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**Interferometric output stabilization of a femtosecond optical  
parametric oscillator**

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# Interferometric output stabilization of a femtosecond optical parametric oscillator

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**Abstract :** In this project we present a new technique to stabilize the cavity length of a tunable synchronously-pumped OPO and consequently achieve wavelength stability using more standard equipment commonly used to stabilize single frequency lasers. This technique is based on a concept that was introduced years ago in the context of mode-locked lasers [1], in which a conventional interferometer is synchronized to the repetition rate (RR) of the laser. In this work, we implemented the use of Pound-Drever-Hall technique to ultrafast OPOs by deploying an external Fabry-Perot interferometer synchronous with high harmonic number (about 14th) of the OPO's RR. In order to stabilize our OPO to this reference cavity, we use standard feedback techniques where the Fabry-Perot is modulated and the signal from the detector is demodulated by a lock-in amplifier, thus providing our error signal. This one is in turn integrated by our stabilizer, before being sent to the OPO piezoelectric driver. We presented characterization of the wavelength stability and fine tuning of the signal output pulse train for both long and short term regimes.

**Keywords:** Ultrafast optics, Ultrafast measurement techniques, Nonlinear optics, Optical parametric oscillators

## 1.1 ) Frequency Combs

A femtosecond frequency comb is a spectrum of discrete frequencies, separated by a consistent spacing called the repetition rate,  $f_{\text{Rep}}$ . Each comb mode has distinct frequency, as can be seen in Fig1(A). In addition, the carrier-envelope offset frequency  $f_0$  explain by the spacing between modes, the comb is characterized by an offset from zero.

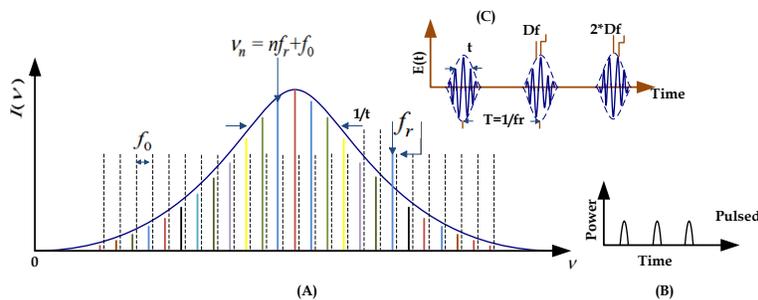


Fig 1 : (A) Time-Frequency domain picture of the mode-locked laser output (B): Power over time output for pulsed operation. (C) : between the peak of the carrier wave and the peak of the envelope function occurs phase shift  $\Delta\phi$ , so it leads to an offset of the entire frequency comb from zero in the frequency spectrum.

The comb equation can describe by  $f_{\text{Rep}}$  and  $f_0$ :

$$\nu_n = i \cdot f_{\text{Rep}} + f_0 \quad (1.1)$$

In this equation the  $i$  is a number of comb lines and a very large number, to reach optical frequencies. To do the stabilize is needed  $f_{\text{Rep}}$  or  $f_0$  or both of them, so the stabilization of these two frequencies means the stabilization of every optical mode in the comb.

The Fourier transform spectrum of a periodic train of light pulses with a fixed phase relationship is a frequency comb.(Fig 1(B))To produce the train of pulses , is needed the mode locked laser.

The laser cavity is supported at several different frequencies of light in a typical laser cavity, which are referred to the eigenmodes of the cavity. If these modes do not have any fixed phase relation, in order this interference is random. However, if there is fixed relationship, so the interference will be steady and the phase coherent mode occurred. The cavity design in modelock laser can support the phase coherent mode. The pulses are propagated with this interference would be around eigenmodes of the cavity.

