Master Lumière et Mesures Extrêmes

Signal et Bruit : travaux pratiques

Stable optical frequency carried through a monomode optical fiber : phase noise study and control

1 Introduction

Since about twenty years remarkable progresses have been made in frequency metrology. It is yet possible to realize optical references characterized by a relative stability of 10^{-17} at 1 second. The goal is the dissemination of those frequencies toward several national laboratories that can then dispose of a local reference. Frequency transfer techniques via satellite such as the GPS degrade considerably the carried frequency. Since a few years several worldwide laboratories work on the development of optical fibered links that allow one to carry a reference frequency through an optical fiber. The optical fiber transfer technique too degrade the frequency stability due to the phase noise created mainly by the refraction index fluctuations along the path. Recent published works shows however that is possible to control the noise brought by the fiber and guarantee thus an optical frequency transfer without degradation of its properties for thousands of kilometers long. The obtained performances are much better than the frequency transfer via satellite techniques, even if the phase noise is, to date, still the fundamental limit.

The fiber transfer technique is used even at the level of a lab experiment, namely in atomic interferometry experiments. In such a kind of applications, is sometimes useful tu use optical fibers for carrying the laser beams to the vacuum system. This allows one to get proper and stable Gaussian spatial modes in the atom-light interaction zone. In the case of atomic interferometry, the phase noise accumulated in the fiber yields a degradation of the fringes contrast and has to be minimized.

The goal of this practical work is the study of an experimental setup that allow one to extract and compensate the phase noise accumulated by the laser wave when propagating through the optical fiber.

2 Principle of the experiment

In Fig.1 is shown the experimental scheme of the principle that allows one to extract the phase noise.

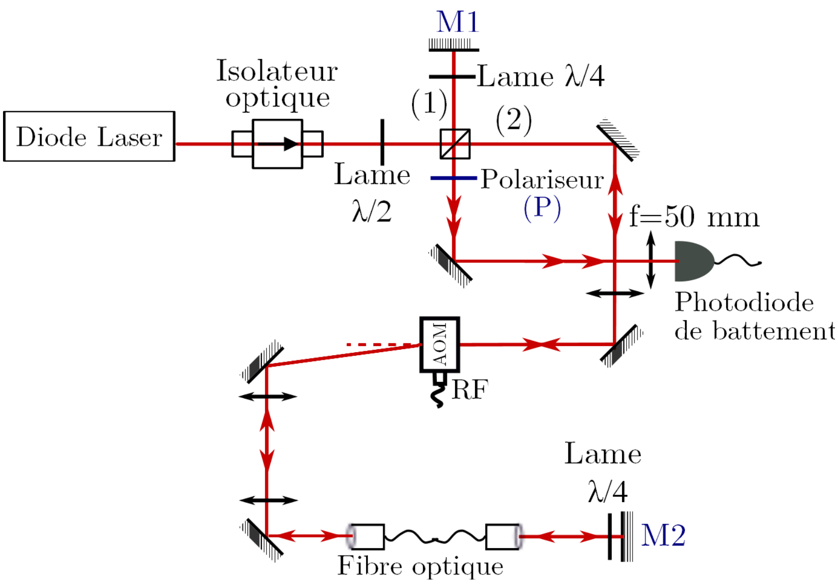

Figure 1: Optical setup scheme.

The source of light is a laser diode. the optical output is split in two beams (1) and (2) by using a half-wave plate and a polarizing beam splitter. One can thus adjust the intensity ratio of the two beams.

- The first beam (1), called reference beam, is sent directly to the photodiode after reflection on the mirror M1; we note E_1 its amplitude at the input of the photodiode.

$$E_1(t) = E_{01}\cos(2\pi\nu t + \phi_L(t)) \tag{1}$$

where $\phi_L(t)$ is the laser phase noise at the time t.

- The second beam (2) passes through an acousto-optical modulator (AOM) excited by a radiowave of frequency ν_{RF}. The first order diffracted beam is reshaped by the use of two lenses and then injected into a monomode optical fiber. At the fiber output, the beam is retro-reflected into the optical fiber after reflexion on the mirror M2; a quarter-wave plate between the fiber and the mirror rotates the polarization of the retro-reflected beam, that goes through the AOM. The first order diffracted beam is thus overlapped with the incident beam.

