

SYNCHRONIZATION OF 3GHZ REPETITION RATE HARMONICALLY MODE-LOCKED FIBER LASER FOR OPTICAL TIMING APPLICATIONS*

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Abstract

We have successfully stabilized a 3GHz Harmonically Mode-Locked fiber ring laser by a PLL feedback control of the cavity length to reduce the pulses RMS timing jitter. The laser cavity is composed of all PM fibers and components to eliminate polarization instabilities and to reduce the vibration sensitivity. The laser stability in terms of timing jitter was around 9ps in the range 10Hz-10MHz. Using a PLL scheme we synchronized the laser repetition rate to an ultra stable RF generator. The noise characteristics of the laser output were measured by observing the SSB noise spectra of the 1st harmonic, from 10Hz to the Nyquist frequency (1.5GHz). We have obtained a global reduction of fiber laser timing jitter value down to less than 100fs in the range 10Hz-10MHz; a complete overlapping between the laser and the RF generator spectral profiles in the loop bandwidth has been observed. An extended investigation has been performed to estimate the phase noise spectra and timing jitter up to 1.5GHz. By doing so, the contribution of the laser supermodes to the phase noise has been taken into account as well, to quantify the true value of the total RMS timing jitter of the optical pulses.

INTRODUCTION

FERMI is the fourth generation Light Source that is currently being designed at ELETTRA. The timing system will play a crucial role in achieving the expected performance in Linac based FELs due to the sub-ps electron bunch length and to the expanded use of fs-lasers as key components in future light sources. Optical timing systems currently seem to be the only technique to enable an RMS jitter at the 10fs level. A fundamental component of the system here analyzed is the optical reference oscillator.

Within EUROFEL DS3 design study, CNIT Pisa developed an “ad hoc” fiber ring laser source: this source works in regenerative Harmonic Mode-Locking (HML) at 3GHz. Currently it is the only one Optical Master Oscillator in the accelerator community working at 3GHz. At ELETTRA, a PLL system has been developed to decrease the HML fiber laser Phase Noise and RMS Timing Jitter. An extended investigation has been performed to estimate the phase noise spectrum and timing jitter up to 1.5GHz.

HML FIBER LASER SETUP

The HML fiber laser setup is shown in fig. 1. The

cavity is composed by an Optical Band Pass Filter (OBPF) that selects the wavelength, an Optical Isolator and an Erbium Doped Fiber Amplifier (EDFA). The laser cavity is composed of all PM fibers and components to eliminate polarization instabilities and to reduce the vibration sensitivity. The fiber laser under test is thermal stabilized. The cavity length is around 63m, that means a mode spacing about 3.18MHz (f_0).

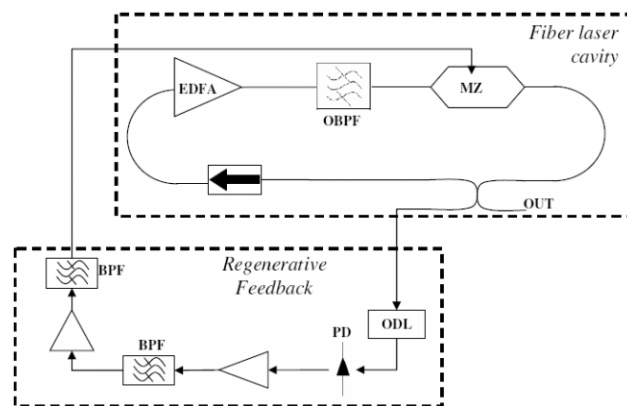


Figure 1: Fiber Laser cavity and Regenerative Feedback; Erbium Doped Fiber Amplifier (EDFA), Optical Band Pass Filter (OBPF), Electrical Band Pass Filter (BPF) Mach Zehnder modulator (MZ), Isolator, Optical Delay Line (ODL), Photodiode (PD).

The stable mode-locking condition is achieved using a Regenerative Feedback loop that selects the 942nd harmonic, this signal drives the Mach Zehnder modulator (MZ) imposing the laser repetition rate of 2.997GHz (f_c). With the Optical Delay Line (ODL) in the regenerative feedback it is possible to adjust the phase of the extracted harmonic respect to the phase of the cavity mode.

PHASE-LOCKED LOOP

A Phase Locked Loop (PLL) is a negative feedback system where an oscillator-generated signal is phase and frequency locked to a reference signal [1].

PLL is a powerful system that can provide elegant solution in many applications such as: skew suppression, frequency synthesis, clock recovery and jitter reduction [2].

The PLL scheme is shown in fig. 2. In these measurements we adopted as Master Oscillator (MO) a low phase noise RF generator (Anritsu MG3692), as Phase Detector a dual balanced mixer (ZX05-2-42). The role of the Voltage Controlled Oscillator (VCO) was covered by the HML fiber laser and the Piezo fiber stretcher (Optiphase PZ2-HE). The piezo fiber stretcher dynamically changes the cavity length to make the laser

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repetition rate equal to the MO frequency. In particular the piezo fiber stretcher introduces a maximum delay of 10ps on the cavity round trip time, which means a fiber length increasing of 3.04mm. Using this piezo fiber stretcher it is possible to correct the fiber laser repetition rate of 130kHz around its nominal frequency (f_c). The *capture range* (Δf_{MAX}) of our system is 250kHz, this is the maximum frequency difference for which the loop locks. By varying the attenuation (LOSS) it is possible to change the phase detector gain (K_{PD}), thus the PLL gain changes to reach the locked state.

