

Lab work in photonics

Optical fibers and telecommunications

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F 1

Optical fiber communication: chromatic dispersion effect

Version Date July 11, 2024

Prior to the lab session :
we kindly ask you to read the following labwork note
and to answer the preparatory Questions.

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Introduction

The chromatic dispersion is one of the major limiting linear effect for optical fiber communication bandwidth. This labwork intends to study :

- the **chromatic dispersion** of a “standard” single mode fiber (SMF) operating in the wavelength range [1500 nm; 1600 nm] ,
- the chromatic dispersion of a length of Dispersion Compensating Fiber (DCF),
- the bandwidth limitation of a fiber link due to dispersion effect. Bite Error Rates (BER) of a single channel fiber link will be estimated through measurements of Quality-Q factors at bite rates varying from 400 MHz up to 12 GHz.

1 Preparatory Questions

Although single mode fibers do not suffer from intermodal dispersion, they exhibit intramodal dispersion related both to the material and the waveguide structure contributions.

As a consequence, the group velocity, which defines the speed at which optical pulses propagate through the fiber, depends on the wavelength. Because the spectral components of the optical pulses experience slightly different group velocity, transmitted pulses undergo a temporal broadening, which limited the bandwidth of a fiber link. This effect refers to the *Group Velocity Dispersion* (GVD) effect (or Chromatic Dispersion). The group delay ΔT_g between two wavelengths λ and $\lambda + \Delta\lambda$ (in nm) is given by the relation:

$$\Delta T_g = D(\lambda) \cdot L_{\text{fibre}} \cdot \Delta\lambda,$$

with $D(\lambda)$ the dispersion coefficient of the fiber (in ps/(nm.km)), and L the fiber length in km. A typical value for the dispersion coefficient of a SMF operating around 1500 nm is about +20 ps/(nm.km).

For further explanations about dispersion effect, one can refer for instance to the textbook « Fiber-Optic Communication Systems » by Govind P. AGRAWAL.

P1 Search for the current maximum bit rates in optical telecommunications.

P2 One considers an optical carrier at 1550 nm (provided by a single mode laser) modulated in amplitude at 12 Gbits/s. Which is the frequency of the optical carrier ? Give an order of magnitude for the spectral bandwidth of the modulated optical carrier in GHz and in nm unities. Considering the propagation of the optical pulses through 50 km of SMF fiber, calculate the expected temporal broadening of the transmitted pulses. Compare with the initial pulse duration, measured at the input of the fiber. Conclusion ?

P3 Remind the relation between the BER and the Q-factor.

P4 What is the difference between PC and APC fiber connectors ?

P5 Explain briefly the operation principle of a wavemeter.

2 SMF Fiber: chromatic dispersion measurement

2.1 Measurement of the group delay variation with operating wavelength

Principle

The measurement consists in modulating the intensity of a tunable laser diode with a sinusoidal signal, and in measuring at the fiber output the variation in the time delay (or the time advance) that can be observed on the sinusoidal signal between two operating wavelengths. It is schematically presented in Fig. 1.1.

The signal is generated by an arbitrary waveform generator (AWG, SONY), which directly modulates the injected current of the tunable laser diode TUNICS OM. The output of the laser is connected to a 5/95 fiber coupler. The 5% port is connected to a wavemeter, allowing the measurement of the laser wavelength. The 95% port is connected with the fiber under test. An optical amplifier is placed after the fiber link to compensate for the fiber losses, prior to the signal detection using the fast oscilloscope (DSA8200, Tektronix).

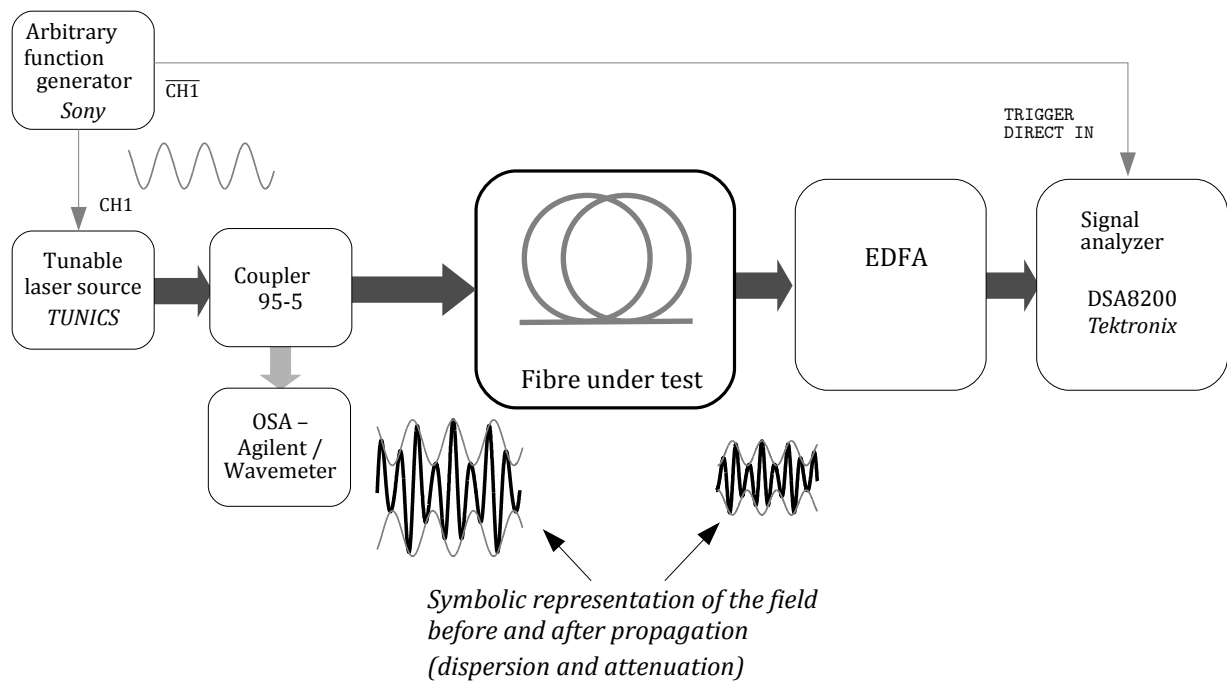


Figure 1.1 – Experimental set-up for the chromatic dispersion measurement.

Operating procedure

↪ Switch ON the Arbitrary Wave Generator Sony/Tektronix (AWG610) and the fast oscilloscope (*Digital Serial Analyzer Tektronix DSA8200*).

The DSA8200 is a digital oscilloscope with a 12 GHz analog bandwidth. It is a crucial (and expensive) instrument for this experiment and we have benefited from the free provision of the device by *Tektronix*.

!!! Precautions !!!

In order to prevent the DSA8200 from any electrostatic discharges, please wear the antistatic wrist strap!

Check that the input applied voltages do not exceed the MAX voltages indicated for the CHANNEL and TRIGGER inputs (written on the front panel).

During the experiment, one should use the input Channel CH3, which is an *Optical Sampling Module*. It comprises a high speed photodiode followed by a high bandwidth amplifier. A **plug-in concerter is provided on CH3, which must never be removed**. Finally, take **caution with the manipulation of the fiber patch connectors**. After unplugging a fiber connector, protect it by using a dust cap. Thank you.

Switch-on the laser diode source

↪ Connect the laser source (TUNICS - fibre patch FC-APC) output to the fiber coupler (95% - 5%)

- ↪ Connect the output 5% to the wavemeter.
- ↪ Check that the laser diode is tunable by changing the length of the external cavity.
- ↪ Measure the power delivered by the laser diode.
- ↪ Check the wavelength with the wavemeter.

Switch-on the Arbitrary Wave Generator AWG610

- ↪ Press the button `Power`. The generator will automatically provide on CH1 and $\overline{\text{CH1}}$ a sinusoidal signal with a 1.4 V amplitude and at a 500 MHz frequency.
- ↪ To generate the signal, press the button `RUN` and then, the buttons CH1 and $\overline{\text{CH1}}$.

Laser Modulation

- ↪ Switch-on the oscilloscope DSA 8200.

CAUTION : please wear the antistatic wrist strap!

- ↪ Using a fiber patch, connect the 95% port of the fiber coupler to the channel input CH3 of DSA 8200.
- ↪ Connect the output CH1 of the AWG to the modulation input of the laser diode. In order to trigger the DSA 8200, connect $\overline{\text{CH1}}$ to TRIGGER DIRECT IN of DSA 8200.

Check that the input applied voltages do not exceed the MAX voltages indicated for TRIGGER input.

Q1 Visualize and check the waveform of the signal obtained at the oscilloscope. Measure its frequency.

Chromatic dispersion measurement of a 50 km SMF fiber coil

- ↪ Connect the 95% exit port of the fiber coupler to a 50 km SMF fiber coil.
- ↪ Connect at the 50 km output an optical amplifier (EDFA, Erbium Doped Fiber Amplifier).
- ↪ and connect the output port of the EDFA to the channel input CH3 of DSA 8200.

Q2 Observe and comment the variation of the detected signal with the operating wavelength of the laser diode TUNICS-OM.

Q3 By increasing operating wavelength of the laser, would you say that the signal is delayed or advanced ? Conclude about the sign of dispersion coefficient $D(\lambda)$?

Measurements and comments

One reminds the relation for the group delay dispersion:

$$\Delta T_g(\lambda) = D(\lambda) \cdot L_{\text{fibre}} \cdot \Delta\lambda$$

Q4 Suggest and explain the method that you will employ to measure the dispersion coefficient $D(\lambda)$ (in ps/(nm.km)) at different operating wavelengths.

Note: The measurements will be limited to the wavelength range 1530 – 1580 nm, which coincides with the tunability range of the laser diode.

→ Measure the dispersion coefficient of the 50 km SMF fibre coil in the range 1530 nm to 1580 nm (take between 5 to 10 points). Plot the curve.

Q5 Compare your measurement with the reported values for SMF fibre around 1550 nm (see figure 1.2). Comment about the precision of your measurements.

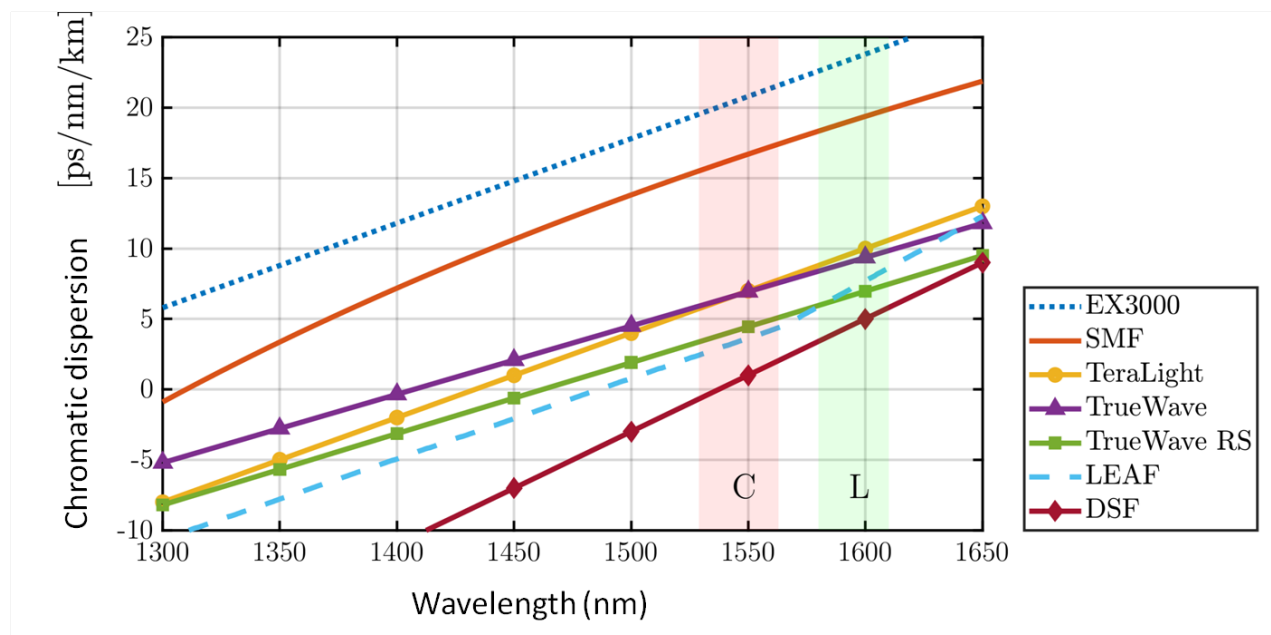


Figure 1.2 – Chromatic dispersion of several kinds of fibers

2.2 Linear attenuation measurement

→ Using the power-meter, measure the linear attenuation of the 50 km fiber coil in dB/km.

Q6 Compare with the expected (or typical) attenuation for such a fiber. Explain the origin of an excess loss in your measurement set-up.

↪ Measure the gain of the optical amplifier with the powermeter.

Q7 What is its role ?

3 DCF Fiber: chromatic dispersion measurement

A coil of Dispersion Compensating Fiber (DCF) is available on the set-up, allowing to compensate the dispersion effect introduced by an SMF fiber coil. The characteristics of the DCF fiber coil are the following:

- Length : $L_{\text{DCF}} = 9,5 \text{ km} \pm 0,1 \text{ km}$
- Attenuation: $0,5 \text{ dB/km}$
- valeurs de dispersion totale de cette fibre DCF :

$$L_{\text{DCF}} \cdot \mathbf{D}(1550) = -831,2 \text{ ps/nm} \text{ and } L_{\text{DCF}} \cdot \mathbf{D}(1590) = -945,0 \text{ ps/nm}$$

(manufacturer's data *for the whole coil*, one needs to divide by approximately 9,5 to get a value in ps/(nm.km)).

↪ Substitute the SMF fiber coil by the DCF fiber coil.

Q8 Check the sign of the group delay versus the wavelength.

↪ Measure the dispersion coefficient of the DCF fibre in the range 1530 nm to 1580 nm (take between 5 to 10 points). Plot the curve.

↪ Measure the linear attenuation of the fiber coil.

Q9 Show that the DCF fiber coil could compensate the dispersion introduced by a 50 km long SMF span.

↪ Use a simple manipulation to verify this.

4 Optical fiber transmission

We next proceed by testing the performance of a numerical transmission through an optical fiber link. The numerical data is provided by a Pulse Pattern Generator (PPG) Anritsu MP1763B, which can generate pulse sequences with a bite rate up to 12 Gbit/s. The Bite Error Rates (BER's), which will be estimated through the measurement of the quality-Q factor, achieved with one span of SMF, with and without the DCF fiber, will be compared. By doing so, we intend to show the limitation introduced by the dispersion effect on the performance of the fiber transmission towards 10 Gbit/s.

4.1 Eye diagram and quality factor

The PPG generates a Pseudo-Random Bit Sequences (PRBS) for which one can adjust the clock frequency (or equivalently the bit rate) and the bit sequence length (expressed in terms of $2^N - 1$, with $N = 7, 8, \dots$). The electrical signal will be used to modulate the intensity of the laser diode, and the modulated signal propagate along optical fiber spans. The optical signal will then be sampled using the high speed sampling oscilloscope. Because the oscilloscope cannot provide a real time sampling, the sampled waveform that will be displayed is the superposition of thousands sampled points of the PRBS sequence. All the sampled points are synchronized with the clock signal provided by the PPG and connected to the TRIGGER input of the oscilloscope, but the sample time randomly varies for each sample. Using the persistence mode of the oscilloscope, the resultant superposition of thousand of samples will form a diagram that looks like an eye, as depicted in Fig. 1.3. Such an eye diagram gives statistical information about the sampled signal. The eye pattern enables to measure the bit period, the rise and fall times, any time jitter... and finally, it allows the measurement of the Q factor.