Let's take a mostly qualitative look at these  $f_{\text{Rep}}$  and  $f_0$ . For  $f_{\text{Rep}}$  the envelope of the pulse is considered. The Fourier analysis shows a continuous frequency spectrum by a width  $\Delta\nu = 1/\tau$  for each single pulse with temporal width  $\tau$ . The spectrum of discreet frequency modes with a spacing equal to the inverse of the period of the pulses:

$$f_{\text{Rep}} = \frac{1}{T} \quad (1.2)$$

Where the period  $T$  is the time, and the relation of the time to the length of the cavity :

$$T = \frac{L}{\bar{v}_g} \quad (1.3)$$

The speed of the peak of the pulse  $\bar{v}_g$ , where is described as the average of the group velocities of all of its frequency components. The phase and group velocities of the pulse are different in the cavity. In Fig 3 is shown this results in a constant shift of the carrier wave with respect to the envelope between successive pulses. In Fourier transform of pulses translates into a rigid shift of the whole frequency spectrum, is constant phase shift  $\Delta\phi$ . The offset of the entire comb is zero, thus the frequency modes still have the spacing  $f_{\text{Rep}}$ . The offset frequency is related to the pulse-to-pulse phase shift by:

$$f_0 = \frac{\Delta\phi}{2\pi} f_{\text{Rep}} \quad (1.4)$$

### 1.2 ) Mode-locked Ti:sapphire laser

Mode-locked laser is a laser can develop a fixed phase relationship across a broad spectrum of frequencies between many longitudinal modes of the laser cavity and generate short optical pulses.

Cause of many various mechanisms for mode-locking, many types of the mode-locked laser create, like low phase-and amplitude-noise mode-locked diode lasers at various wavelengths (4,3), mode-locked Er+3 fiber lasers at 1550 nm (9, 5, 6, 7, 8), and Cr:forsterite lasers near 1300 nm. In this research, has been used the One of the most famous technic, because of its excellent performance and relative simplicity to generate the ultrashort optical pulses is Kerr-Lens-mode-locked Ti:sapphire (KLM Ti:sapphire) laser that pumped by a solid-state laser at 532-nm.

Ti:sapphire laser use optical Kerr effect to induce the modelocking, and this technic use a third-order ( $X^3$ ) nonlinear interaction between light and a material. This laser to achieve the minimum pulse use a self-phase modulation (SPM) mechanism. This mechanism induced by Kerr-Nonlinearity in the active medium to generate extra bandwidth .

On the other hand, an intensity-dependent beam waist and waist location for a Gaussian pulse propagating through the cavity can develop the nonlinear Kerr-lens results. This comes because the nonlinear index of the pulse showed the Gaussian profile in transveres direction.

### 1.3) Optical Parametric Oscillator principles

In an optical parametric oscillator, use nonlinear medium to convert the frequency of pump wave  $\omega_p$  into two different frequencies signal  $\omega_s$  and idler  $\omega_i$ .



Fig 2: Principle of an OPO

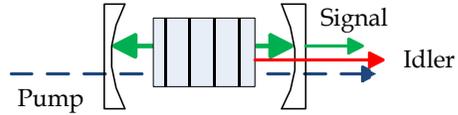


Fig 3 : Schematic setup of a singly resonant OPO

An OPO consist of Nonlinear crystal to make nonlinear medium to perform the frequency conversion, which crystal set in the resonator.

The brilliant property of OPO is the broad tunability from the ultra-violet (UV) to the mid-infrared (MIR), the temporal versatility from CW to femtoseconds and the high efficiencies of typically 50% to 90%.

The first demonstration of optical parametric oscillation in 1965 used lithium niobate and a nanosecond visible pump laser and achieved tuning around 1  $\mu\text{m}$  [9]. Publications of OPOs in many operational regimes and with many different nonlinear crystals followed this demonstration, the first femtosecond SPOPO [10].

When an electric field  $E$  is applied to this medium, the electrons in a medium are forced into a dipole oscillation and hence become polarized. If the electric field is very intense, the response of the medium is no longer linear and the polarization must be expanded in a power series about the electric field to:

$$P(t) = \epsilon_0 [X^{(1)}E(t) + X^{(2)}E^2(t) + X^{(3)}E^3(t) + \dots] \quad (1.7)$$

The second-order term can explain optical phenomena such as second-harmonic generation, sum-frequency generation, the linear electro-optic effect or parametric oscillation, whereas the third-order term induces phenomena such as the Kerr effect, two-photon absorption or Raman scattering.

