the building-up power to reach the expected value. The 72 kW average power stacked in the 1,400 enhancement factor cavity of [8] was indeed already limited by thermal effects. Thermal lensing in the injection mirror can distort the incident wavefront and spoil the beam mode matching. Similar effects are also expected to occur in the high-reflectivity mirror coatings although their efficiency is supposed to be excellent. Still, several dozens ppm absorption at such an average power is sufficient to create an index gradient or a surface deformation. Nevertheless, we are confident in the potential to reach the MW power level if ps pulses are used to mitigate the coating damage issues observed with fs pulse stacking [8].

5. Conclusion

We have reported, for the first time to the best of our knowledge, the locking of a 28,000 finesse cavity with

a mode-lock oscillator. A stable laser-cavity coupling of 80% has been demonstrated. The present achievement is based on an independent and very stable control of both the repetition rate and $\Delta\phi_{ce}$. This work paves the way to extreme power storage where the MW level is within reach. Additional controls are being developed to further decrease the noise, and conventional techniques optimized for femtosecond frequency combs will be adapted to the picosecond regime.

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