As shown in Fig. 1.3, one can actually measure from the eye pattern the zero and one average levels, respectively denoted I_0 and I_1 , and the r.m.s widths σ_0 and σ_1 related to the zero and one levels (see Fig. 1.3). It can be shown that the BER can be estimated through the calculation of the Q factor defined as:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

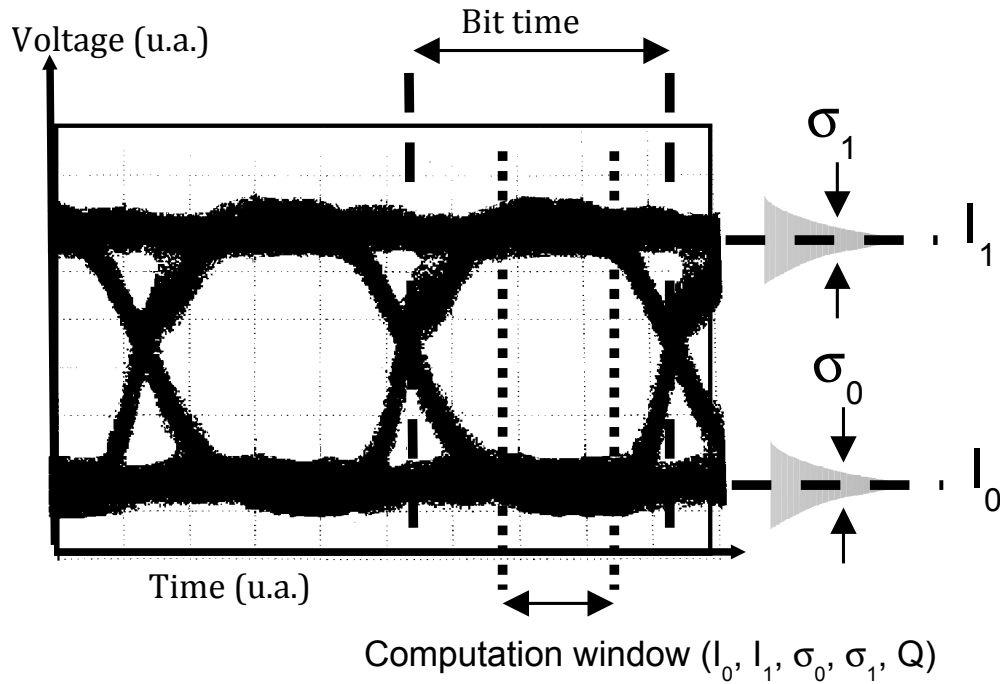


Figure 1.3 – Eye diagram

Assuming a gaussian noise distribution, an equiprobability of emitting "0" and "1" bits (respectively coded by a "zero" and a "one" amplitude levels), the relation between the Q factor and the BER is:

$$\text{BER} = \frac{1}{2} \left(1 - \text{erf} \left(\frac{Q}{\sqrt{2}} \right) \right) \quad \text{with} \quad 1 - \text{erf}(z) \approx \frac{e^{-z^2}}{z\sqrt{\pi}}$$

The fast oscilloscope DSA 8200 enables to display eye diagrams and level histogram distributions for the signal, and finally to calculate the Q factor.

Explanation of the eye diagram. In the temporal acquisition-visualization window, the trigger is done on each edge of the clock, the rising edge for example. All possible bit combinations are present in the pseudo-random sequence (0-0-0, 0-0-1, etc.) : the eye diagram is the superposition of all these combinations (see fig. 1.4 below).

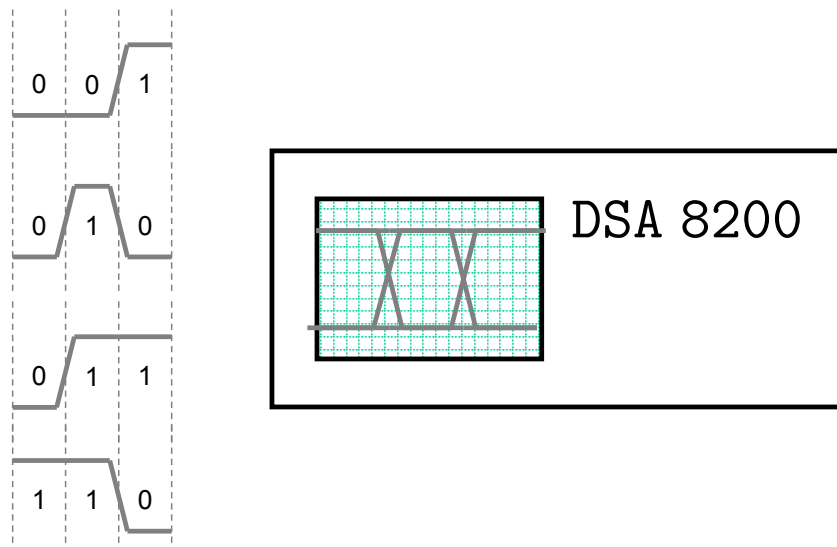


Figure 1.4 – Visualization of successive 0 and 1 during a time interval Δt (2 'bit times' typ.)

4.2 Experimental set-up

Because of its limitation in the modulation bandwidth, the tunable laser diode is replaced for this experiment by a Distributed FeedBack (DFB) laser diode emitting at a fixed wavelength (1528 nm). This DFB laser diode integrates an external modulator (electro-absorption type modulator) enabling intensity modulation up to 10 Gbit/s. The laser diode source is mounted inside a metallic box (to protect it).

→ As it will be clarified below, check that the **Red LED** set on the metallic box is **switched ON**, prior to plug the modulation signal.

External Modulator

The electro-absorption type modulator that is directly integrated onto the laser diode chip is controlled by applying the input voltage that must be comprised between 0 V and 2 V. As shown in Fig. 1.5, the transmission varies, under such a modulation, between 0 to -16 dB.

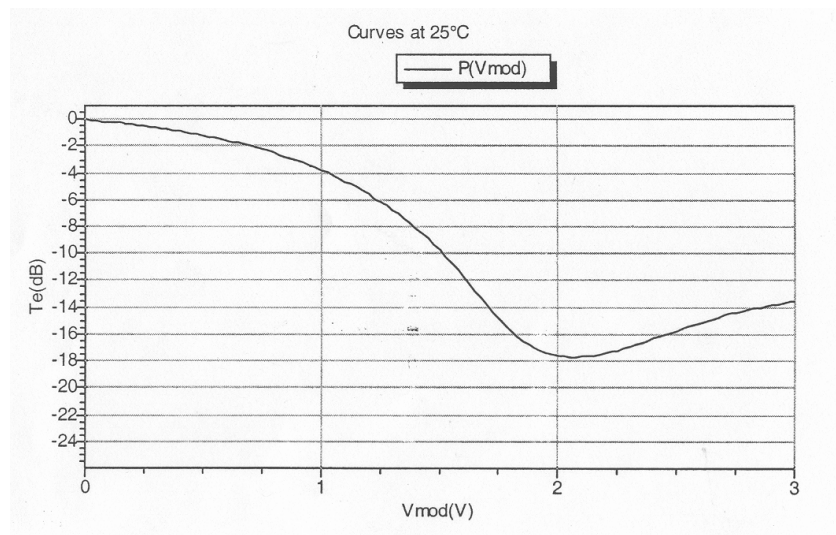


Figure 1.5 – Transmission curve for the electro-absorption type modulator with the modulation signal voltage.

The modulator is a fragile component that needs to be polarized with a fixed continuous voltage of +12 V, prior to the application of the modulation signal. Once the device is polarized, the Red LED is ON.

CAUTION

Before applying the input modulation signal, check that the Red LED set on the metallic box is ON !!!

Pseudo-Random Bit Sequences Generator

As said before, the PPG (Anritsu MP1763B) generates a Pseudo-Random Bit Sequences (PRBS) for which one can adjust the clock frequency (or equivalently the bit rate). Hereafter the length of the sequence is set to $2^7 - 1 = 127$ bits. The contents of the sequence is predefined and is "continuously" displayed at the output DATA.

→ The only parameter to be changed during the experiment will be the Clock frequency that can be varied from 500 MHz to 12 GHz.

DSA 8200 Oscilloscope Trigger Control

The DSA 8200 oscilloscope can be triggered by either using:

The signal PATTERN SYNCH provided by the PPG, which is synchronized with the PRBS sequence. It can be plugged to the input TRIGGER DIRECT INPUT.

→ This operating mode enables to visualize the transmitted signal modulated by the pseudo-random bit sequence.

or the CLOCK signal to synchronize the data sampling of the oscilloscope with the clock signal.

- This operating mode enables to get the eye diagram and to measure the quality factor on the transmitted modulated signal.

Caution The maximum signal frequency for the TRIGGER DIRECT INPUT is set to 3 GHz. Beyond this value, use the TRIGGER PRESCALE INPUT, and select it in the TRIGGER menu of the oscilloscope.

CAUTION

Please wear the antistatic wrist strap!

For each DSA 8200 inputs, please check that the applied voltage is set within the maximum voltage range indicated on the front panel.

4.3 « back-to-back » configuration

In this configuration, the emitter is directly linked to the transmitter.

↪ Check that the Red LED is ON, then connect the PPG output DATA to the input signal modulation of the DFB laser diode.

↪ using a fiber patch, connect the laser diode output directly to the CH3 input of the oscilloscope.

PATTERN SYNCH Trigger

↪ Set the clock frequency of the PRBS signal to 10 GHz. Visualize the signal trace on the oscilloscope. Explain why the sampled signal gives a representation of the DATA sequence. Compare the bit period with the clock frequency and measure the power for the "0" and "1" levels.

CLOCK SYNCH Trgger

↪ By triggering the oscilloscope with the CLOCK SYNCH signal, visualize the eye diagram.

↪ Proceed by measuring the Q factor for bit rates varying between 5 to 12 Gbit/s.

Q10 Give an estimation of the corresponding Bit Error Rates.

DSA 8200 NOTICE

Quality Factor Measurement Menu : SETUP

Measurement source : select the channel under used (CH3)

Select *Use Wfm Database*, and the type modulation format (NRZ)

Select the measurement *Q Factor*

Select *annotation* and use *Waveform*

Clear press CLEAR prior to any measurement (to clear the internal memory).

Save One can record the signals by using internal memories labeled R1, etc. . .

4.4 Transmission over one span SMF+DCF - Compensated configuration

↪ Set a transmission link made of 50 km long SMF fiber, followed by the DCF fiber coil, and the optical amplifier.

↪ Repeat the Q factor measurements for the bite rates applied in the Back-to-Back configuration.

Q11 Give an estimation of the corresponding Bit Error Rates. Compare with those of the Back-to-Back configuration. Conclusion

4.5 Transmission over one span SMF - Un-Compensated configuration

↪ Un-plugged the DCF fiber coil and directly connect the SMF to the optical amplifier.

↪ In order to compare the performance of this uncompensated configuration, with the previous compensated configuration, one needs to **intentionally** insert a lossy connection between the SMF and the optical amplifier, which coincides with the loss of the DCF fiber coil.

↪ Repeat the Q factor measurements for the bite rates applied in the Back-to-Back configuration.

Q12 Give an estimation of the corresponding Bit Error Rates. Compare with those of the Back-to-Back configuration, and of the compensated configuration. Conclusion

↪ At a 12 Gbit/s bit rate, visualize and compare the DATA sequences detected at the end of the compensated and uncompensated configurations (use `PATTERN SYNC` to trig the oscilloscope).

Q13 Explain the relation between the chromatic dispersion effect and the performance of the transmissions.

↪ In the case of the uncompensated configuration, measure the rise time of the transmitted data signal.

↪ Compare the measured value with that calculated in the question **P2**.

F 2

Fiber optic gyroscope

« *Eppur se muove* »

Galileo Galilei, June 22, 1633

Version date: July 11, 2024

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Introduction

The reliable and accurate determination of the geographic positioning of boats and planes is a key element for both civilian and military applications. Global Positioning Systems (GPS) devices provide an interesting solution but, for some specific applications, may not offer a complete one in terms of availability and reliability.

Embedded and stand-alone positioning solution might be necessary in some applications. This may be provided by inertial navigation systems based on a combination of accelerometers and gyroscopes.

Various models of gyroscopes exist, mechanical or optical gyroscopes, even atomic gyroscopes ! The optical gyroscopes can either be a Ring-Laser gyroscope or an interferometric fiber optic gyroscope. Optical gyroscopes are often more sensitive than mechanical gyroscopes. They are mainly used in navigation system devices used in airplanes, drones or missiles.

Reference For a complete and detailed review about fiber optic gyroscopes, one can refer to the textbook entitled "Fiber-optic gyroscopes" by Hervé Lefèvre.

1 Preparation questions

P1 Which devices enable to dephase a wave ? Give briefly the principle. Does the dephasing depend on the propagation sense ?

P2 Give the principle and interest of synchronous detection (or lock-in amplifier).

2 Interferometric fiber optic gyroscope: operating principle

2.1 The Sagnac effect

The Sagnac effect is related to the dependence of the interference pattern observed at the output of a rotating interferometer (and possibly accelerating). This effect has been demonstrated experimentally by G. Sagnac in 1913 using a pentagonal interferometer placed on a rotating table. The first evidence of the Earth's motion of rotation by means of Sagnac effect was realized by Michelson and Gale Pearson in 1925 with a giant interferometer of 0.21 km^2 in surface. The first optical gyros appeared shortly after the invention of laser (1963 for the first laser gyro) and the industrial manufacture of optical fibers (1976 for the first fiber optic gyro).

The Sagnac effect appears in a two-wave interferometer in which the two waves propagate through the same closed path in opposite directions, see Fig. 2.1. If the interferometer is not moving, the two waves, injected at point A, interfere in phase after one round trip at A, as they propagate through exactly the same optical path. Such a geometry refers to a *perfect reciprocity* interferometer as the two paths of the interferometer are strictly equivalent. The interference between waves 1 and 2 at the output is then constructive.

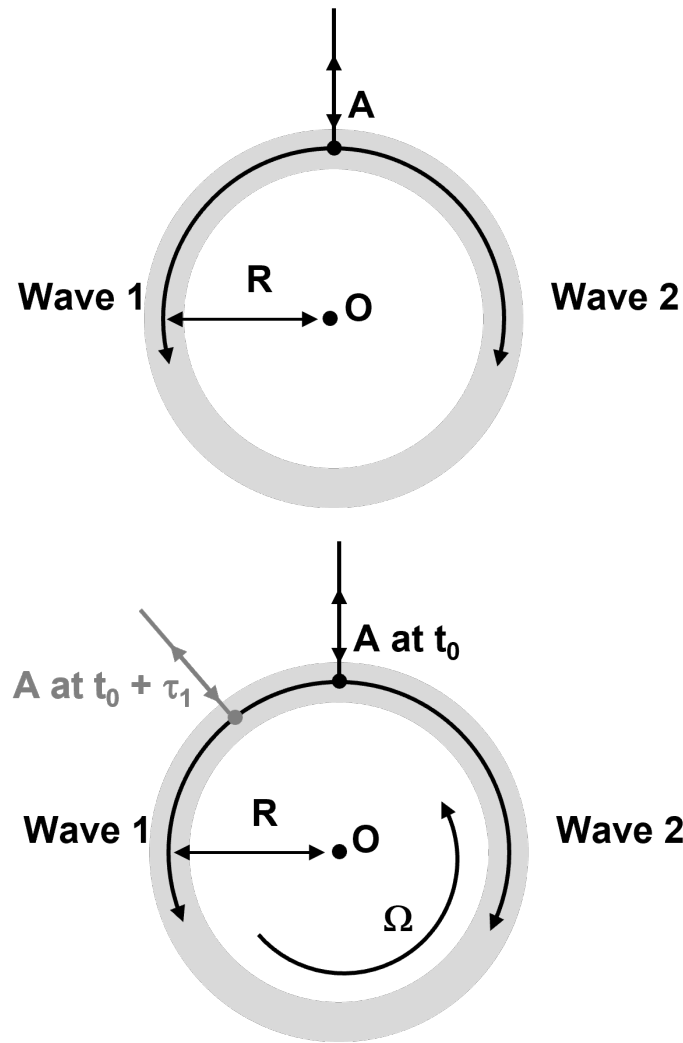


Figure 2.1 – Sagnac Interferometer

If the interferometer is now experiencing a motion of rotation at the frequency Ω , the two waves will acquire a phase shift after one round trip: *this is the signature of the Sagnac effect !* This ‘Sagnac phase shift’ can be simply calculated using the following steps, see Fig. 2.1.