The difference frequency generation can also be considered as an optical parametric amplification (OPA) process, where one input photon (signal) triggers the annihilation of one high-energy photon (pump) generating another signal photon and one additional photon (idler) at low energy. This shows that the pump field is depleted, a new field at the idler frequency is generated and the input signal field is amplified in the nonlinear medium. Energy conservation dictates that:

$$\omega_p = \omega_s + \omega_i$$

The gain that the signal field experiences in an OPA can be significantly enhanced, if the  $X^{(2)}$  nonlinear crystal is placed in between two or more mirrors to form an optical resonator. The device is then called an optical parametric oscillator.

In an OPO the nonlinear crystal acts as a difference frequency generator, splitting pump photons into signal and idler photons. Thus, the idler is generated and the signal is amplified at the expense of the pump which is partially depleted. If The nonlinear gain of the signal exceeds the linear losses in the resonator the signal will increase or (if no signal is present ) it will start building up, like in a laser resonator.

For an efficient conversion process and for achieving gain, it is essential that the photon momentum is conserved as well and this is expressed with the phase-matching condition for OPO:

$$\Delta k = k_p + k_s + k_i = 0$$

The wide-gain bandwidth provided by the QPM geometry enabled the femtosecond OPO to be tuned across a broad wavelength range by only adjusting the length of the resonator.

The rapid rate of cavity-length tuning which we observed is a consequence of the small amount of intracavity group-delay dispersion (GDD) in the OPO. The net cavity GDD decreases with increasing wavelength with the result that longer wavelengths are generated from a physically longer resonator. (12,13,14)

#### 1.4) Measurement of Fabry-Perot cavity length

Fabry-Perot cavity is composed of two highly reflective parallel mirrors which transmit light only when the optical path length of the cavity is an integer multiple of half the wavelength of the incident light beam. Transmitted optical resonance frequencies fulfill following condition :

$$f_m = \frac{mc}{4nL} \quad (1.8)$$

Where  $m$  is a longitudinal mode of the FPC in confocal geometry with mirrors separated by  $L$ ,  $c$  is the speed of the light,  $n$  is the refractive index of air inside the cavity.

On the other hand, the frequency combs are based on the generation of femtosecond pulses. Train of the pulses then produces a comb of frequencies that fulfilled the condition:

$$\nu_n = i \cdot f_{\text{Rep}} + f_0 \quad (1.9)$$

For a single spectral component of a comb at coincidence with the resonance frequency of the FPC ( $f_m$ ), optical frequency of the laser comb follows this condition:

$$\nu_n = f_m = \frac{mc}{4nL} = i \cdot f_{\text{Rep}} + f_0 \quad (1.10)$$

Extracting the exact length of the FPC from (1.10) then:

$$L = \frac{mc}{4n(i \cdot f_{\text{Rep}} + f_0)} \quad (1.11)$$

Because  $i$  and  $m$  are integer constants and  $c$  is exact speed of the light in vacuum, the exact length  $L$  of FPC is determined by frequencies  $f_0$  and  $f_{\text{req}}$ .

In a scanning Fabry-Perot cavity, one of the mirrors is translatable, mounted on Piezoelectric transducer. By modulating the cavity's FSR, the scanning Fabry-Perot essentially performs a Fourier transform on the incident light beam, transmitting the various frequencies composing the input light as a function of cavity length. The breadth of the frequency comb associated with femtosecond length pulses makes available scanning Fabry-Perot cavities. In the other language, to achieve the femtosecond pulse, we need a corresponding between the cavity length and the repetition rate of frequency.

## 2)Optical Parametric Oscillator frequency Locking With Pound-Drever-Hull Technique

### 2.1)Introduction

In many precision optical measurements, it is desirable to have a OPO with a well-defined frequency. For tunable OPO, it is therefore necessary to have a means of controlling the OPO's operating frequency, stabilizing it and often "locking" it at a desired value.

The first step for locking process is generating the electronic error signal.to generate the error signal tow most popular technics are proposing , 1) side-locking, 2) Dither locking and 3) Pound Drever hall (PDH) method.

The side locking method we produce the voltage signal as a function of laser frequency  $V(\omega)$ , with select the optical element frequency, and the next step to lock the laser is make error signal  $\epsilon(\omega) = V(\omega) - V(\omega_0)$  and send it to the feedback loop. Totally this method has some disadvantages. First because it is modulation free, second it has a small acquisition range, third, the lock is less strong because perturbations, fourth, in this method the optical power in the cavity reduce so the noise of intensity is increasing because of the one lock to the side. In fact the side-locking method is suited to lock the side of the peak resonance.