The two different frequencies, one taken from the MO and the other from the regenerative feedback, beat at the mixer and generated the Phase Error Signal. The phase error signal is amplified (Gain) and processed by the Proportional-Integrative (P-I) regulator. The gain factor of each arm of the P-I regulator has been adjusted to obtain a stable loop response. When the PLL is locked the I-arms compensates the phase drift. The DC-offset adds a DC voltage offset to the error signal to force the PZT fiber stretcher to work in the middle of the stretching range.

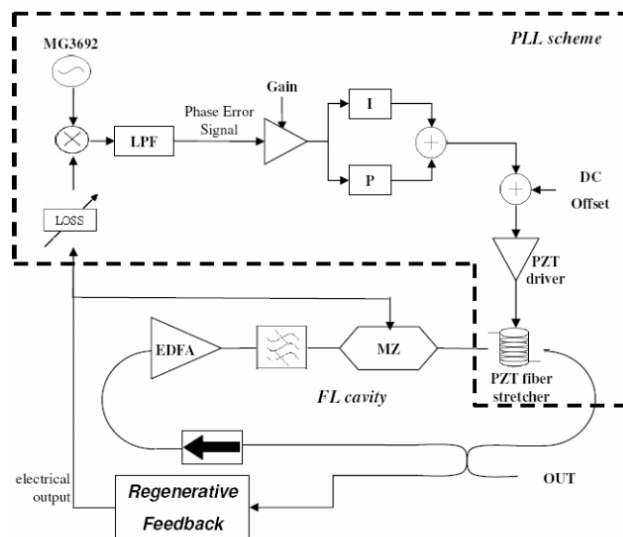


Figure 2: Phase Locked Loop scheme where the VCO is the fiber laser.

EXPERIMENTAL RESULTS

The usefulness of the Harmonically Mode-Locked (HML) laser is highly dependent on the output stability, which makes stabilization and noise characterization crucial for practical applications.

In HML lasers there are two kinds of phase noise contributions depending on the correlation between the pulses inside the cavity: *correlated noise* and *uncorrelated noise*. Correlation of noise on different pulses can arise from: gain dynamics, composite cavity HML lasers, RF oscillator noise [3, 4]. To characterize the correlated noise we photodetected the optical pulses with a photoreceiver (NewFocus 1544B) and we observed the photoreceiver output signal on the Agilent SSA E5052A performing an out-of-loop analysis. The SSB phase noise power spectral density ($L(f)$) has been

integrated from 10Hz up to 1.6MHz ($f_0/2$) when the PLL was OFF giving an RMS timing jitter about 9ps. When the PLL was locked the RMS value of the timing jitter decreased to 98fs (J_{corr}). This value is perfectly in accordance with the specification for the narrow band timing application such as: S-band structure, Photoinjector laser, streak camera driver [5]. In fig. 3 the SSB phase noise spectral profile of the HML laser is compared, up to 40 MHz, with its RF reference: a complete overlapping between the two phase noise spectral profiles in the loop bandwidth (1kHz) has been observed.

A strong reduction of “low frequency” contributes of phase noise occurs when the HML fiber laser is stabilized with the PLL.

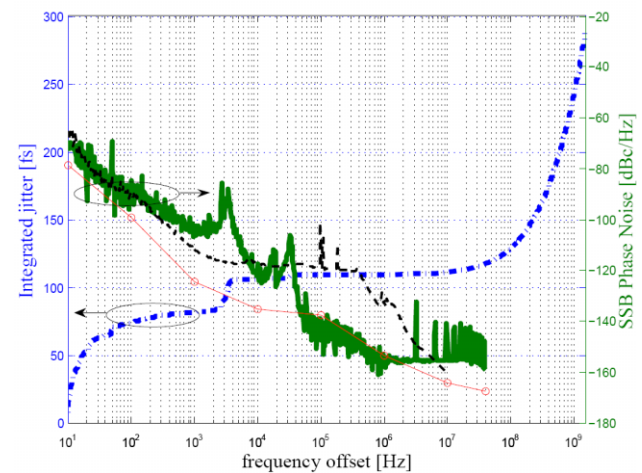


Figure 3: Left axes: integrated RMS timing jitter up to 1.5GHz (tick dashed line). Right axes: SSB phase noise of the HML laser (solid line) and the reference MO (dashed line). Interpolated SSA phase noise floor (circle).

The peak of phase noise at 3.5kHz is due to the PLL dump oscillation, the peak at 30kHz is the laser relaxation oscillation, the peaks beyond 3MHz are the supermodes.