One considers a rotating interferometer, which is observed in a Galilean reference frame. Next, the counter-propagating waves will be assumed to propagate at the vacuum speed c . Along their propagation inside the rotating interferometer, the path difference between the two waves after one round trip, or equivalently the time delay, can be calculated through:

- For wave 1:

$$c\tau_1 = 2\pi R + \Omega R\tau_1 \quad \text{giving a round trip time} \quad \tau_1 = \frac{2\pi R}{c - \Omega R}$$

- For wave 2:

$$c\tau_2 = 2\pi R - \Omega R\tau_2 \quad \text{giving a round trip time} \quad \tau_2 = \frac{2\pi R}{c + \Omega R}$$

Consequently, the time delay between the two waves is:

$$\Delta\tau_{\text{Sagnac}} = \tau_1 - \tau_2 = \frac{4\pi R^2\Omega}{c^2 - R^2\Omega^2}$$

$$\Delta\tau_{\text{Sagnac}} \approx \frac{4\pi R^2\Omega}{c^2} \quad \text{because } |R\Omega| \ll c \quad (2.1)$$

Introducing $A = \pi R^2$ the interferometer area and ν the optical frequency of the waves, or $\lambda = c/\nu$ the wavelength, the Sagnac phase difference is given by the relation:

$$\Delta\varphi_{\text{Sagnac}} = 2\pi\nu\Delta\tau_{\text{Sagnac}} \approx \frac{8\pi\nu A}{c^2}\Omega = \frac{8\pi A}{\lambda c}\Omega = K_0\Omega \quad (2.2)$$

assuming $\left(\frac{R\Omega}{c}\right)^2 \ll 1$.

($\Delta\varphi_{\text{Sagnac}}$ in rad, A in m^2 , ν in Hz, λ in m, c in m/s, and Ω in rad/s.)

Q1 The coefficient K_0 refers to a scaling factor and is related to the sensitivity of the fiber gyro. Which is the unity for K_0 ? Check the homogeneity of formulas (2.2).

Note It turns that this simple calculation gives a correct expression for the Sagnac phase difference, even if we should have taken into account c/n , the speed of light in the fiber, instead of c . Behind this subtlety, one has to notice that the Sagnac effect is a purely relativistic effect. Actually, and for a set frequency ν , the Sagnac phase difference **does not** depend on the speed velocity of the waves inside the interferometer !!

For a non-circular shaped interferometer, one can show that the relationship (2.2) remains with A the interferometer area. More precisely, the area A coincides with the projected area of the interferometer on a plane that is perpendicular to the instantaneous rotation vector $\vec{\Omega}$. In the case of the Sagnac interferometer built with a multiturn fiber coil, the total area is $A = N \times A_{\text{loop}}$ with N the number of fiber loop and A_{loop} the loop area.

Finally, the intensity measured at the output of the interferometer follows the relation:

$$\mathcal{I} \propto 1 + m \times \cos(\Delta\varphi_{\text{Sagnac}})$$

The sensitivity of the fiber gyro is governed by the operating wavelength and the interferometer area. The major advantage of fiber gyro rises from the possibility to realize very compact gyro by "simply" increasing the number N of loop fiber. The sensitivity is then directly increased by the N -fold area of a single loop. In practice, fiber gyro consists in 1000 of fiber loops, realized with polarizing maintaining single mode fibers.

As it will be shown during this labwork session, the sensitivity of such fiber gyros allows the measurement of the angular speed of Earth's rotation (the sensitivity of commercial system can detect the Earth's rotation around Sun!!).

2.2 Use of Sagnac effect

In order to have optical gyro that are both sensitive and compact, formula (2.1) shows that one can only plays with λ and A . So only an increase of the area of the interferometer can really improve the sensitivity. There are two technical solutions to increase this area without increasing the dimension of the interferometer : the *gyro-laser* the *fiber optic gyroscope*.

The **gyro-laser** is built with a ring laser cavity in which two counter-propagative modes lase simultaneously. The gain over the area A is obtained by the high quality factor of the cavity (typically one can reach values as high as ~ 5000) that increases substantially the effective number of rotations covered by the two waves dephased by the Sagnac effect.

The **fiber optic gyroscope** uses the fact that optical fibers can be wound over thousands rounds on small size coils. The fiber has to be a singlemode polarization maintaining fiber.

3 Experimental Set-up

The pictures below show the industrial fiber gyro (prototype provided by *SAGEM* company) that will be tested during this labwork.

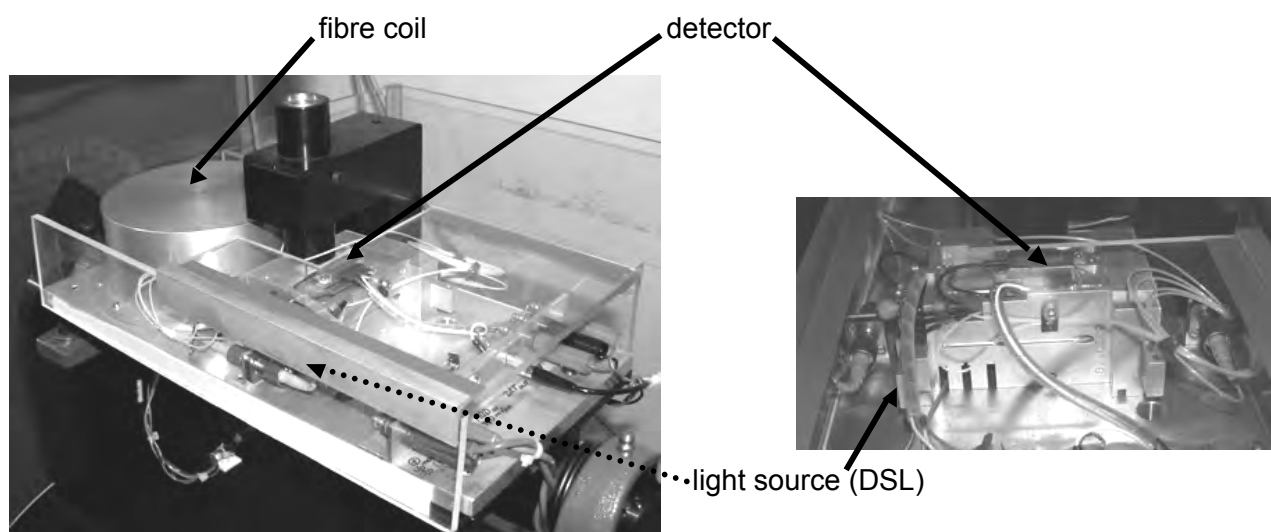


Figure 2.2 – Fiber gyro prototype.

One can first notice the cylindric piece, which contains a single mode fiber coil at 850 nm and with an approximated length of 2 km. The light source is a super luminescent diode (SLD) emitting a broad spectrum around 850 nm.

A **superluminescent diode** is a laser diode with an anti-reflection coating on the output facet. As a consequence, the diode operates below threshold and the emitting light consists in an amplified spontaneous emission with a broad spectrum. The interest in using such a broadband source, instead of a laser diode, concerns its very short coherence length to prevent multiple interference paths, originating from the reflections between connectors, which would parasite the Sagnac interference signal between the two counter-propagating waves.

The **detector** is an amplified silicon PIN photodiode.

Most of the **electrical connections** of the gyro have been already set and **should not be modified**, especially those related to the DSL (risk of destruction). The only connections the user can set are the LEMO type coaxial connectors to connect the detector output and modulation input, see Fig. 2.3 below.



Figure 2.3 – Connectors used for the detector output and the modulation input.

4 Fiber gyro characterization

4.1 Sagnac effect measurement

In this first experimental part, we propose to show the interferometric signature of the Sagnac effect by recording the intensity evolution with the angular speed of the table on top of which the gyro is mounted. The angular speed of the table will be about a few tens of revolutions per minute (rpm).

From the analysis given in § 2.1, the variation of the signal S_g provided by the detector with the angular speed Ω of the table will be:

$$S_g = \frac{S_0}{2} [1 + m \cos(K_0 \Omega)], \quad (2.3)$$

with m the modulation depth and $K_0 = \frac{8\pi A}{\lambda c}$ the scaling factor given in (2.2). Note that Ω is expressed in rad/s.

↪ BEFORE running the engine and that drives the table rotation, imperatively check:

- that no cable is connected between a fixed device and the rotating gyroscope,
- that the brake of the table is unlocked and that the orange brake lever is pointing outwards,
- check manually that the table can freely rotate during one complete rotation.

↪ Open the LabVIEW VI for the gyro experiment (available on the computer).

↪ For table rotation :

- Do not exceed an angular speed rotation of 40 rpm,
- and be careful that no cable falls nor wraps around the rotating gyroscope!

↪ Start the acquisition of the signal S_g and of the instantaneous speed rotation of the table using the LabVIEW VI program. Modify the speed rotation and observe the evolution of the signal. Stop the table and plot S_g in terms of Ω by clicking of the button Visualiser Sg versus Vrot.

NOTE : The measurement of the speed rotation is provided by a rotary encoder connected to the axis of rotation of the table.

↪ Perform quick measurements in order to answer the following questions.

Q2 Determine the interferometer area A by using the relation (2.3).

Q3 Assuming a loop fiber with an average radius of about 5 cm, how many loops do the fiber coil contain? Which is the approximated length L of the fiber coil?

Q4 Why does the signal reach a maximum value at $\Omega = 0$?

Q5 Why is the modulation depth m close to 1?

Q6 Which is the fiber gyro sensitivity nearby very low speed rotation?

Q7 How do we need to proceed to measure "high" speed rotations? Is it possible to determine the sign of the rotation?

4.2 Fiber gyro operating with a phase modulation

Principle

The reciprocity of the interferometer results in an almost null sensitivity of the gyroscope a very low speed rotation. A solution would be to move the operating point nearby a portion of the $S_g = f(\Omega)$ curve where the slope is maximum, which implies to add a fixed phase shift $\Delta\varphi$ between the two counter-propagating waves.

Q8 Explain why the optimised phase-shift $\Delta\varphi = \varphi_{\text{opt}}$ is:

$$\varphi_{\text{opt}} = \frac{\pi}{2} \pm k\pi$$

Q9 For such a phase-shift, show that the interferometric signal, under low speed rotation, $|\Omega| \ll \frac{\lambda c}{8\pi A}$, takes the approximated expression

$$V_d = \frac{V_0}{2} (1 + m\Delta\varphi_{\text{Sagnac}})$$

with V_0 the maximum voltage measured for $\Delta\varphi = 0$.

Q10 Why can not we apply such a **FIXED** phase shift between the two waves?

Electro-optical modulators In the next part of the experiment, a modulation phase $\Delta\varphi(t)$ will be introduced by means of electro-optical modulators (made in Lithium Niobate crystals, LiNbO_3). One reminds the capability of electro-optical effect to modify the phase shift of a wave propagating through a crystal, by applying a controlled voltage. The amount of phase shift is controlled by the amplitude of the applied voltage:

$$\Delta\varphi_{\text{MP}} = kV_{\text{mod}}$$

The architecture of the fiber gyro is actually the following:

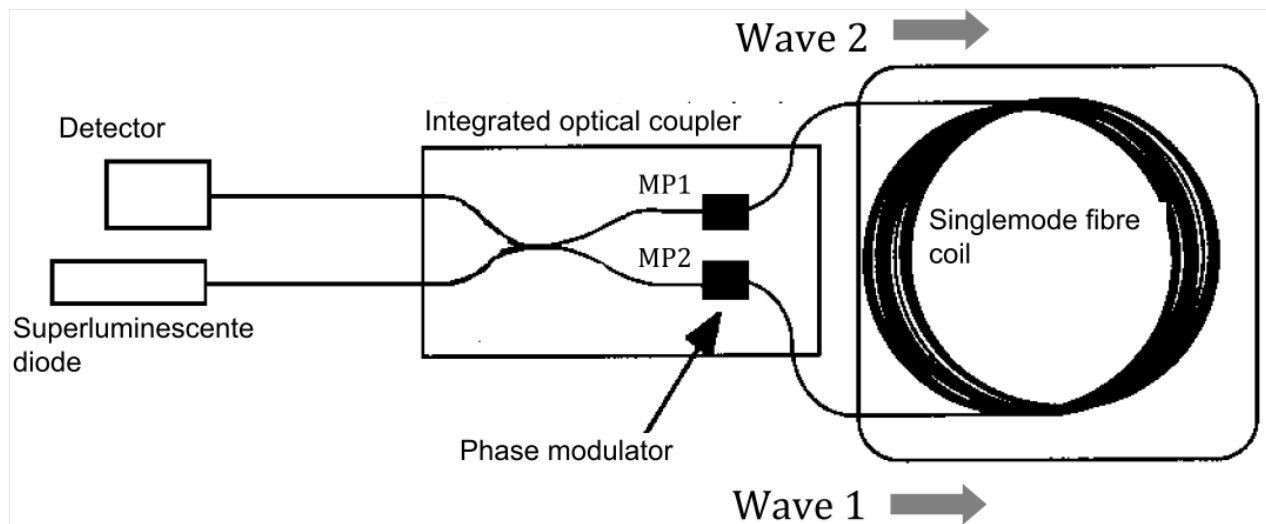


Figure 2.4 – Interferometric fiber gyroscope architecture.

Phase modulation In a first step, the modulator will be driven by a square waveform:

- Suppose that at $t = 0$, we apply an appropriate voltage to modulators MP1 and MP2 (see Fig. 2.4), then two initial wave packets propagate through the modulators and respectively acquire the phases :

$$\Delta\varphi_{MP1} = +\frac{\pi}{8} \quad \text{and} \quad \Delta\varphi_{MP2} = -\frac{\pi}{8}$$

Note : For a given driven voltage, the phase shifts introduced by each modulator are equal in magnitude but opposite in sign.

- The two initial wave packets propagate along the fiber coil with an equal propagation time T :

$$T = \frac{Ln}{c}$$

where L is the length of the fiber coil and n the refractive index of the silica fiber $n \approx 1,47$.

- At time $t = T$, the sign of the driven voltage is reversed, such that each wave packet 1 and 2 after one round trip will respectively see an additional phase shift $+\frac{\pi}{8}$ and $-\frac{\pi}{8}$.
- At the output of the interferometer the phase difference between the two wave packets is then equal to $\frac{\pi}{2}$.
- After a period of time T , the sign of the driven voltage is reversed again, and the phase difference between them is now set to $-\frac{\pi}{2}$.

Q11 Determine an approximated value for the time T using the estimation of the fiber length in Q3

Q12 Deduce from the previous question the square waveform frequency f_{mod} that will drive the modulators.

Experimental study

↪ Prior to any manipulation:

- Switch off the alimentation "Fontaine" used to control the engine,
- unplug the coaxial cable between the output `Détecteur` and the on-board microcontroller
- Connect the output `Détecteur` to the oscilloscope.

↪ Check the signal variation provided by the fiber gyro under a manual rotation of the table.

↪ Lock the rotating table with the brake and measure the value of the detector signal V_0 at rest position.

↪ Select a square waveform on the GBF and adjust its peak-to-peak voltage below 1.5 V (1 V is sufficient).

↪ Connect the output of the GBF to the input `modulateurs` of the fiber gyro and, using a T-connector connect also the output of the GBF to the oscilloscope.

↪ Observe the signal variation provided by the fiber gyro under a manual rotation of the table.

↪ At rest, observe the gyro signal variation with the amplitude and frequency of the driven square waveform.

Q13 Explain your observations by using the curve $V_d = f(\Delta\varphi)$.

Q14 Determine a method to adjust the amplitude and frequency of the driven square waveform, enabling to alternatively introduce a phase shift of $\pm\frac{\pi}{2}$ between the two counter-propagating waves.

↪ Adjust with precision the frequency and amplitude of the square waveform

Q15 Deduce from your adjustments a measurement of the fiber coil length (precise the accuracy).