In the other technique, which is called Dither locking, can lock the peak of the resonance feature. In fact with this technique, produce this voltage signal  $V(t) = V(\omega(t)) \approx V(\omega_{\text{Center}} + \Delta\omega \cos(\Omega t))$  with dither the laser frequency at the modulation frequency( $\Omega$ ).Now we have  $\epsilon(\omega_0) = 0$  with a  $d\epsilon/d\omega(\omega_0) \neq 0$ , so with these conditions we can lock laser in  $\omega_0$ .

The disadvantage of this method is the limitation of servo bandwidth. ( $\beta \gg 1$  is modulation index)

The PDH technic can overcome this problem by increasing modulation frequency and we will deal with this in the regime where ( $\beta \ll 1$ ). In this technique reduce the acoustic noise on the laser.

### 2.1) Pound-Drever-Hall Technique (15,16)

The technique was invented for stabilizing the frequency of a laser by locking it to a Fabry-Perot reference cavity. It was invented by Ron Drever, based on an earlier microwave technique invented by R. V. Pound, and much of the implementation was worked out at JILA by Jan Hall's group.

In this experiment we demonstrate PDH technique for stabilizing the frequency of the femtosecond Optical Parametric Oscillator. We lock the Fabry-Perot resonator to femtosecond OPO. (explain in 1.4 and 1.1)

In this technique we use the frequency modulated (FM) as the frequency of the laser the frequency of the laser is frequency modulated (FM) and locked in reflection to the resonance frequency of a high finesse interferometer. In this technique to gain the depressive error signal is used phase sensitive detection.

The frequency modulated spectrum consist of to side-bands with high frequency and low frequency, which one on of them is in phase and the other out of phase by 180°, respectively.

The optical reflection of the cavity with considering to the sideband component is phase shifted, in order the power appears at the modulation frequency with detector photocurrent. In the next step, the frequency noise of the laser mixed to base-band. Consequently the frequency discriminator with odd symmetry is provided.

Here the detector light consists of two parts first a fraction of input beams, plus the fraction the transmitted back out of the output coupler. The PDH technique gives us a frequency error signal with sensitivity that can be measured in volts per hertz of optical frequency . One technique for obtaining a correct error signal is by using lock-in amplifier and in this experiment to do the phase-sensitive detection and make error signal, is used the commercial lock-in amplifier.

### 2.2) Lock-in Amplifier

In a nutshell, in the lock-in amplifier, the signal is frequency modulated and then multiplied with a signal that has the same frequency as the modulation signal. In the next step, compares the phase and if it I correct, the modulated signal is amplified.

The lock-in amplifier operates on very simple scheme: assume a sinusoidal input signal and the reference signal, respectively :

$$V(t) = V_0 \sin(\omega t + \phi) \quad (2.1)$$

$$V_r(t) = \sin(\Omega t) \quad (2.2)$$

The product of these two gives beats at the sum and difference frequencies:

$$V_R(t)V(t) = \frac{V_0}{2} \{\cos[(\omega - \Omega)t + \phi] - \cos[(\omega + \Omega)t + \phi]\} \quad (2.3)$$

When the difference frequency  $\Omega$  between these signals detect , oscillates in time with an average value of zero.

When the  $\omega = \Omega$  is appeared , the output is :

$$V_R(t)V(t) = \frac{V_0}{2} \{\cos[\phi] - \cos[(2\Omega)t + \phi]\} \quad (2.4)$$

The DC level is clarified by  $V_0$ , if we can extract the DC component, and are able to adjust  $\phi$  , we get a direct measure of the signal amplitude  $V_0$  . This technique helps us to reject any unwanted signals oscillating at different frequencies and also any random3 noise that does oscillate at  $\Omega$  will also be rejected. Fig(4) illustrates the lock-in amplifier in simple way.The following figure illustrates how a lock-in works:

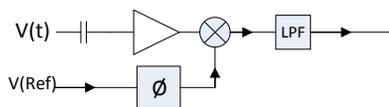


Fig 4. Schematic of lock-in amplifier

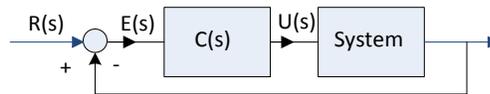


Fig 5: simple SISO control loop

### 2.3)PI-controller (17)

All the system need the control system to track something based on the error between the desired target and actual data so the PID controllers are becoming quite common in the commercial, institutional, and industrial fields.