In HML laser uncorrelated noise arises because spontaneous emission and vacuum fluctuation on different pulses are independent. The consequence of the uncorrelated noise is the formation of peaks in the HML laser spectrum at multiple of the f_0 , called supermodes [3, 6, 7]. The supermode phase noise peaks contribution increases significantly timing jitter of the HML laser when they are used in wide band applications such as: cross-correlation, seeding, optical sampling. There are $N-1$ identical noise peaks in a bandwidth equal to the pulse repetition frequency (f_c), where $N=f_c/f_0$. The RMS value for the pulse timing fluctuations due to the supermodes can be obtained by the integration of phase noise PSD over a bandwidth equal to f_0 centred on the supermode, then multiplying the results by square root of N [3]. Experimentally we analyzed the 1st supermode measuring the residual phase noise respect the cavity feedback signal. The experimental setup is showed in fig. 4; where the phase shifter ($\Delta\phi$) was used to maintain the quadrature between the two mixer (ZX05-2-42) inputs to reduce AM noise [8, 9]. The mixer output was amplified by a series

of two amplifiers (ZFL-1000LN, ZFL-1000) to increase the spectrum analyzer sensitivity.

The RMS value of the timing jitter of a single supermode is 12fs and the total contribution of the uncorrelated noise (J_{unc}) is 265fs up to 1.5GHz.

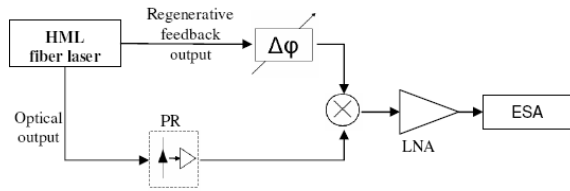


Figure 4: Residual phase noise measurement setup; phase shifter ($\Delta\phi$), photoreceiver (PR), low noise amplifier (LNA), spectrum analyzer (ESA).

The global timing jitter (J_{RMS}) of the HML fiber laser RMS is 283fs, according with $J_{RMS}^2 = J_{corr}^2 + J_{unc}^2$ [3]. In fig. 3 we report the RMS timing jitter of the HML fiber laser as a function of the frequency offset from the carrier integrated up to 1.5GHz.

Moreover the long term stability of the locked system has been observed. The PLL remain locked for tens of hours and it has a good capacity to recover the locking as showed in fig. 5.

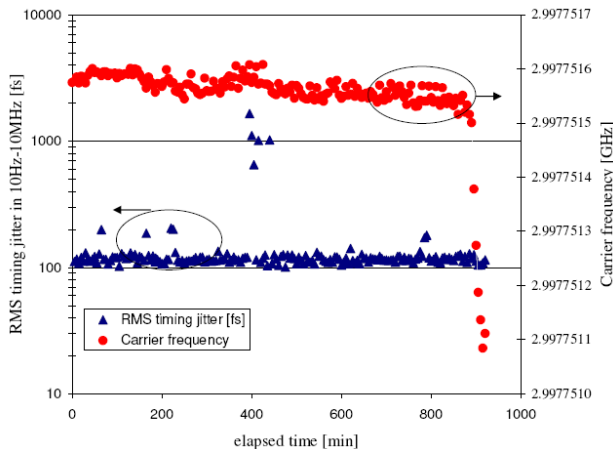


Figure 5: Long term stability of the locking: RMS timing jitter (triangle), carrier frequency drift (circle).

The RIN of the HML laser has been estimated by measuring the spectrum of the photocurrent at baseband with network analyzer (Stanford SR780). The network analyzer provided the AM noise spectrum with no PM noise present. We obtained a RIN of 0.35% integrating the RIN spectral profile, showed in fig. 6, in 10Hz-100kHz.

The PLL stabilization of the laser repetition rate does not have any effect on the amplitude noise of the laser in agreement with [8].

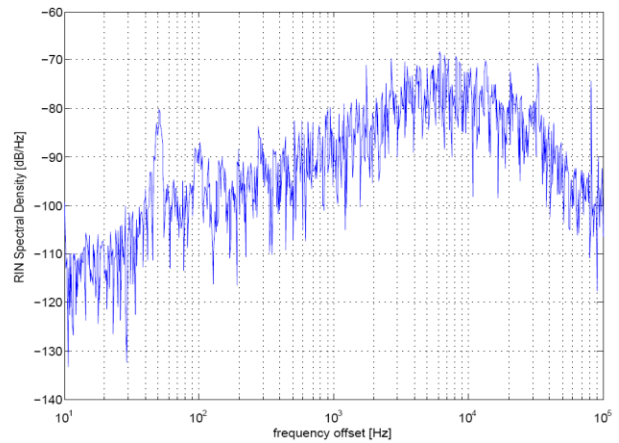


Figure 6: RIN of the HML fiber laser.

CONCLUSIONS

With this work we have performed a complete characterization of the phase noise of the HML fiber laser up to the Nyquist frequency (1.5GHz), and the characterization of the amplitude instability of the laser up to 100kHz

Using a PLL system we locked the 3GHz repetition rate HML fiber laser with a RF master oscillator. In this way we reduced the timing jitter of the laser down to 100fs. We reached the reference oscillator intrinsic RMS timing jitter limit in the PLL bandwidth. Moreover the PLL has showed strong long term stability and a good recovery capacity.

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