↪ Observe again the signal variation provided by the fiber gyro under a manual rotation of the table. Comment about the sensitivity of the gyro.

Q16 Why does the gyro signal depend now on the rotation direction ?

↪ Visualize the Fast Fourier Transform (FFT) of the signal (see menu `MATH` on the oscilloscope).

↪ Apply a triangle modulation then a sinusoidal modulation of same frequency and amplitude.

Q17 In each case give an interpretation of the detected signals and of their FFT.

5 Earth's rotation: measurement of the angular speed

5.1 Eppure se muove !

Q18 Calculate the angular speed of Earth's rotation in rad/s. Taking into account the scaling factor K_0 of the fiber gyro, calculate the related Sagnac phase difference $\Delta\varphi_{\text{Sagnac}}$.

Q19 Using the measured value V_0 , calculate the expected amplitude for the gyro signal V_G induced by the Earth's rotation. Why this signal can not be directly detected with the oscilloscope ?

About the interest in using a lock-in amplifier To measure such a weak signal, a lock-in amplifier would be necessary. To proceed, we will apply a sinusoidal modulation to the modulators, and we will show hereafter that the Sagnac signal can be extracted using a lock-in amplifier, which allows to detect even very weak signal levels.

5.2 Sinusoidal modulation

→ Apply a sinusoidal driven voltage, keeping the modulation frequency f_{mod} previously optimized with the square waveform. Observe the variation of the gyro signal under a manual rotation of the table.

Q20 Explain your observations by using the curve $V_d = f(\Delta\varphi)$. Under rotation, explain the presence in the gyro signal of a component at f_{mod} .

In the case of a sinusoidal waveform driving the modulators, the phase shift between the two counter-propagating waves follows

$$\Delta\varphi(t) = \Delta\varphi_0 \cos(2\pi \cdot f_{\text{mod}} t)$$

The gyro signal can now be expressed as

$$V_d(t) = \frac{V_0}{2} [1 + m \cdot \cos(\Delta\varphi_{\text{Sagnac}} + \Delta\varphi_0 \cdot \cos(2\pi \cdot f_{\text{mod}} \cdot t))]$$

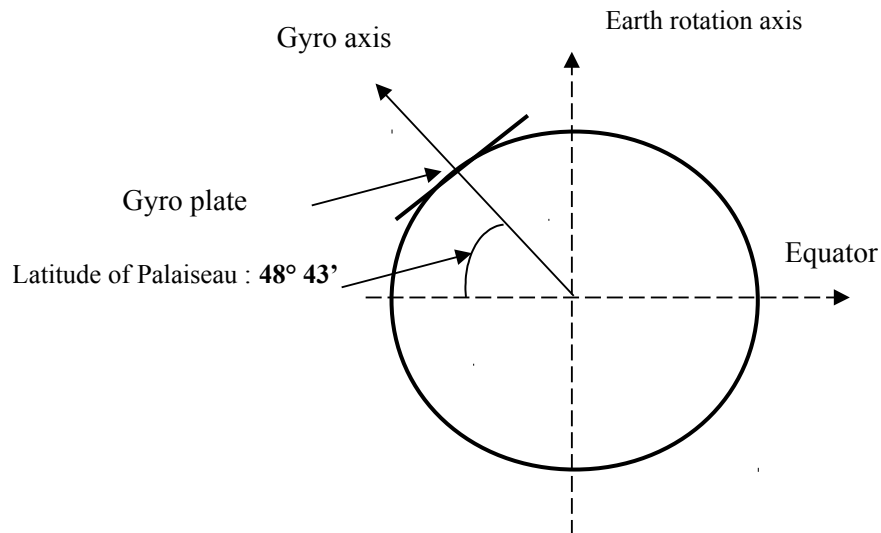
with $\Delta\varphi_{\text{Sagnac}} = K_0\Omega$.

The Fourier series expansions of this signal can be expressed using Bessel functions and the amplitude of the first harmonic (at the frequency f_{mod}) is equal to

$$V_{H1} = -V_0 \cdot m \cdot \Delta\varphi_{\text{Sagnac}} \cdot J_1(\Delta\varphi_0)$$

with J_1 the first order Bessel function.

Q21 Considering that $J_1(\pm\pi/2) \approx \pm 0.567$, determine the expected amplitude and effective values for the gyro signal tension corresponding to the measurement of Earth's rotation.



Q22 Using the figure above, explain how the angular position of the gyro must be set to maximise, minimise, or maximise with a π phase shift, the Sagnac signal induced by the Earth's rotation.

Next part is facultative

↪ Switch ON the lock-in amplifier: connect the gyro signal to the input channel `voie A`, and the modulation to the input `reference`.

↪ Set the following parameters on the lock-in amplifier (from left to right side of the front panel) :

- Sensitivity : $20 \mu V$,
- Filter BP track on,
- Time constant : 300ms or 1s, time constant of the low-pass filter,
- Slope 12 dB, slope of the low-pass filter ($-12 \text{ dB/Octave} = -40 \text{ dB/Decade} = \text{Ordre } 2$)
- DYNamic RESolution : Hi Res
- Display $R\theta$, display the effective amplitude value of the signal at the modulation (or reference) frequency and its phase.
- PRESS on the red buttons `Auto + Phase` : the lock-in amplifier automatically set the phase difference between the signal and the reference.

↪ For each of these angular positions, measure the gyro signal delivered by the lock-in amplifier. A compass and a protractor displayed of the rotating support of the gyroscope will help you to adjust angular positions of the gyro.

↪ At the position which should minimize the Sagnac effect from the Earth's rotation, try to minimize the lock-in signal by finely adjust the modulation frequency. Measure the bias voltage of the gyro.

Q23 Deduce from the measured effective amplitude given by the lock-in amplifier the angular speed of the Earth's rotation. Assess your measurement uncertainties. Comment your results.

↪ Visualize the Fourier transform of the signal (see menu *MATH* of the oscilloscope).

↪ Apply a triangular modulation then a sinusoidal modulation of same frequency and amplitude.

Q24 Give an interpretation of the signals you obtain.

F 3

Optical time domain reflectometry (OTDR)

Version date: July 11, 2024

Prepare questions P1-P9 before the session.

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This labwork will be an opportunity to become more familiar with fiber optics. You will use and characterize fiber components. These components are the different parts of an OTDR, a very common and useful tool to test telecommunication fibers.

1 Introduction

1.1 Singlemode fibers

An **optical fiber** (or **fibre**) is a glass or plastic fiber designed to guide light along its length by confining as much light as possible in a propagating form. In fibers with large core diameter, the confinement is based on total internal reflection. In smaller diameter core fibers, (widely used for most communication links longer than 200 m) the confinement relies on establishing a waveguide.

The index of the core, n_1 , is larger than the index of the cladding, n_2 . The plastic buffer is a protection for core and cladding made in silica.

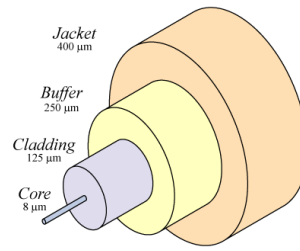


Figure 3.1 – Optical fiber composition

The spatial selectivity of a fiber depends on the diameter of the core. Depending on this parameter, fibers may be singlemode or multimode. Light is guided along the fiber core by total internal reflection on the cladding. So the critical angle is determined by the index difference between core and cladding numerical aperture. And the critical angle determines the acceptance angle of the fiber (about 10°), often reported as its numerical aperture, NA::

$$NA = \sin \alpha = \sqrt{n_1^2 - n_2^2} \text{ between } 0,12 \text{ and } 0,5 \quad (3.1)$$

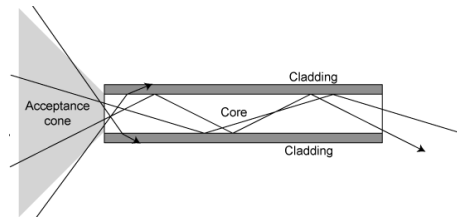


Figure 3.2 – Numerical Aperture of an optical fiber.

Single-mode fibers are step index fibers with a core diameter of about the same size as the transmitted light wavelength. More precisely, a fiber is **singlemode** if $V = (\pi/\lambda) \cdot \phi_c \cdot NA$ is less than 2,405.

In this labwork, we will use $\phi_c = 9 \mu\text{m}$ core diameter fibers and $NA = 0,12$.

P1 Check that these fibers are single-mode at $\lambda = 1550 \text{ nm}$.

1.2 Principle of Optical Time Domain Reflectometry (OTDR)

An OTDR (Optical Time Domain Reflectometer) is used to test optical communication fibers. OTDR allows to characterize the attenuation in the fiber and to find defects on the line. A laser pulse is sent in the fiber and reflected on the defects of the fiber on test.

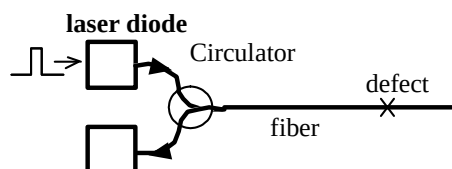


Figure 3.3 – Reflectometry principle

The time delay between the emission and the reception of the pulse gives the position of the defect in the fiber. Furthermore, the light scattered along the fiber travelling backward (**Backscattering**) allows the measurement of the attenuation.

Silica index is $n=1.4645$

P2 What is the time delay between the pulse emission and the reception of the reflected pulse on a default located at 10 m, 1 km, 10 km far from the fiber input?

Even if μs and km are not S.I. units, they are more convenient for OTDR measurements.

1.3 OTDR signals

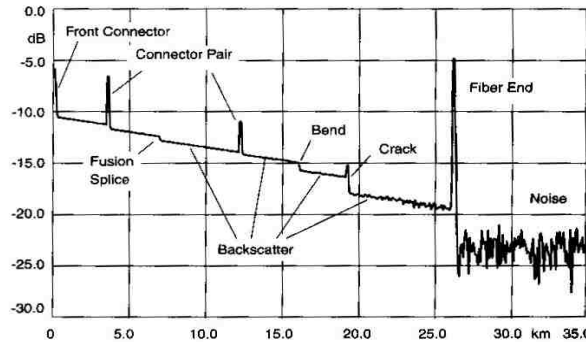


Figure 3.4 – Example of an OTDR signal. Evolution of the local power along the fiber: $\frac{P}{P_0}$ (dB) vs D (km).

You can notice on the curve above:

Pulse reflections on local defects, connectors or cracks: characterized by a coefficient R . The power detected at a delay T is:

$$P_R(T) = R \cdot P_{in}(T=0) \cdot e^{-\alpha \cdot v_g T} = R \cdot P_{in}(T=0) \cdot e^{-2\alpha z}$$

where:

- z is the defect position,
- $P_{in}(T=0)$ is the input power
- $v_g = \frac{c}{n}$ is the group velocity
- α is the attenuation coefficient. Notice the factor 2 in the exponential because signals are attenuated on both ways (forward and backward).

Backscattering of a very small part of the optical power during the pulse propagation. This phenomenon allows us to measure:

- some **local defects, excessive bend or fusion splice**: they do not lead to any reflection, only attenuation.
- **attenuation coefficient**. Indeed, the light power in an optical transmission line undergoes attenuation during propagation as:

$$dP_{in}(z) = -\alpha P_{in}(z) dz$$

where α is the linear attenuation coefficient in m^{-1} or in km^{-1} . This coefficient takes into account the absorption and scattering losses. We therefore obtained an exponential decay of power:

$$P_{\text{in}}(z) = P_{\text{in}}(z=0) e^{-\alpha z} \quad (3.2)$$

Thus, on log-scale a linear decay appears. The slope of this signal characterizes the global attenuation in the fiber. In telecom optics, the power is expressed in dBm. The attenuation coefficient is expressed in dB/km:

$$\alpha_{\text{dB}} = 10 \log_{10} \frac{P(z)}{P(z+1 \text{ km})}$$

Warning α_{dB} is not the value of α in dB-scale

P3 On the previous OTDR signal curve (Figure 3.4), verify that the attenuation factor is approximately 0,2 dB/km.

P4 What is the maximum distance on which the transmission line may be tested with the noise level displayed by this OTDR?

P5 If the attenuation of a fiber is 0,2 dB/km, without any other defect, after how many kilometers the power will be divided by 2? by 4?

1.4 Attenuation in optical fibers. Backscattering

Rayleigh scattering

Rayleigh scattering, due to microscopic index inhomogeneities, is the main source of attenuation in telecommunication domain around 1,5 μm :

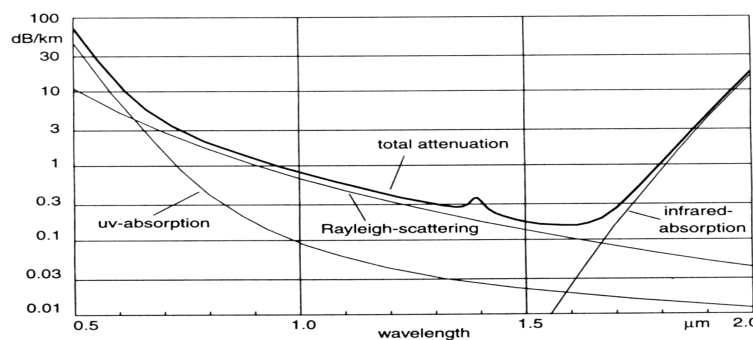


Figure 3.5 – Losses in a silica fiber versus the wavelength (from Derickson). Attenuation coefficient (dB/km) vs wavelength (μm)

For this wavelength, the scattering coefficient is $\alpha_{\text{s,dB}} = 0,14 \text{ dB/km}$.

P6 Show this value corresponds to $\alpha_s = 0.032 \text{ km}^{-1}$.

Backscattering

A part of scattered light is backscattered and propagates in the fiber core backward.

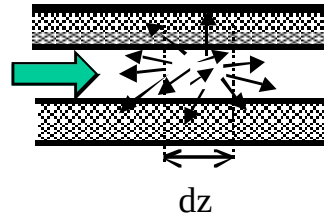


Figure 3.6 – Backscattering from a part dz of the fiber

The proportion of light backscattered may be calculated by a "capture" coefficient S . This coefficient S depends on fiber parameters (numerical aperture NA, mean index n , index profile). For a single-mode fiber:

$$S = \frac{1}{m} \left(\frac{\text{NA}}{n} \right)^2$$

with $m = 4.55$.

P7 Calculate S value.

Evaluation of the backscattered power

Let us consider a rectangular pulse of duration τ injected in the fiber at time $t = 0$:

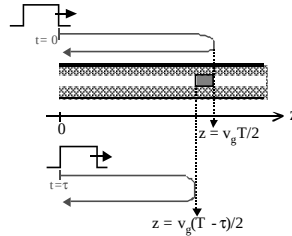


Figure 3.7 – Backscattering of the pulse

The detected signal at time $t = T$ is the sum of backscattered signals corresponding to different portions of the light pulse in the fiber. The beginning of the pulse is backscattered at $z = \frac{v_g T}{2}$, the end of the pulse is backscattered at $z = \frac{v_g T}{2} - \frac{v_g \tau}{2}$. $v_g = c/n$.

So the backscattered power is:

$$P_{\text{rd}}(T) = \int_{v_g(T/2-\tau/2)}^{v_g T/2} S \cdot \alpha_s \cdot P_{\text{in}}(z=0) \cdot e^{-2\alpha z} \cdot dz \quad (3.3)$$

$$P_{\text{rd}}(T) = S \cdot \frac{\alpha_s}{2\alpha} \cdot P_{\text{in}}(z=0) \cdot e^{-\alpha v_g T} (e^{\alpha v_g \tau} - 1) \quad (3.4)$$

Because the attenuation is very weak during the pulse length ($\alpha v_g \tau \ll 1$), backscattered power is:

$$P_{rd}(T) = S \cdot \frac{\alpha_s}{2} \cdot v_g \tau \cdot P_{in}(z=0) \cdot e^{-\alpha v_g T}$$

$$P_{rd}(z) = S \cdot \frac{\alpha_s}{2} \cdot v_g \tau \cdot P_{in}(z=0) \cdot e^{-2\alpha z}$$

So, the **backscattering coefficient** R_{bs} , is:

$$R_{BS} = S \cdot \frac{\alpha_s}{2} \cdot v_g \tau$$

P8 We remind that $\alpha_s = 0,032 \text{ km}^{-1}$. Calculate the coefficient R_{BS} for a pulse duration $\tau = 1 \mu\text{s}$ at $\lambda = 1550 \text{ nm}$.