PID control is a theory to be able to achieve this kind of control challenges. This control theory is one of the classic controls, which is simple, easy to implement, and cheap. P gain define the speed of the system response , D is used to reduce the magnitude of the overshoot, and I is used to eliminate the steady-state error.

PID controller is mostly used in Linear-Time Invariant (LTI) system and Single-Input Single-Output (SISO) system not in non-linear and complex Multi-Input Multi-Output (MIMO) system.

PI controllers operate about 90% control systems and the PID controllers that cover about 95%(13).

The controller used in this project was a PI-controller This correction signal can consist of two different parts: a proportional to the error itself (P) and a proportional to the integral of the error (I).

The steady state error in the proportional controller has an inverse relation with proportional gain. The constant  $K_P$  (proportional Gain) is multiplied to the error and this method gives an adjustable proportional response.

The proportional term is given by:

$$P = K_p \cdot error(t) \quad (2.5)$$

If the proportional gain is very high, the system can become unstable and If the proportional gain is very low, the control action may be too small when responding to system disturbances. Consequently, a proportional controller ( $K_p$ ) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error. The responsibility of the Integral controller (IC) is proportional to both the magnitude of the instantaneous error and the duration of the error. The integral in a PI controller is the sum of the error over time and gives the accumulated offset that should have been corrected previously.

In order, an integral control ( $K_i$ ) will have the effect of eliminating the steady-state error, but it may make the transient response worse. The integral term is given by:

$$I = K_i \int_0^t error(t) dt \quad (2.6) \quad U(s) = K_p \cdot error(t) + K_i \int_0^t error(t) dt \quad (2.7)$$

Fig9, the PI controller is illustrated, so we can analysis the response of this system:

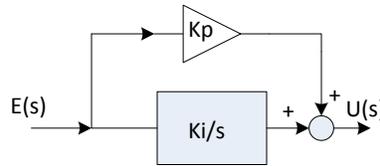


Fig 6: A PI control system

### 3) Experimental setup (Fig 11)

#### 3.1) Pump source:

In this experiment the Optical parametric oscillator (OPO) was pumped by Kerr-lens Mode-locked (KLM) Ti:Sapphire laser oscillator (Model 900-P Mira). The Ti:Sapphire laser was pumped by 10W at 532nm continuous-wave laser (Verdi V10). The Verdi V10 consists of a Nd:YVO4 ring laser end-pumped by two fiber coupled diode bars and with an intra-cavity LBO frequency doubler. Finally, we could produce a stable output of 1W average power, and was continuously tunable from 780 to 830 nm with pulse duration of 150fs.

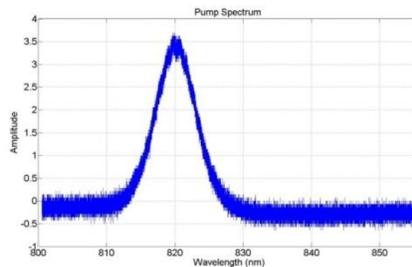


Fig 7: Pump Spectrum

The stability of the pump in long term and short term temporal scales are shown in Fig 8(a)-(b). In Fig 8(a) is shown the maximum peak-to-peak fluctuation in a short time for pump spectrum and in the Fig 8(b) is shown shown the maximum fluctuation in a long time for pump spectrum. We can discover the maximum fluctuation in both figures just 0.8nm. (The method to save data will be explained in the next part)

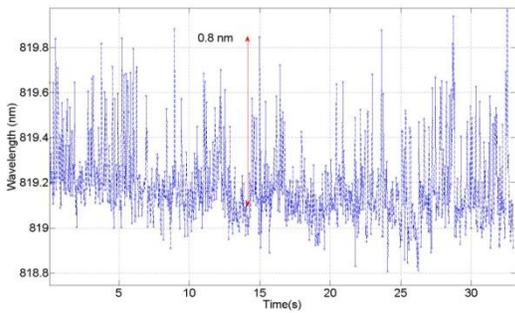
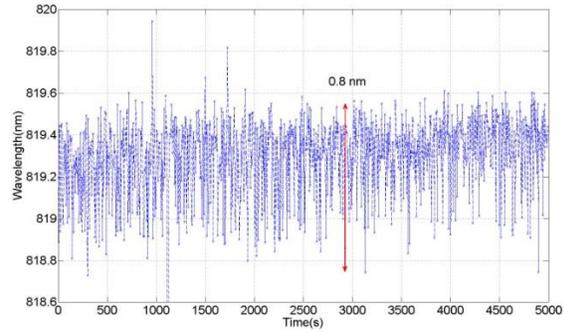