  We note E_2 its amplitude at the input of the photodiode.

$$\overrightarrow{E}_2(t) = \overrightarrow{E}_{02}\cos(2\pi(\nu + 2\nu_{RF})t + \phi_f(t) + \phi_L(t - 2\tau)) \tag{2}$$

with

- $\phi_f(t)$: the phase accumulated in the optical fiber.

- $\phi_L(t - 2\tau)$: the laser phase noise.
- τ the transit time of the laser beam through the optical fiber.

The beams (1) et (2) are recombined by a polarizer (P); the total wave amplitude at the input of the photodiode is then :

$$E_D(t) = E_{2/P}(t) + E_{1/P}(t) \tag{3}$$

The detector measures the time averaged quadratic value of the field, that is the energy term.

$$E_D^2 = |E_{1/P} + E_{2/P}|^2 \tag{4}$$

To simplify we make the hypothesis that $E_{01/P}$=$E_{02/P}$=E_0

$$\begin{aligned} E_D^2 &= E_0^2\cos^2(2\pi\nu t + \phi_L(t)) \\ &+ E_0^2\cos^2(2\pi(\nu + 2\nu_{RF})t + \phi_f(t) + \phi_L(t - 2\tau)) \\ &+ E_0^2\cos\left(4\pi(\nu + \nu_{RF})t + \phi_f(t) + \phi_L(t - 2\tau) + \phi_L(t)\right) \\ &+ E_0^2\cos\left(4\pi\nu_{RF}t + \phi_f(t) + (\phi_L(t - 2\tau) - \phi_L(t))\right) \end{aligned} \tag{5}$$

The detector has a bandwidth of the order of a few GHz, so the only component that we can measure, filtered by the detector, is the one at the beat frequency $2\nu_{RF}$. This signal contains the signature of the phase noise ϕ_f :

$$S_{batt} = S_0\cos\left(4\pi\nu_{RF}t + \phi_f(t) + \Phi_L(t)\right) \tag{6}$$

where S_0 is the maximal amplitude of the beat signal and

$$\Phi_L(t) = \phi_L(t - 2\tau) - \phi_L(t) \tag{7}$$

$\Phi_L(t)$ is the laser phase noise printed on the beat signal.

The optical setup thus allows one to measure the different phase noises accumulated by the laser beam during its propagation by detecting the frequency beat between the retro-reflected beam (2) and the reference beam (1).

2.1 Study of the optical setup

- Measure the optical power of the laser beam before the AOM and the one of the diffracted beam. Optimize the optical power of the diffracted beam by the help of the screws on the AOM holder. Calculate the diffraction efficiency (ratio between the diffracted beam and the incoming beam optical power). One would expect an efficiency of about 80%.
- Optimize the injection of the laser beam into the optical fiber by using the two mirrors fixed before the fiber. Measure the coupling of the injection (ratio between the output and the input optical power).
- Insert the powermeter in front of the detector and block the reference beam (1). Optimize the beam (2) by the help of the screws of the mirror M2 holder and by rotating the quarter-wave plate fixed at the output of the fiber. Write down the value of the measured power.
- Send the beat signal measured by the detector to the spectrum analyzer. Explain the shape of the signal.
- Look at the same signal at the oscilloscope. Measure the pic-to-pic amplitude.

2.2 Chain for frequency control

The chain for the radio-frequency control that allows one to extract the error signal carrying the phase noise signature is described in Fig.2.