P9 Calculate the maximum backscattered power (in W and in dBm) at the entrance of the fiber. Calculate the backscattered power to be detected in our setup if the power of the laser pulse is 12 mW and its duration is 1 μs .

~> **You will compare this value to your measurements during the labwork!**

2 Measurements

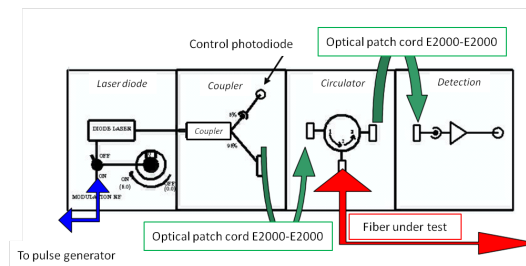


Figure 3.8 – SupOptique OTDR Front panel

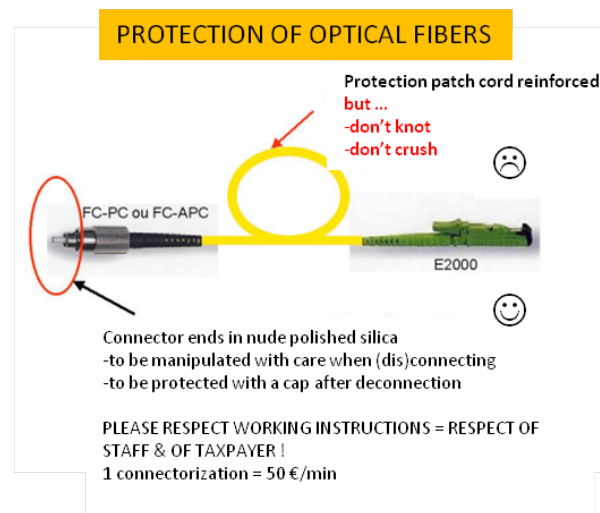
2.1 Fibers

Connectors used during labwork are FC-PC connectors (Fiber Connection-Physical Contact connectors: black), FC- APC (Fiber Connection-Angle Physical Contact connectors green) or E2000 (protected connectors).

- FC-APC (Green): No reflection even if not connected
- FC-PC (Black): Reflection (4%) if not connected

Important

Fibers and especially their connectors are delicate. Don't drop them on the table! Always protect the connectors with a cap ! Put them back in their boxes when you have finished. Never connect a PC connector (black) to an APC connector (green)!



2.2 Components characterization

Laser diode

The laser diode (20 mW, 1550 nm) will be used in continuous mode in this part (see appendix for characteristics)

~ The modulation knob must be on OFF position and 0, 0.

~ Amplifier supply: ON

~ Laser Diode *ILX* power supply:

- key ON
- TEC Mode: ON (*green led*). Temperature should be around 20°C.
- Laser Mode: ON (*green led*)
- Laser Adjust: ON, increase intensity in the diode

~ Connect a E2000 to APC fiber between the 95% output and the EXFO power meter adjusted at 1550 nm.

Q1 With a few points from 0 to 100 mA, measure the characteristic, $P = f(I_{LD})$ of the laser diode. What is the threshold of the laser diode?

~ At the same time, observe the voltage on the photodetection channel (5% Channel). This voltage will be a measure of the flux at the input of the OTDR.

Q2 Measure the voltage for 100 mA current in the Laser. Deduce from this measurement the calibration (in V / W) of the control photodiode.

Circulator

A circulator allows to:

- guide the light from a fiber connected at port number 1 exclusively to a fiber connected at port number 2.

- guide the light from a fiber connected at port number **2** exclusively to a fiber connected at port number **3**

This magic component is based on polarization rotators and is described in the appendix 3.

- ~ Measure the power at the 95% output for $I_{LD} = 60 \text{ mA}$ for example.
- ~ Connect **95% output** to port number **1** with a fiber (E2000-E2000) and measure power at port number **2** and port number **3**.
- ~ Connect **95% output** to port number **2** with a fiber (E2000-E2000) and measure power at port number **1** and port number **3**.

Q3 Explain how the circulator works.

Q4 Measure the losses in the circulator (in % and dB) between port number **2** and **3** and between port number **2** and **3**.

OTDR detection

The detector is a high-speed PIN photodiode in InGaAs: 0,5 ns rise time on 50Ω . The response is 0.95 A / W at 1550 nm (see appendix). The electronic circuit is:

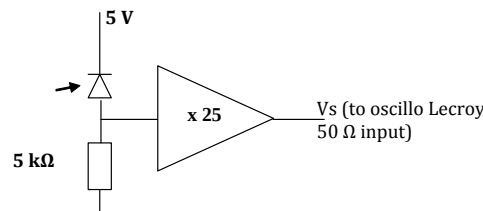


Figure 3.9 – Detection circuit

- ~ Adjust a very low current in the Laser diode (below the threshold) and connect a fiber directly from the 95%exit to the detection system.
- ~ Connect the output, V_s , to Lecroy oscilloscope and measure the offset and the saturation voltage of the photodetection circuit.
- ~ The response of the detector should be around: $G = 0.95 \times 5000 \times 25 = 120 \text{ kV / W}$.

Q5 Measure this response. Be careful not to saturate the amplifier output and to take into account the offset voltage of the photodetector.

2.3 Time resolved reflectometry

- ~ Connect one end of the 10 km fiber to the circulator output **2**.

Pulse mode of the laser diode

- ~> Decrease the intensity in the Laser diode to 0 (**But do not shut off ILX power supply !**).
 - ~> Switch on the pulse generator
 - ~> Switch on the modulation and turn the knob at the maximum (but gently !). (Do not forget to turn off and go back position 0.0 at the end of the labwork)
 - ~> You can adjust period and duration of the pulses. (**But never adjust amplitude and offset** behind the plastic protection). Adjust the pulse duration to $1\ \mu\text{s}$ with the control photodiode signal on the Lecroy oscilloscope. The oscilloscope will be triggered on this signal.
- Q6** With the oscilloscope and using the control channel calibration calculated in question **Q2**, measure the laser pulse power at the 95% output of the coupler.
- Q7** What is the laser pulse power injected in the fiber?
- Q8** Modify the pulse period. What is the minimum period needed to do a correct measurement?
- Q9** Measure accurately the length of the fiber.
- ~> Observe now the exponential attenuation of the backscattered signal.
 - ~> Observe the detector output signal. You should see the backscattered power along the fiber. But the signal is weak and very noisy. It will be necessary to average this signal. Use the math functions of the Lecroy oscilloscope. A configuration of these functions can be found in the directory OTDR.

Using the Scope

Recall of a configuration by the menu Fichier/Rappeler la configuration

Clear Sweep will reset the average

Save measurements under Matlab format via
the menu Fichier/Sauvegarder le signal

Save a screenshot by using menu Fichier/Créer une entrée dans le journal,
then Fichier/LabNotebook then Create Report. You can save in .pdf or
rtf.

- Q10** Comparing voltages corresponding to the backscattered powers at the beginning of the fiber and at the end of the fiber, measure the attenuation in the fiber, α_{dB} , in dB/km.
- Q11** Knowing that the photodetector response is about $120\ \text{kV/W}$, measure the backscattered power at the beginning of the fiber (in nW). Deduce the backscattering coefficient, R_{BS} . Explain how you take in account the losses of the circulator Compare to the value of R_{BS} obtained in preparation.

↪ Measure the backscattered power at the beginning of the fiber (in nW) for different pulse durations from 0 to $5\ \mu\text{s}$.

Q12 Calculate the corresponding coefficients R_{BS} . Which property is verified by this measurement?

Q13 What is the disadvantage of increasing the duration of the pulse?

Signal analysis with Matlab

Save the data in a "Matlab" format and use in Matlab the following functions:

Using Matlab functions

Reduce the window of the oscilloscope by the menu `File/Minimize` then open Matlab.

To display in linear or log scale and to calculate attenuation coefficient you can use the following functions :

```
>> Affiche_signal_brut; (Display voltage signal measured with the oscilloscope)
>> Affiche_signal_dB (display the backscattered power in dBm versus the distance along the fiber)
>> Fit_exponentiel. (Exponential fit to measure  $\alpha$ )
```

Q14 Verify the backscattered power level at the beginning of the fiber and measure the attenuation along the 10 km fiber.

↪ Connect the 15 km fiber to the end of the 10 km fiber. Study the OTDR signal.

Q15 Use the Matlab functions to measure attenuations and connector losses in dB.

Q16 Same questions when you connect also the 5 km fiber. What is the maximum fiber length you can measure with the OTDR?

Q17 Compare the attenuation factor to the attenuation factor in electric coaxial cable.

F 4

Noise figure of an optical amplifier

Version date: July 11, 2024

Prior to the lab session :
we kindly ask you to read the following labwork note
and to answer all the preparatory Questions BEFORE the session.

We kindly ask you to report your measurements in an Excel sheet during the session.

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3	Experimental set-up	42
4	Optical characterizations	43
5	Amplifier noise characterizations	45
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1 Introduction

This labwork session intends to study noise properties related to optical amplification process.

Hereafter, we study an optical amplifier made of an Erbium doped optical fiber that amplifies optical signal at a wavelength nearby 1550 nm. Optical amplification, which is based on stimulated emission of radiation, requires a pump beam to realize the population inversion between the two energy states of the transition around 1550 nm. It is achieved by coupling inside the doped fiber, simultaneously with the signal to be amplified, a pump laser diode beam (actually, there are two pump laser diodes at 1480 nm). As illustrated in the figure below, the signal amplification results in an energy transfer from the pump to the signal through stimulated emission process.

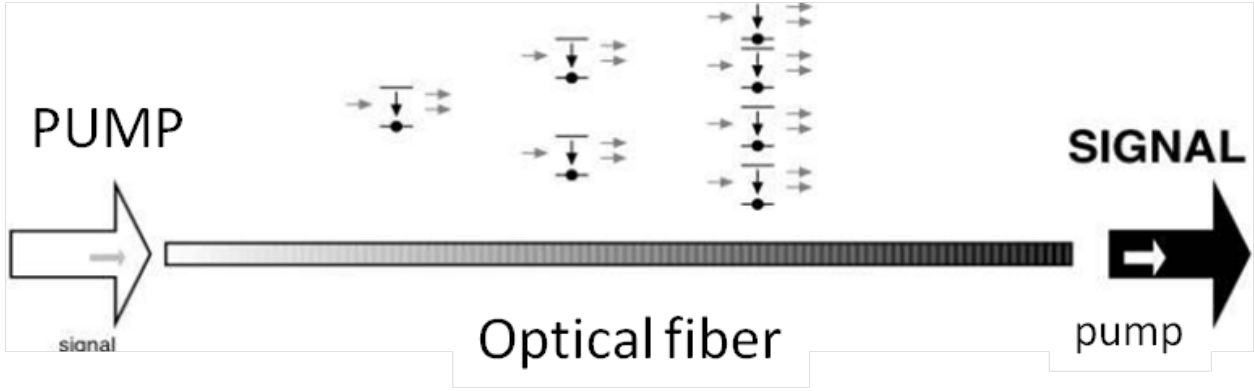


Figure 4.1 – Optical amplification: schematic description.

Any photons generated through stimulated emission of radiation are emitted in phase with incident photons (same direction, same frequency and polarization state). Along the propagation, and in addition to amplification of the incoming signal, one has to account for amplification of photons initially generated through spontaneous emission. Actually, ions on a excited energy states can spontaneously relax into a lower energy state, which is accompanied by spontaneous emission of photons towards 1550 nm. Conversely to amplified signal photons, those "spontaneous" photons are not in phase relation with the incident signal. In addition, some of them are emitting within the numerical aperture of the fiber, as they propagate along the active fiber, they are amplified by stimulated emission of radiation. This effect refers to the so-called *Amplified Spontaneous Emission* (ASE), which generates additional photons superimposed with the amplified signal photons.

As a consequence, one can anticipate that the ASE process generates a noise, due to phase and amplitude fluctuations on the generated number of photons, and which impacts the performance of optical amplifiers. In order to account for this effect, characterization of optical amplifiers should not only measure the optical gain, but also the *Noise Figure* (NF) that quantifies the noise level generated by the amplifier. As optical amplifiers are periodically inserted along optical fiber transmission link, the noise level produces by the first amplifier will be amplified by the following amplifiers. This noise accumulation will be detrimental to the transmission performance and justify to carefully characterize the amplifier Noise Figure (defined in the following).

The Noise Figure (NF) is defined by the ratio between the Signal-to-Noise Ratio (SNR) measured at the input of the amplifier (prior to amplification) and the SNR measured at the output of the amplifier, which gives:

$$NF = \frac{SNR_{@1\text{ Hz},IN}}{SNR_{@1\text{ Hz},OUT}}$$

Usually, it is expressed in dB unity:

$$NF_{dB} = 10 \log \left(\frac{SNR_{@1\text{ Hz},IN}}{SNR_{@1\text{ Hz},OUT}} \right).$$

The general definition can be applied to characterize either optical or electrical amplifier noise figures. It is interesting to note that, conversely to the SNR, the NF does not depend on the type of amplified signal. In order to give physical insight, one can rewrite the NF expression as:

$$NF = \frac{SNR_{@1\text{ Hz},IN}}{SNR_{@1\text{ Hz},OUT}} = \frac{S_{IN}}{S_{OUT}} \frac{N_{OUT}}{N_{IN}} = \frac{1}{G^2} \frac{N_{OUT}}{N_{IN}},$$

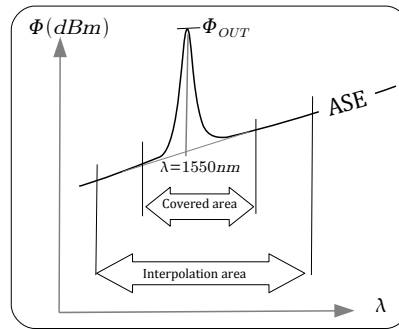
where N_{IN} and N_{OUT} are the power spectral density of the noise measured respectively at the input and output of the amplifier. In the previous relation, we use electrical powers, justifying that the ratio $S_{\text{IN}}/S_{\text{OUT}}$ between the electrical signal power is equal to $1/G^2$, with G the optical gain of the amplifier. This expression highlights the relation between the NF value and the quantity of noise N_{OUT} generated by the amplifier. The lower N_{OUT} is, the lower the noise figure will be. Interestingly, one sees that the noise figure is inversely proportional to G^2 , meaning that a high gain amplifier contributes to reduce the noise figure and so to improve the quality of the amplifier.

It is important to note that the noise figure measurement should be an intrinsic property of the amplifier. As it will be shown during the labwork, the major output noise contribution arises from the beating between the optical signal frequency and the spectral components of ASE (the demonstration would be out of the scope of the present work), which means that N_{OUT} only depends on optical parameters (optical gain, power spectral density of ASE, signal power). Now, the input noise contribution N_{IN} will be assumed to be limited to the shot noise contribution. Such an assumption can be easily justified. First, it means the NF quantifies the amount of noise generated by the optical amplifier respect to the shot noise limit. Second, setting the input noise limited by the shot noise allows to define a NF parameter independently of the photodetector used in the measurement set-up. Since, the SNR_{in} is limited to the shot noise, one can anticipate that $NF > 1$. Actually, it can be shown that the noise figure can not be lower than 3 dB.

Following these assumptions, it can be demonstrated that the noise figure can be measured by analyzing the input and output optical spectra. From the output spectra shown in the figure below, the noise figure can be calculated through:

$$NF \simeq \frac{\eta P_{\text{ESA}}}{h\nu G \Delta\lambda_{\text{res}}},$$

with P_{ESA} the power of ASE measured towards the signal peak, integrated over the spectral bandwidth $\Delta\lambda_{\text{res}}$ and η the quantum efficiency of the optical analyser detection system.