Fig 8(a): Pump Stability in short time,



(b): Pump stability in long time

### 3.2) Nonlinear Crystal

The Periodically Poled Lithium Niobate (PPLN) crystal used in this experiment is antireflection coated for the pump, signal, and idler wavelengths. In Fig 2 is shown that the pump beam is injected into the crystal by the mirror (M2). The crystal with (0.5 mm long\*1 mm thickness\* 3.4 mm wide) size and also with a grating period of  $\Lambda = 21.4 \mu\text{m}$  is used in this experiment. The crystal was settled in an oven at  $100^\circ\text{C}$  to avoid the photorefractive damage.

### 3.3) The OPO Resonator

Fig 9 shows the OPO schematic. It is set up as a singly resonant OPO pumped in a single pass and resonating the signal in a V cavity. The repetition rate of the oscillator was 76 MHz, corresponding to a cavity length of 197.4 cm. In the OPO cavity, all the mirrors have dielectric coating. In addition, M1 and M2 are concave mirrors with curvature radius of 10 mm. All mirrors are coated with high reflection ( $R > 99\%$ ) over the 1400–1580nm wavelength range, and the output coupler (OC) has a transmission rate of 5% in the 1400–1580nm wavelength range. The OC is used mounted on an adjustable mirror mount which can move the mirror with micrometer accuracy .

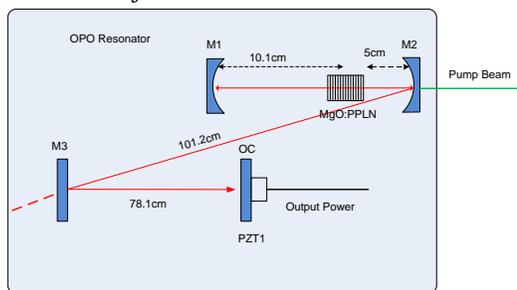


Fig 9: OPO schematic. M: Dichroic Mirror. OC: Output Coupler. PZT: Piezoelectric transducer

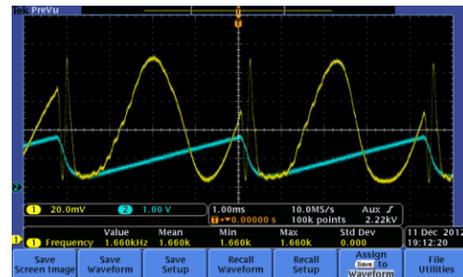


Fig 10: Fabry Perot resonator

### 3.4) Fabry-Perot Interferometer

The Fabry-Perot Interferometer, that used in this experiment, is a high finesse interferometer. (Model FPI 100). We used FPI to produce a comb of absolute reference frequencies. The interferometer, which can give a free spectral range (FSR) of 1 GHz to 4 GHz.

The FPI mirrors, is used with high reflectivity ( $>99.7\%$ ), with losses low enough for high interferometer transmission. Fig 13 the resonance of the FPI is shown. We can discover easily, that resonance does not have good finesse. This phenomenon has different reasons . The first reason relates to the pump spectrum, is shown above (Fig 7), it is not a narrow ( $\sim 7\text{nm}$ ) and it is not very smooth, the second reason, because of the isolation of the setup and the stuff is used in the experiment and also temperature variable can have a huge effect on results.

Additionally, as I explained in the theoretical part about the FPI, to find good resonance, we must scan the length of the FPI that is synchronized with the train of femtosecond pulses of OPO.

### 3.5)Electronic feedback

In this experiment, as has been mentioned in the part 2, we used the Pound–Drever–Hall (PDH) technique to frequency stabilize the femtosecond optical parametric oscillator to optical cavity resonances.