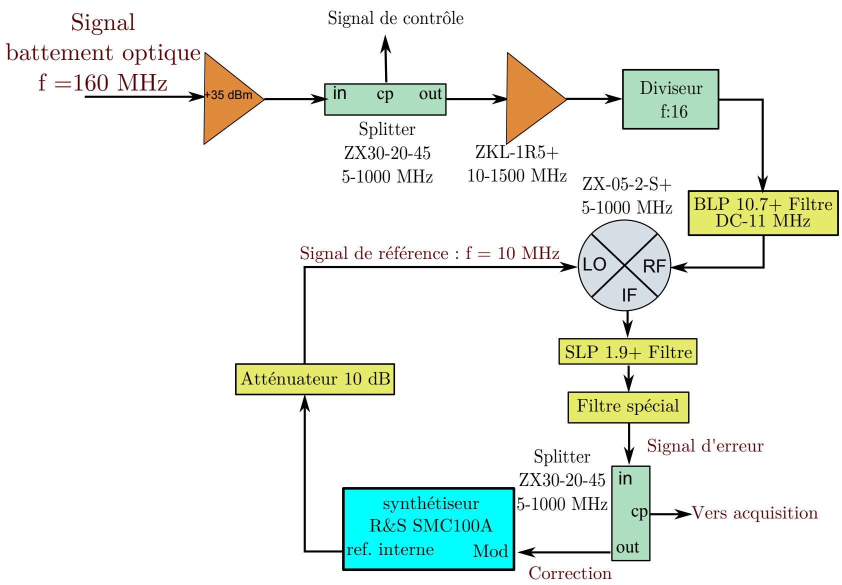

Figure 2: Radio-frequency chain scheme.

The fast photodiode detects the beat signal that is then amplified by two amplifiers in cascade. A RF-coupler inserted between the two amplifiers is used to take a fraction of the beat signal for monitoring purpose. The other output of the RF-coupler is sent to a frequency divider (by 16). The divider output is filtered and then mixed to a 10 MHz reference signal (coming from the internal reference of the synthesizer that drives the AOM). The mixer output carries the phase noise signature. After a proper filter, this signal is sent to the external modulation frequency input, realizing in this way an active compensation.

- Why the frequency divider is needed?
- In a first step, let's calibrate the phase noise at the output of the frequency chain. To do this, set the frequency of the Rohde & Schwarz synthesizer at 80,800 MHz. Look at the error signal (output of the RF-chain) on an oscilloscope and calculate its frequency. By using this signal, give the conversion factor phase-output voltage that is expressed in V/rad.

- Set the synthesizer frequency to 80.000 MHz and send simultaneously the error signal to both the external frequency modulation of the synthesizer and the AI0 input of the acquisition card.
- Run the data acquisition program "TP-fibre-LUMMEX" by following the instructions given here below in the paragraph "useful informations"; insert the data acquisition parameters listed there.
- Verify that the synthesizer external modulation switch is disabled. Record the error signal and calculate its power spectral density (PSD); save the obtained graphs.
- Enable the synthesizer external modulation switch. Record the error signal and calculate its power spectral density (PSD); save the obtained graphs.
- By comparison between the two PSDs, give the noise rejection rate obtained after correction, and conclude.

Useful informations :

- To run the program for data acquisition and PSD calculation, open the editor window PythonXY, go to the folder .\ bureau\ TPfibre\ and then type "execfile('Tp-fibre-LMMEX.py')".
- The data acquisition parameters are : sampling frequency of 10 000 samples/s; number of points equal to 1000 000, that corresponds to an acquisition time of 100 s.

3 Appendix : list of the components

3.0.1 Optical setup

- Extended cavity diode laser (780 nm) + current source + temperature control.
- acousto-optical modulator.
- 1 polarizing beam splitter.
- 5 high reflecting mirrors for 780 nm.
- 3 lens of focal length 30 cm, 20 cm et 5 cm respectively.
- 1 half-wave plate ($\lambda/2$).
- 2 quarter-wave plates ($\lambda/4$)
- 1 polariser
- 1 fast photodiode mounted on a bias tee.
- 1 10 m fiber

3.0.2 RF-chain

- Frequency synthesizer Rohde & Schwarz SMC100A
- 35 dB amplifier.
- 2 x Splitter Mini-circuit ZX30-20-4S+ (5-1000 MHz) with ratio 10%-90%.
- Mini-circuit ZKL-1R5+ (10-1500 MHz) amplifier (30 dB)
- Frequency divider (:16) Analog-Devices ; Eval-ADF4007
- Low pass filter, Mini-circuit BLP 10.7 (DC-11 MHz)
- Frequency mixer, Mini-circuit ZX05-2S+ (5-1000 MHz)
- 10 dB attenuator, Mini-circuit HAT-10+ (DC-2 GHz)
- Special filter
- Spectrum analyser
- Oscilloscope Tektronik TDS3014B
- National Instrument acquisition card
- Mini-pc on which python is installed for data acquisition and analysis