The objective of the labwork will be to compare the optical measurement of NF , with a direct electrical measurement of the ratio $NF = \frac{SNR_{@1 \text{ Hz}, \text{IN}}}{SNR_{@1 \text{ Hz}, \text{OUT}}}$. By doing so, the various noise contributions will be clearly identified, the difficulty in precisely measure the NF will be underlined.

2 Preparatory Questions

During this labwork session, optical and electrical powers will be evaluated in dBm unity. One reminds the relation between optical powers given in mW unity and in dBm:

$$P_{\text{dBm}} = 10 \log \left(\frac{P_{\text{mW}}}{1 \text{ mW}} \right) \quad (0 \text{ dBm} = 1 \text{ mW})$$

Detection will be performed by a photodetector defined by its sensitivity $\sigma(\lambda)$ in A/W given by:

$$\sigma(\lambda) = \frac{I_{\text{ph}}}{\Phi_{\text{reçu}}(\lambda)} = \frac{\eta(\lambda) \cdot e}{h \cdot \nu}$$

with $\eta(\lambda)$ the quantum efficiency of the detector at the wavelength λ , set to $\lambda = 1550 \text{ nm}$ in our case.

P1 Explain briefly the operating principle of an optical spectrum analyzer and of an electrical spectrum analyzer. Which physical characteristic is measured in each case ?

P2 Explain briefly the Amplified Spontaneous Emission (ASE).

P3 Calculate the quantum efficiency of a detector with a 0.88 A/W sensitivity at 1550 nm . Calculate the generated photo-current I_{ph} for an incident optical power set to 0 dBm .

P4 A 10 km long optical fibre, with a $0,2 \text{ dB/km}$ linear attenuation, is inserted between the previous optical source and the photodetector, calculate the optical power on the detector in dBm. Deduce the photo-current I_{ph} .

In the experiment, the photodetector is a pigtailed GaAs photodiode, followed by a current-voltage converter with a very large bandwidth (up to 12 GHz). The electrical circuit diagram is as follows:

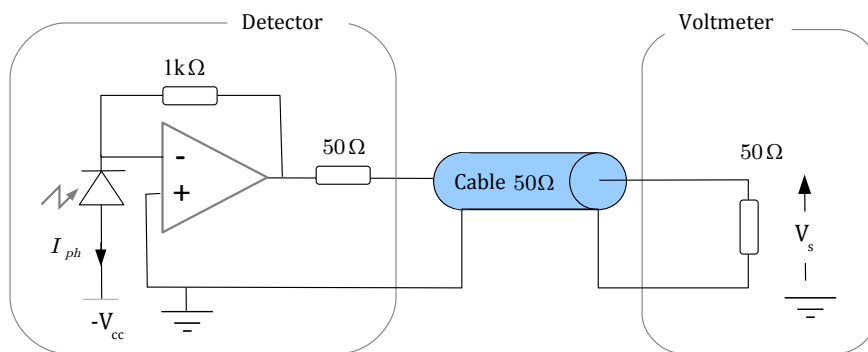


Figure 4.2 – Electrical circuit diagram of the detection set-up measurement.

P5 Justify the relation between the measured voltage V_s and the generated photon current I_{ph} :

$$V_s = 500 \Omega \cdot I_{\text{ph}}$$

P6 Calculate the measured voltage V_s for an incident optical power of 0 dBm and the corresponding electrical power P_{elec} dissipated in the terminal $50\ \Omega$ resistance (give the value in W and dBm unities).

P7 Following the insertion of a 10 km long optical fibre, with a 0,2dB/km linear attenuation, calculate the modified voltage and electrical power. Show that a 1 dB variation in the optical power gives rise to a 2 dB variation in the electrical power.

The next questions are related to shot noise. One reminds that the power spectral density for shot noise current is given by

$$\frac{\sigma_{\text{SN}}^2}{B_e} = 2e \langle I_{\text{ph}} \rangle,$$

with B_e the spectral bandwidth.

P8 Explain briefly what shot noise is. For a 0 dBm incident optical power, calculate the power spectral density for the shot noise current in A^2/Hz unity.

The measurement of the electrical power spectral density (PSD) will be next performed with an Electrical Spectrum Analyzer, as it is schematically depicted in Fig. 4.3:

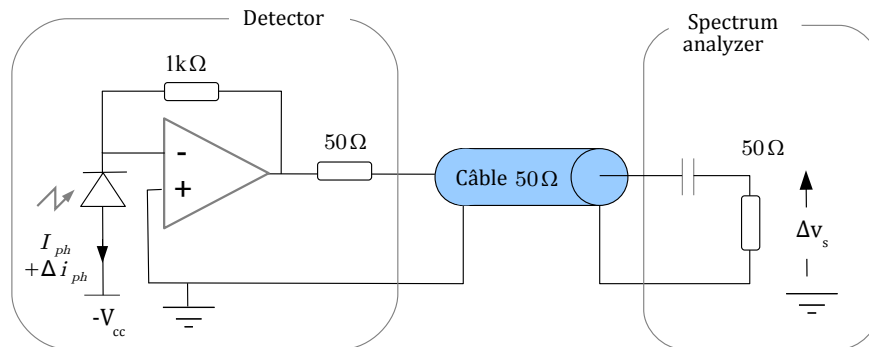


Figure 4.3 – Electrical circuit diagram for the detection set-up: electrical power measurement.

P9 Show that the PSD at the output mesured with a spectrum analyzer having an input impedance of $50\ \Omega$ can be written as :

$$PSD_{ph,W/Hz} = \frac{\sigma_{\text{SN}}^2}{B_e} \times \frac{500^2}{50}.$$

For a 0 dBm incident optical power, calculate the measured PSD for the shot noise in nW/Hz and in $\text{dBm}_{@1\text{Hz}}$ unities. Which is the value if the incident power is attenuated by -20 dB?

3 Experimental set-up

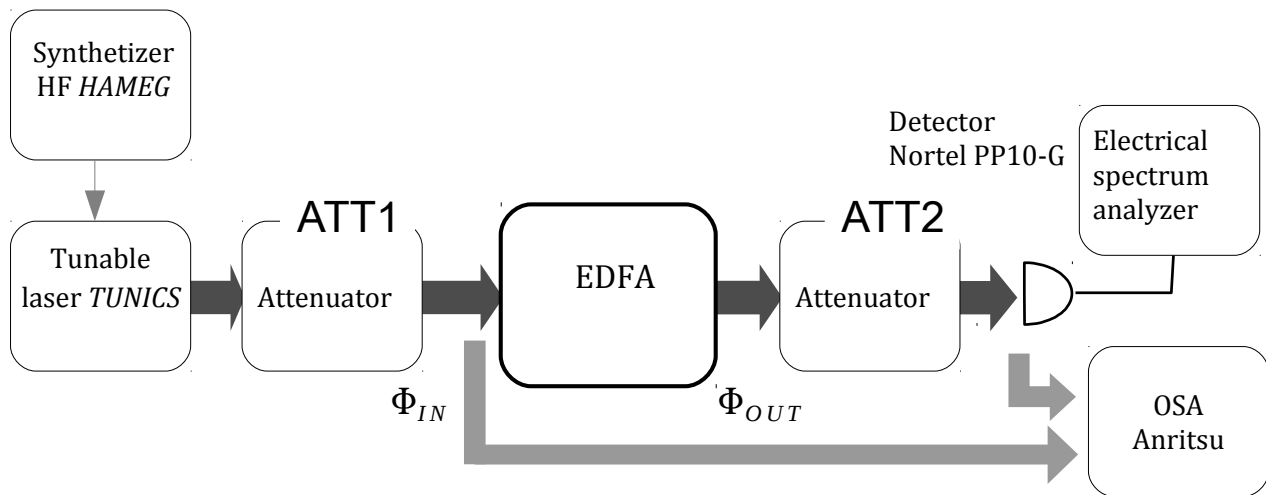


Figure 4.4 – Experimental set-up

Input connectors of fiber devices and instruments (detector, optical power meter, optical spectrum analyser) are protected with dedicated plug-in connector, which must never be removed. Finally, take caution with the manipulation of the fiber patch connectors. After unplugging a fiber connector, protect it by using a dust cap.
Thank you.

↪ The experimental set-up comprises:

An EDFA optical amplifier with connectors for input and output signal, OPT IN and OPT OUT, and with two electrical switches to set on the two laser diode pump, P1 et P2, operating at 1480 nm.

Variable optical attenuators allow to insert calibrated attenuation and to shut-down the transmitted signal (∞ ou shutter). The minimum insertion loss of the device is 0,65 dB.

Tunable laser diode operating around 1550 nm, with the possibility to modulate the power by an external electrical signal (input Mod.).

Photodetector: It is a GaAs photodetector from Nortel connected to a current-voltage converter (ref PP-10G). The photodetector characteristics are :

- noise current: 165 pA/√Hz
- spectral bandwidth: 11 GHz
- transimpedance resistance: 500 Ω
- Sensitivity (at 1550 nm) : 088 A/W

Optical Spectrum Analyzer (OSA) : Do not unplug the plug-in connector.

Electrical Spectrum Analyzer: used to measure power spectral density of noise and signal to noise ratio (SNR).

High-Frequency synthesizer: Used to generate a sinusoidal waveform at the frequency of 100 MHz.

Optical power meter

Multimeter: measurement of DC voltage, provided with a $50\ \Omega$ termination.

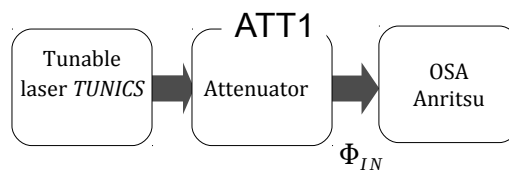
4 Optical characterization of the EDFA

This first part is dedicated to the optical characterization of the EDFA, i.e. optical gain and NF measurements. Beside the gain measurement, we will show that the NF can be measured in two steps using an optical spectrum analyser.

4.1 Optical gain measurement

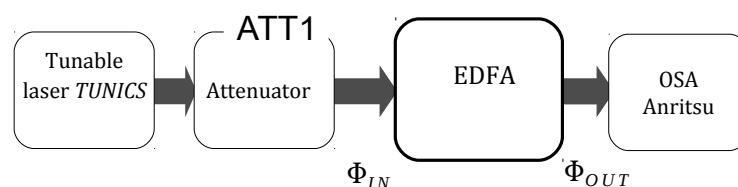
↪ Connect the laser diode to the optical attenuator and adjust the attenuation level such that the output power is equal to -20 dBm.

↪ Connect the attenuator output to the optical spectrum analyzer:



↪ Measure the optical spectrum of the laser signal between 1530 to 1590 nm. Check that the power is in agreement with the power measured with the powermeter. The shift may be due to the wear connector at the input of the OSA. Adjust the laser wavelength nearby 1550 nm.

↪ Realize the set-up shown in the figure below and measure the spectrum of the amplified signal.



Q1 For a maximum pump power (that is P1 and P2 ON), comment about the shape of the output spectrum and identify the contribution from ASE. To do so, one can compare the output spectra with and without the input signal. Justify the variation in the ASE power level between the two situations.

Q2 Measure the power of the signal at the output of the EDFA, Φ_{OUT} , and the gain of the amplifier defined by :

$$G = \frac{\Phi_{\text{OUT}} - \Phi_{\text{ASE}}}{\Phi_{\text{IN}}}$$

where Φ_{IN} is the optical power at the amplifier input and Φ_{ASE} is the ASE power at the output, at 1550 nm. One can simplify by :

$$G = \frac{\Phi_{\text{OUT}}}{\Phi_{\text{IN}}} \quad \text{car} \quad \Phi_{\text{OUT}} \gg \Phi_{\text{ASE}}$$

that is $G_{\text{dB}} = \Phi_{\text{OUT,dBm}} - \Phi_{\text{IN,dBm}}$

↪ Modify the resolution bandwidth (RBW) of the OSA by a factor 10 (from 0.1 nm to 1 nm for example) and compare the measured spectra. Comment.

4.2 Noise figure measurement with an OSA

INSTRUCTIONS FOR THE MEASUREMENT OF THE NF WITH THE OSA

To measure the gain and the NF select the menu `Applications` in the horizontal menu then `optical amplifier test` in the vertical menu on the right. Once in the application `optical amplifier test` follow the instructions :

- at the input of the OSA put the input signal Φ_{IN} (you should see on the screen $\frac{P_{\text{IN}}}{P_{\text{OUT}}}$)
- press on P_{OUT} in the left vertical menu (you should see on the screen $\frac{P_{\text{IN}}}{P_{\text{OUT}}}$ changing to $\frac{P_{\text{IN}}}{P_{\text{OUT}}}$)
- present on the OSA input the output signal.

In the top left corner of the screen you should see the measurements, in particular G , Φ_{ASE} and NF. You can notice them on the spectrum of figure 4.5 where you recognize on the screen the input signal (bottom) and the output signal (top).

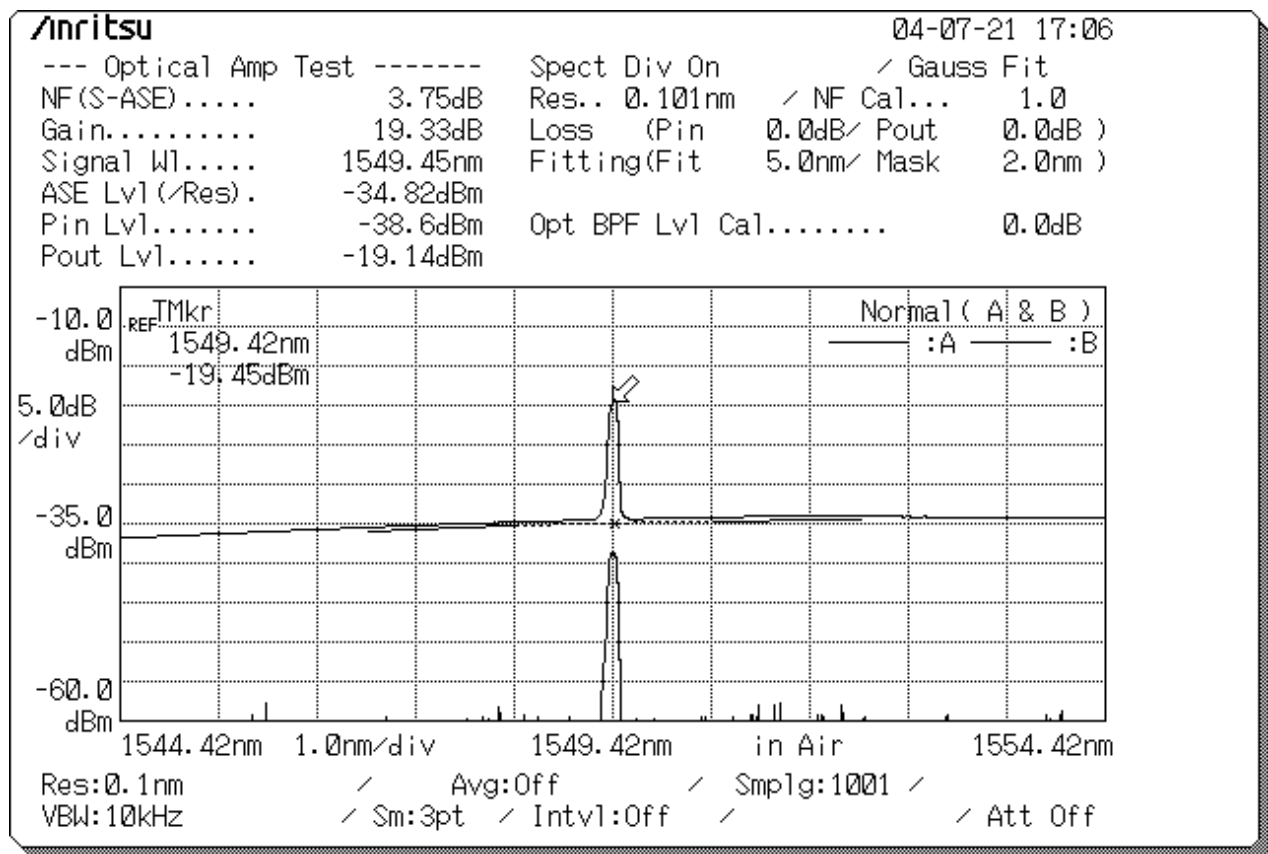


Figure 4.5 – Screenshot of the OSA Anritsu

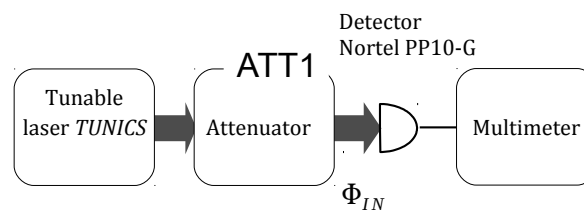
Q3 Note down the optical gain and the noise figure reported on the OSA for an attenuated power of 20 dB.