We used the Lock-in amplifier (Model 410 Analogue Single Phase) to generate the error signal from the cavity reflection is detected by the detector.

To correct the error signal, PI- Controller (ICFO) is used. This controller consists of two parts to correct the error signal: 1) a proportional to the error itself (P), 2) a proportional to the integral of the error (I).

To send the improved error signal to the PZT transducer, we used the high voltage driver (Piezomechanik Dr.L. Pickelmann GmbH).

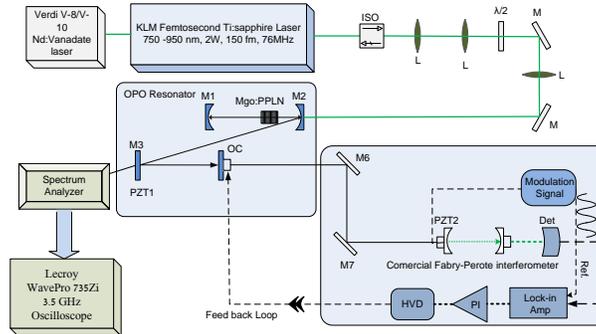


Fig 11: Experimental Setup. M:Dichroic Mirror. OC: Output Coupler. PZT: Piezoelectric transducer. HVD:High Voltage Driver. PI: Proportional-Integral-Controller. Det: Photo Diode Detector. ISO: Faraday Isolator. L: Lens.  $\lambda/2$ : half-wave plate.

We use a Lecroy Oscilloscope to save data and prove the stabilization method. In the result section, we will show the wavelength of the femtosecond OPO has a large fluctuation without stabilization, versus the fluctuation with stabilizing is very negligible. The Lecroy has math function and especial ability to measure the variation of the wavelength.

In the first step, we detected the maximum of the femtosecond OPO spectrum, with this measurement the Lecroy shows the amount of the maximum of spectrum for each moment, in the next step, we used the math function, which depends on the maximum of spectrum value, we can show the trend of the OPO spectrum.

Fig 12 shows the screen of Lecroy, which is seeing the spectrum of femtosecond OPO and the trend of it.

In the other explanation, we can show this steps in this way. For short time:

- 1) Choose measure section for a spectrum of femtosecond OPO
- 2) Select Max. from the measure section to measure the maximum of the spectrum in time
- 3) Choose a math function for a maximum of OPO spectrum
- 4) Choose the Trend from the math function to show us the variable of wavelevgh in time

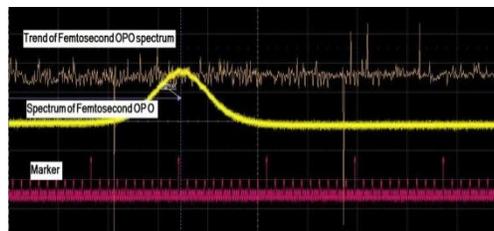


Fig 12: Lecroy Oscilloscope Screen

For long time: In long time, all the steps are the same as the short time and after the fourth step we should choose the trigger part to set the hold-off time for a long measurement.

### 3.6) Result

To show the stability of Femtosecond Optical Parametric Oscillator (OPO), we measured the fluctuation of wavelength in short and long time in Fig. 13(a)&(b). Fig. 13(a) is clarified that the fluctuation of the OPO spectrum in a short time is just 0.2nm and in the figure 13(b), shows the fluctuation for a long time is 2nm. In addition, the figure 13(b) defined the drift of the wavelength with stabilization for 5000 seconds is just 3nm and also we can see the drift of wavelength in short time is just 0.1 nm. Fig. 14 shows the OPO spectrum without stabilization, where the maximum fluctuation is 11nm and the drift of wavelength is 19nm. These results confirm that stabilization can limit the fluctuation and also drift of wavelength.