5 Amplifier noise characterizations

In the following part of the labwork, the noise contributions will be analyzed from the electrical signal delivered by the photodetector using the electrical spectrum analyzer.

5.1 Quantum efficiency of the detection

↪ Disconnect the input signal from the optical amplifier, and connect it to the photodetector.



↪ Shut-off the optical signal by selecting the shutter button of the attenuator and measure the DC voltage at the output of the photodetector.

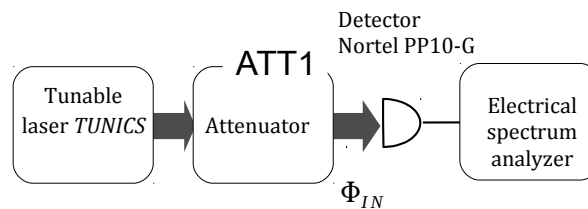
↪ Switch on the optical signal and select a minimum attenuation ($ATT1 = 0\text{dB}$). Measure the DC voltage.

Q4 Deduce from your measurements the sensitivity of the detector in V/W, the photocurrent detection and the quantum efficiency.

Important Note: The quantum efficiency that is measured here accounts for any additional losses between the input fiber and the photodetector, and it integrates the quantum efficiency of the photodiode.

5.2 Dark noise

↪ Shut-off the optical signal and connect the output of the photodetector to the electrical spectrum analyzer:



↪ Nearby a frequency of 100 MHz, measure the power spectral density in dBm/Hz generated by the photodetector.

SHORT NOTICE OF THE SPECTRUM ANALYZER FOR NOISE MEASUREMENTS

Choice of the frequencies (SPAN) Menu : MKR/FREQ

7 FREQUENCY START STOP

0 FREQ START ENTRY Choose 90 MHz

1 FREQ STOP ENTRY Chooser 110 MHz for a measurement at 100 MHz

Resolution bandwidth (RBW) Menu : RBW Here the automatic choice will be convenient (RBW auto).

Power calibre Menu : REF LEVEL Choice of the calibre of the attenuator (or amplifier) on RF INPUT.

REF LEVEL corresponds to the lign on the top of the screen. It can vary between 20 and -70 dBm . Choose -50 dBm .

Measurement of the PSD Menu : APPL

2 Noise normalized : When this option is ON, the spectrum analyzer measures and displays $\text{dBm}_{@1\text{Hz}}$ (top right of the screen) the power spectral density of the noise at the frequency corresponding to the position of the cursor.

5.3 Input noise characterization

Measurements

↪ Adjust the attenuation $ATT1 = 0\text{dB}$ (with the laser diode operating at the maximum power, i.e. few mW) and connect the output of the photodiode to the spectrum analyzer.

↪ Measure the power spectral density in dBm/Hz at 100 MHz. Identify the dark noise of the photodetector and the noise level of the spectrum analyzer.

Q5 Deduce from the previous measurement, the power spectral density (in W/Hz and in dBm@1 Hz) of the noise generated by the optical signal detection. Explain how the noise contributions from the spectrum analyzer and from the dark current can be subtracted.

Q6 Is it a white noise ? Compare the power spectral density with that expected from the shot noise. To do so, one can use the photocurrent value I_{ph} measured at question **Q4**.

↪ Repeat the measurement for attenuation $ATT1$ varying from 0, 1, 2, 3, 5, 15, 20 dB.

Q7 Plot the variation of the noise power spectral density in dBm/Hz with the applied attenuation in dB. Similarly, plot the noise power spectral density in W/Hz in terms of the detected optical power in mW. Explain the observed variation. Justify the fact that the photodetector operates at the shot noise level at low attenuation (or at "high" optical power). What happens for high attenuation ?

Quantum efficiency correction

The shot noise power depends on the optical power, but also on the quantum efficiency of the detection set-up.

Q8 Show that the shot noise power is proportional to the quantum efficiency η of the detection system.

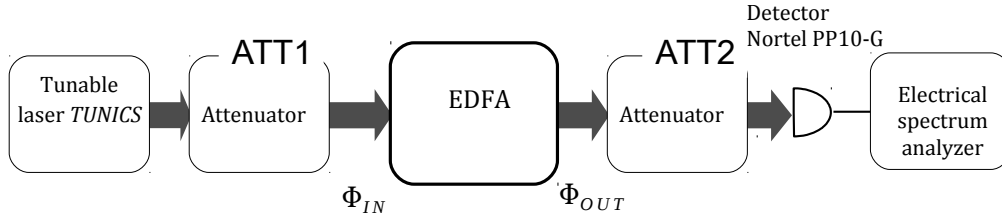
Q9 From the measured quantum efficiency realized in question **Q4**, give the noise power spectral density in dBm/Hz with the correction in dB from the quantum efficiency.

5.4 Output noise characterization

As underlined in the introduction, optical amplification of an input signal is accompanied by the generation of ASE, characterized by a broad spectrum around 1550 nm and with no phase relation with the amplified signal. We show hereafter that, the photodetection noise detected at the amplifier output is then no longer limited by the shot noise. Its dependence with optical power will show that the predominant noise arises from the beating effect between the spectral components of ASE, and the beating between the amplified optical signal and ASE spectral components.

Without input signal

↪ With no input optical signal, connect the EDFA output to the optical attenuator:



↪ Adjust the attenuation to ATT2=0 dB and measure the power spectral density in dBm/Hz and in W/Hz at 100 MHz.

↪ Measure this noise power varying the attenuation between 1,2,3,5 dB.

Q10 Plot the noise power variation with attenuation, and compare with that obtained in question Q7. Conclusion about the origin of the noise ?

With input signal

↪ Adjust the attenuation for the input optical signal to ATT1= 20dB and adjust ATT2 at minimum.

↪ Measure the power spectral density in dBm/Hz at 100 MHz at the amplifier output.

Q11 Discuss about its variation with the input signal power (adjusted by means of the optical attenuator).

6 Noise figure measurement

In this last part, we proceed by measuring signal to noise ratios (SNR) at the input and the output of the amplifier. By doing so, we will be able to measure the noise figure (NF) of the amplifier. Prior to that, an intensity modulation of the laser diode will be introduced, which will represent the effective "electrical" signal to be transmitted through the optical fiber link. Hereafter, the signal will be a sinusoidal waveform at 100 MHz.

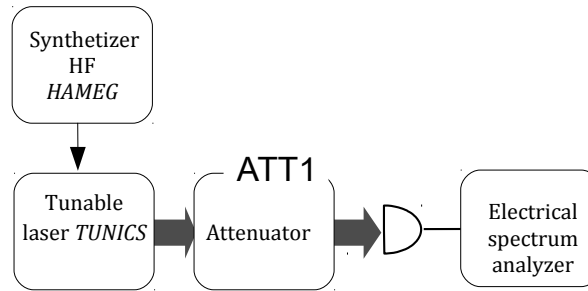
Now, the electrical spectrum will be composed by a peak at 100 MHz, related to the electrical signal, which "seats" on a noisy background level. From such a spectrum, one can easily measure the SNR by dividing the power spectral density of the signal peak by that of the noise. We then define input and output SNRs (as introduced in the introduction):

$$\text{SNR}_{@1\text{ Hz},\text{IN}} = \frac{S_{\text{IN}}}{B_{\text{IN}}} \quad \text{SNR}_{@1\text{ Hz},\text{OUT}} = \frac{S_{\text{OUT}}}{N_{\text{OUT}}} = \frac{G^2 S_{\text{IN}}}{N_{\text{OUT}}} \quad (4.1)$$

6.1 Input signal at the input of the amplifier

↪ Switch-on the HF synthesizer, which should deliver a sinusoidal waveform at 100 MHz.

↪ Connect the synthesizer output to the modulation input of the laser diode:



↪ For varying attenuation $ATT1 = 0, 1, 2, 3, 5$ dB, measure the variation of the electrical signal power at 100 MHz (in dBm) with the electrical spectrum analyzer. You can use the function `peak find`.

Q12 Justify its variation with the optical power.

Q13 Show that the electrical signal power is proportional to η^2 .

6.2 Input signal to noise ratio

↪ Set the attenuation $ATT1 = 0$ dB.

↪ Measure the SNR with the spectrum analyzer. For that, leave the mode of noise measurement and use the function `peak find`.

Measurement of the SNR for a bandwidth of 1 Hz

Menu : APPL

1 Carrier to noise C/N : When this option is ON, the analyzer measures and displays in dB_{@1 Hz} (up right of the screen) the value of the SNR at the position of the two cursors.

Q14 Show that $SNR_{@1\text{ Hz},IN}$ is proportional to η . Give the correction we need to set on the measured SNR to account for the quantum efficiency of the detection system. We remind that NF factor should be independent of the detector properties, so we need to refer our measurements to an ideal detector with a quantum efficiency $\eta = 1$.

↪ Measure $SNR_{@1\text{ Hz},IN}$ for varying attenuations $ATT1 = 0, 1, 2, 3, 5$ dB.

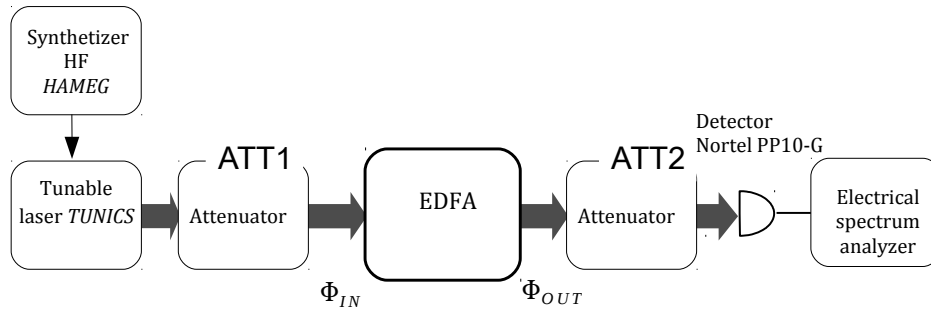
Q15 In practise why is this measurement not feasible for an attenuation of 20 dB ?

Q16 With the measured $SNR_{@1\text{ Hz},IN}$ at $ATT1 = 0$ dB, extrapolate the $SNR_{@1\text{ Hz},IN}$ value at $ATT1 = 20$ dB.

6.3 Output signal to noise ratio

↪ Connect the attenuator output to the EDFA input.

↪ Set the attenuation $ATT1 = 20$ dB.



↪ Measure the power of the output signal at 100 MHz (in dBm) with the electrical spectrum analyzer.

Q17 Deduce from this measurement the optical gain of the amplifier.

↪ Measure $SNR_{@1\text{ Hz},OUT}$ for different values of the attenuation $ATT2$.

Q18 Justify that the output signal to noise ratio $SNR_{@1\text{ Hz},OUT}$ is independent of the losses inserted between the amplifier output and the photodetector.

6.4 Noise figure of the EDFA

Q19 With the measured values for $SNR_{@1\text{ Hz},IN}$ and $SNR_{@1\text{ Hz},OUT}$, at an attenuated input signal (−20 dB, which simulates the propagation of the optical signal through 100 km fibre link), give the measured noise figure of the amplifier. Compare with that measured with the optical spectrum analyzer.

Q20 Conclude and comment your measurements.

F 5

Coherent fibered Lidar

Version date: July 11, 2024

Prior to the lab session :
we kindly ask you to read the following labwork note
and to answer all the preparatory Questions BEFORE the session.

Contents

1	Introduction to LIDARs	52
2	Description of the experimental set-up	55
3	Measurements of the velocity of a hard target	57
4	Study of the noise	60
5	Study of the tornado	60

Aims of the labwork

At the end of the session, you will be able to :

- use optical fibers and couplers
- align and use a LIDAR, analyze its performances
- identify noise sources in a set-up.

In the first part of this labwork you will learn how to use properly the different components of the set-up. Then you will study a hard target composed with a wheel and its mounting in order to deduce a measurement of the velocity of the wheel.

P1 The laser is emitting at the wavelength of 1550 nm. Give the advantages to work at this wavelength.

P2 In which other applications LIDARs are used ?

1 Introduction to LIDARs

A LIDAR ¹ is a sensor that analyzes the signal of a laser that is backscattered on a target. Several characteristics of the target can be deduced from this signal.

There are two families of LIDARs :

- LIDARs on hard target,
- atmospheric LIDARs.

Two detection modes are possible :

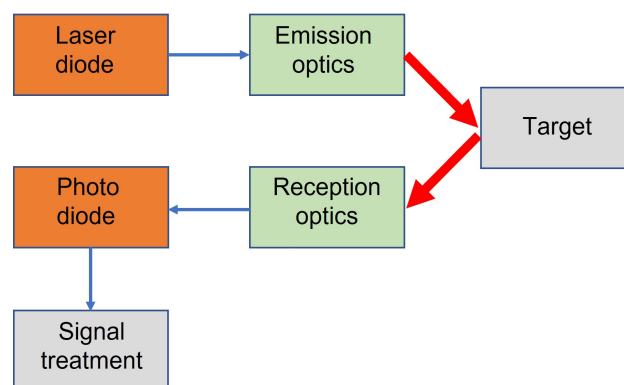
- the direct detection,
- the coherent detection.

¹Light Detection and Ranging

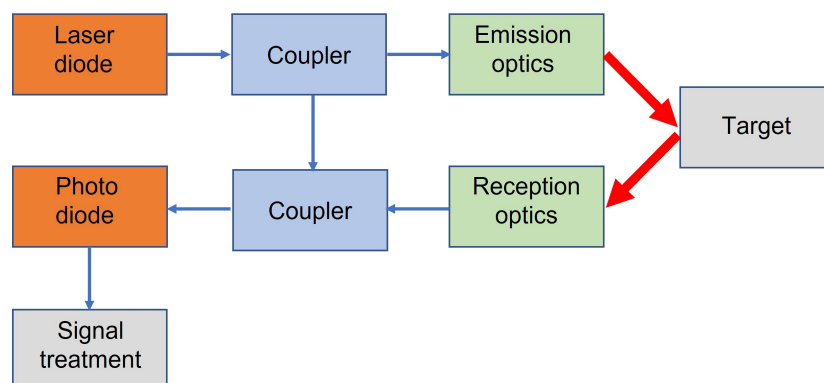
Two geometries are possible for the emission-reception system :

- the bistatic geometry,
- the monostatic geometry.

These two detection modes and these two geometries are described in figures 5.1 and 5.2 below.



Set-up using the direct detection



Set-up using the coherent detection (studied here)

Figure 5.1 – Principle of the two possible detection modes of a LIDAR

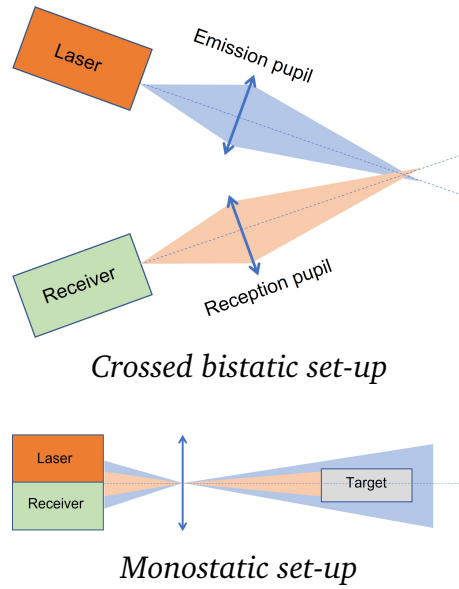


Figure 5.2 – Principle of the two possible geometries

During the labwork, you will study the measurement of the velocity of a hard target by coherent detection in a bistatic set-up.