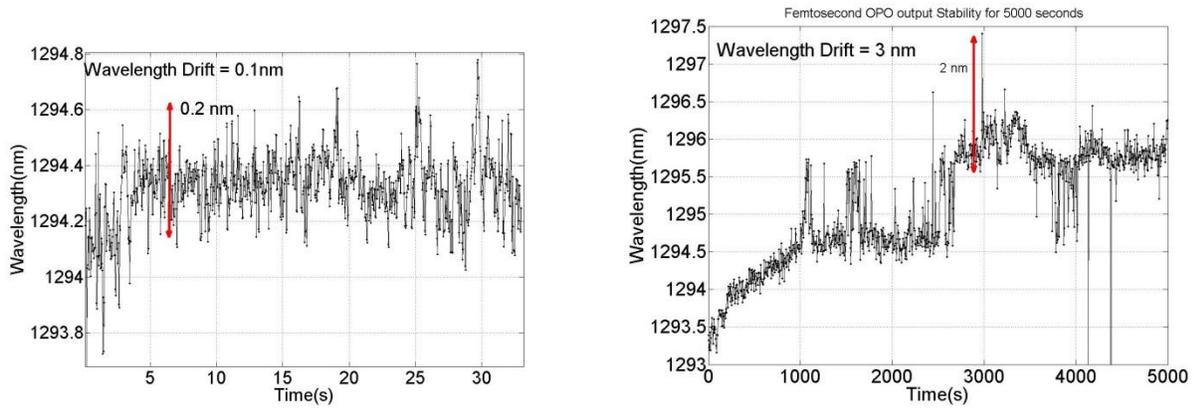


Fig13(a): OPO Spectrum in a short time with stabilization

(b):OPO Spectrum in a long time with stabilization

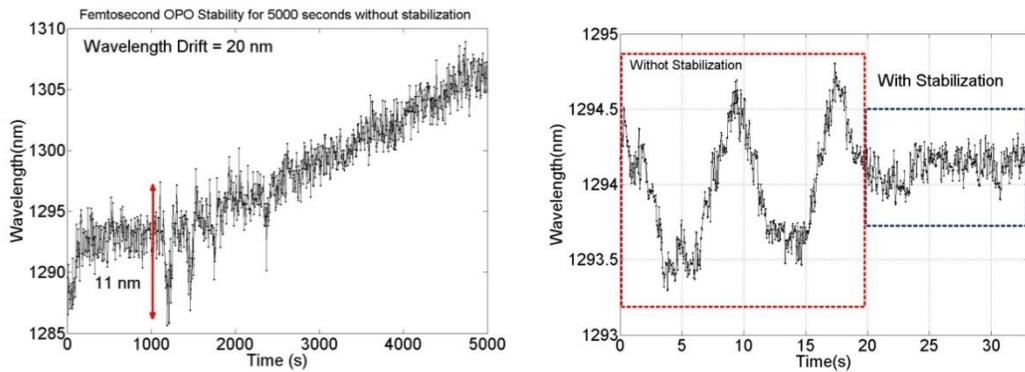


Fig14: OPO Spectrum in a long time without stabilization

Fig 15: Fluctuation of the OPO spectrum with PZT changing

In next Fig 15, indicates that the effect of the PZT changing with and without stabilization.

Fig 15, we can clarify the fluctuation of the OPO spectrum without stabilization is nearly 1.2nm and with stabilization is just 0.2nm. In this experiment we try to show that stabilization can compensate the mirror move around nanometer, otherwise without stabilization, we can see the effect of the mirror movement on wavelength.

In the next step, we try to improve the setup by aligning the OPO, synchronizing length of the FPI, optimizing the parameters (gain, time constant, etc...) and the also electronic feedback loop. The best result after this improvement is shown in Fig 16.

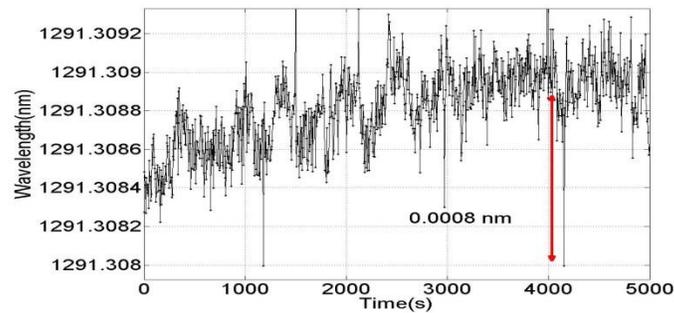


Fig 16: OPO Spectrum in a long time with stabilization

Fig 16 we can see clearly the effect of the improvement of setup. The fluctuation of the Femtosecond OPO spectrum in 5000 seconds is just 0.0008 nm and the drift of the wavelength is 0.0006 nm.

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