1.1 Coherent detection

Coherent detection is based on the interferences between the backscattered signal and the reference signal named local oscillator (LO). In case of harmonic signals, the sum of the two electromagnetic fields is written :

$$E_r = E_S e^{i(2\pi f_S t + \Phi)} + E_{LO} e^{i2\pi f_{LO} t}$$

We obtain a photocurrent that is composed of 3 terms, signal current, LO current and interference or heterodyne current :

$$i = I_S + I_{LO} + 2\sqrt{I_S I_{LO}} \cos(2\pi \Delta f t + \Phi)$$

The heterodyne current contains the information on the amplitude and the phase of the LIDAR wave. It also contains information on its frequency (which is the temporal derivative of the phase). This current is amplified by the LO current.

The aim of this session is to measure the velocity of the hard target by Doppler effect. The laser beam that is backscattered by the target is frequency shifted by Doppler effect. The acquisition card calculates the Fourier transform of the beating signal that is produced, which enables to measure the frequency shift produced by the target and to deduce the velocity that is **projected** on the beam axis.

P3 Give the expression of the frequency shift Δf in function of the velocity of the target v_{target} by considering Doppler effect on a round trip.

1.2 Geometry of the set-up

The set-up you are going to study is composed of two separated emission and reception pupils : such a set-up is called a **bistatic crossed set-up** (figure 5.2). The emission field crosses the reception field only at a certain distance called the "blind area".

This set-up is more difficult to align and to use than a monostatic set-up. However if a continuous-wave laser is used, less noise is introduced.

2 Description of the experimental set-up

The set-up you will use during this labwork (see figure 5.3) is composed of a fibered block that contains the laser source, the photodiode and some couplers (figure 5.4). You will also find an acousto-optic modulator and its power supply, an optical amplifier, an optical assembly composed of an emission part and a reception part, a hard target and its power supply.

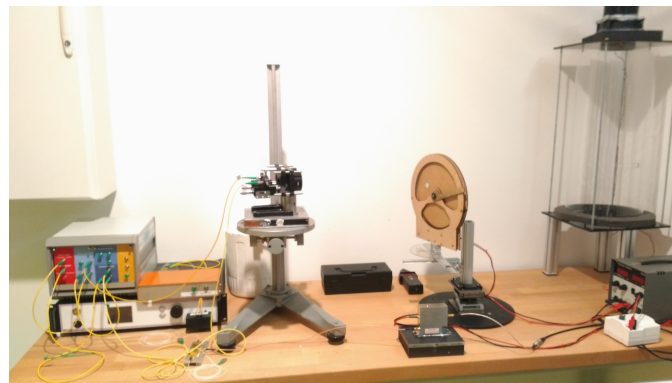


Figure 5.3 – Set-up used in the labwork

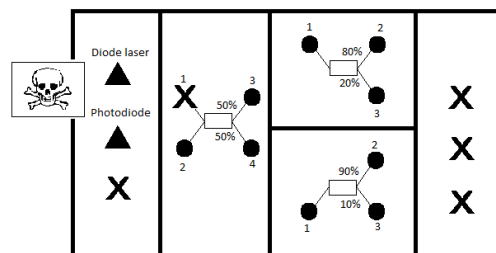


Figure 5.4 – Simplified schematic of the fibered block. DO NOT TOUCH THE FIBERS THAT ARE CONNECTED TO THE LASER DIODE AND TO THE PHOTODIODE.

2.1 Use and cleaning of the fibers

CAUTION : an optical fiber is very fragile ! It has to be manipulated with care. A bad use of the fiber can damage it and prevent from a good execution of the experiments. Do not apply pressure on it, do not curve it, do not stretch it. Do not put its ends in contact with metal. Always put the protection cap on the fiber if not used.

Q1 The optical fibers you are using in this labwork are called Non Polarization Maintaining (PM) fibers, meaning they don't maintain the polarization state during the propagation. Why don't we use PM fibers here ? Think about the use of the hard target.

↪ Check the cleanliness of the fibers labelled "fibre 1" and "fibre 2". To do that, use the fiberscope with the help of your teacher.

↪ Clean the fibers if necessary with the help of your teacher. To clean a fiber, one needs to realize some "8" with the end that is put on the cleaning paper.

CAUTION : do not put your fingers on the cleaning paper. Do not forget to shut down the cover after having renewed the paper.

↪ Connect these optical fibers to the emission and reception optics of the set-up. Do not disconnect these fibers anymore.

2.2 Characteristics of the laser diode and of the photodiode

The measurements and the driving of the laser diode are performed from the script `Interface.py` on the desk ².

A user guide explaining the operating modes is available in the labroom.

↪ Plot the curve current-power of the laser diode by using the interface for the current measurement and the powermeter with a fibered input for the measurement of the optical power. Then connect the laser diode on the photodiode. The interface enables to plot the laser power in arbitrary units versus the current by clicking on `Plot caractéristique`. Use this plot to determine the laser power corresponding to the saturation threshold of the photodiode.

2.3 Characterisation of the couplers

A coupler is a fibered component that connects one or several inputs to one or several outputs. Here we use couplers to mix two signals or to separate a signal in two parts. This mixing or this separation can be realized for different power divisions, for example 50/50, 90/10.

↪ Measure the power division at the outputs of the 50/50 and 90/10 couplers. Measure also the losses introduced by each coupler. Don't forget to close properly the outputs of the fibered block after using them to avoid dusts and to avoid that the laser beam exits without control.

Q2 Give the origin of the power losses of the couplers.

²The modules `Oscillo` and `Spectrum` enable both to drive the laser diode. For the current measurements it is advised to use the module `Oscillo`. For the velocity measurements it is advised to use the module `Spectrum`.

2.4 Principle of the coherent measurements

In order to optimize the signal, the limiting noise has to be the shot noise, meaning that the photodiode has to receive a power which is just below its saturation voltage.

Q3 With the help of paragraph 1.1 and of the characteristics of the couplers, choose the couplers to use as well as their order of use. Justify your choices. Calculate the laser power which is necessary to be under the saturation threshold while sending at the same time a maximum of signal on the target. You will consider that the signal that is backscattered by the target has a negligible power.

Q4 Complete the schematic of figure 5.5 to summarize your previous measurements.

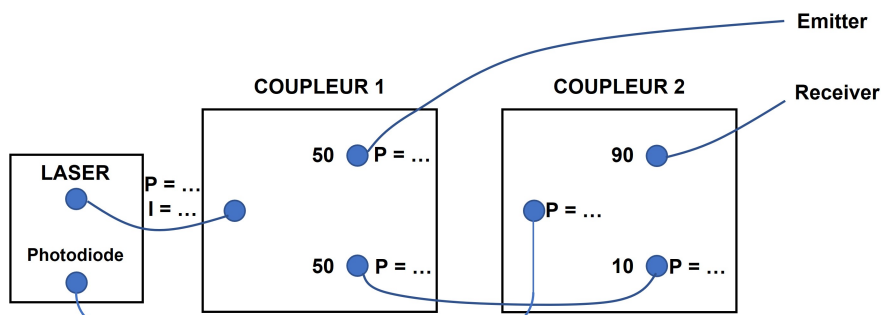


Figure 5.5 – Powers involved (to be completed)

Q5 Realize the set-up above and check experimentally that you are at the saturation threshold of the photodiode.

3 Measurements of the velocity of a hard target

In this part you will measure the velocity of the hard target (figure 5.6).

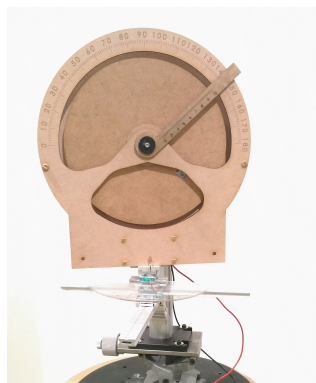


Figure 5.6 – Hard target used in the labwork

LIDARs on hard target can give information localized in space (ponctual information) and can characterize a floor, a vehicle, a surface etc ... Low power lasers can be used when the reflexion coefficient of the target is high. The parameters of the target that can be measured are :

- its distance
- its velocity
- its vibration spectrum
- its surface chemical composition

3.1 Realization of the bistatic set-up

Alignement of the optics

↪ You are going to realize a crossed bistatic set-up, described in figure 5.2. For the alignment of the set-up, connect the laser diode at the input of the 50/50 coupler and connect the emission and reception fibers to the outputs of the coupler. Put the wheel at a distance of 60 cm of the optics (approximately). Superpose the focus spots of the two laser beams on the vertical axis of the wheel, at a point which has to be nearly at the same distance of the center than the reflecting tape.

You won't touch the alignment of the optics anymore. In the following you will move the hard target in order to put the focus spot on it.

LIDAR set-up

↪ Realize the set-up as shown in figure 5.5.

↪ Switch on the laser from the interface and set the current to be under the saturation threshold of the photodiode.

3.2 Velocity measurement

↪ Introduce an angle between 0° and 90° at the base of the hard target. Note the distance to the center and the angle of the wheel. Turn on the hard target supply power at maximum.

↪ **Measurement with the tachometer** : use the tachometer to measure the velocity of the wheel. Aim at the reflecting tape which is put on the surface of the wheel.

Q6 What is the principle of measurement of a tachometer ?

↪ **Measurement with the software** : Take a reference measurement with the wheel at rest and the laser on. Then make the wheel rotate at its maximum speed and make a measurement of the velocity with the interface. Don't forget to subtract the reference before doing the measurement.

Q7 Compare your measurement, the one realized with the tachometer and the value calculated by the software.

↪ Measure the velocity on both sides of the equatorial plane of the wheel. You can use the vertical translation of the wheel mounting.

Q8 What do you observe on the spectrum ? Give an interpretation. According to you, is it possible to know the sign of the velocity ?

3.3 Velocity profile of the hard target in function of the angle

↪ Measure the velocity in function of angle ϕ (mesured at the base of the wheel) on a range of 90 degrees by step of 10 degrees around the graduation 90 degrees. Don't forget to take some supplementary points around this graduation. If you loose the signal, move the wheel along the optical axis to be at the focus spot of the two beams again.

Q9 Plot the velocity of the hard target in function of the angle. Comment the shape of the plot. What is the velocity of the wheel at normal incidence ? Give an interpretation.

3.4 Measurement with the acousto-optic modulator

An acousto-optic modulator (or AOM) enables to introduce an offset, which is here of 40 MHz.

↪ Connect the AOM in the set-up according to figure 5.7.

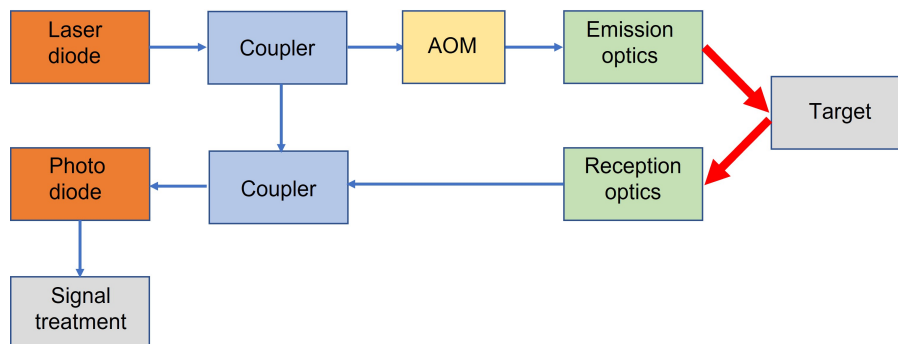


Figure 5.7 – Principle of the set-up using the AOM

↪ Observe once again the velocity on both sides of the equatorial plane of the wheel.

Q10 What do you observe on the spectrum of the signal ? What is the interest of the AOM ?

3.5 Analysis of the step response of the wheel

The step response of the wheel enables to give several of its mechanical characteristics. To do that, we use a simple modelling of the wheel. Let's assume that :

- the wheel is a perfect revolution cylinder, homogeneous and the motor axis corresponds to the one of the wheel.
- the engine torque is a constant of time.

- It is possible to model all the other effects by a frictional fluid force with a parameter α that we are going to measure.

The equation describing the rotation of the wheel is then :

$$J\dot{\omega} = C_{mot} - \alpha\omega$$

where J is the moment of inertia around the rotation axis of the wheel, C_{mot} is the engine torque, supposed to be constant, and ω is the rotation speed of the wheel.

It is reminded that for a uniform cylinder, we have on the revolution axis :

$$J = \int_0^R 2r^3 \rho h dr$$

where $h = 3 \text{ mm}$ is the thickness of the wheel, $R = 100 \text{ mm}$ its radius, $\rho = 750 \text{ kg/m}^3$ the density of the material.

↪ Use the interface by pressing the button `Acquisition` in order to plot the temporal evolution of the velocity of the wheel.

Q11 Comment the shape of the plot. Is it compatible with the proposed model ?

Q12 Evaluate the frictional coefficient α in the low velocity regime by using the coefficients calculated by the script (cf : Notice section 8).

4 Study of the noise

4.1 Parasitic signals

↪ Go back to the menu by pressing button `accueil` then reopen `spectrum` (to suppress the reference, see notice section 8).

↪ Measure the velocity of the hard target without taking the reference.

Q13 Compare the velocity measured by the software and the velocity measured with the cursor. Why do we have to take a reference ?

Q14 Which kind of noise is suppressed when the reference is taken ? What are the sources of this noise ?

4.2 Shot noise

Q15 Why is it important to be slightly under the saturation threshold of the photodiode ?

5 Study of the tornado

In this part, you are going to study the case of an atmospheric LIDAR that measures the velocity of aerosols. To do that, you are going to measure the velocity of an artificial tornado.

5.1 Atmospheric LIDARs

The laser beam is continuously scattered by particles and gas molecules that are present in the atmosphere (aerosols). This backscattering occurs all along the propagation axis of the laser beam. The parameters that can be measured in the atmosphere are :

- the velocity of the air mass
- the air temperature
- the air density
- the concentration of the atmospheric gases
- the charge and the nature of the aerosols and atmospheric dusts

Among the atmospheric LIDARs, we can distinguish the atmospheric LIDARs called *profilers* (realized with pulsed lasers), which give the profile of a physical parameter along the targeting line, and the atmospheric LIDARs called *localized* (realized with continuous-wave lasers), which detect the signal coming from a precise and delimited area (this is the case studied here).

5.2 Experimental study

↪ Align again the optics in order to measure the velocity inside the tornado.

↪ Realize the following set-up :

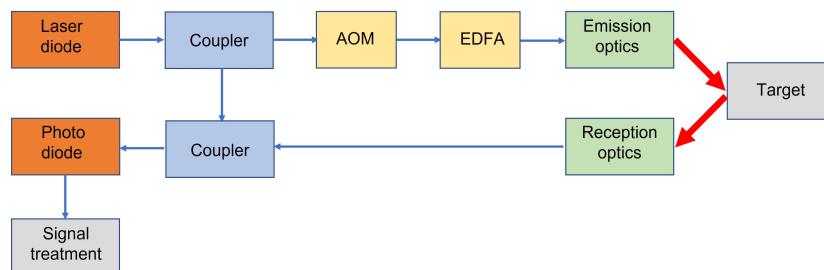


Figure 5.8 – Schematic of the set-up for the measurement of aerosols

Q16 Why do we need to use an optical amplifier ?

CAUTION : do not switch on the optical amplifier if there is no input power. Wear the laser protection glasses.

↪ Take an acquisition of the velocity of the tornado during time.

Q17 Give an estimation of the range of variations of the velocity.

↪ Move the tornado to observe the repartition of the velocities.

Q18 Comment.