Optical fiber sensors

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I.Présentation

Module :

Guided optics and optical fiber

Auteur(s) :

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Résumé :

This course presents the three main families of optical fiber sensors which are: intensity modulation, phase modulation and polarization modulation. We detail each of these families in a section. We return in particular to the theoretical aspects and the most common practical configurations. Finally we give some examples of applications of these sensors.

Mots-clés :

sensor, optical fiber, intensity modulation, phase modulation, polarization modulation

Pré-requis :

Guided optics

Objectif(s) pédagogique(s) :

This course aims to present the various optical fiber-based measurement techniques both theoretically and practically. The learner will then be able to choose this or that sensor depending in particular on the measurand and sensitivity sought.

Plan du cours :

- Introduction
- Intensity modulated sensors: examples and applications
- Phase modulation sensors, interferometric sensors: examples and applications
- Polarization modulated sensors: examples and applications

Conception & production :

Le Mans Université

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II.Cours

Optical fibers are generally used for transmissions and telecommunications. Because of their low attenuation and large bandwith, they made it possible to create land and transoceanic networks to carry information for telephone, the Internet, etc. The refraction's indexes of silica (i.e. of glass) vary with the bandpass (i.e. the dispersion), the temperature, possible strain, pressure... all these influences modify the wave propagating in the fiber. These modifications are generally detrimental to telecommunications but can be used to make captors sensitive to temperature variations, strain, ...

Optical fibers are very interesting in many respects:

- small transverse dimensions, do not disrupt their environment and can be used in the medical field,
- they are insensitive to electromagnetic disturbances,
- they have low attenuation, so that the sensor can be set up far away,
- regarding light, they can be used for spatial and aeronautical applications,
- Optical fibers have good stability over time,
- and good resistance to corrosion.

However they have some downsides:

- fragility,
- related connections are complex,
- some fibers can only withstand a limited range of temperature ($+85C$ for plastic fibers),
- optical fiber sensors prices are (for the time being) higher than traditionnel sensors, but there performances are not higher in standard applications.

The purpose of this lesson is to give a general survey about the various techniques used to make sensors from optical fibers. We will successively detail the various techniques of modulation of information in this lesson, which means :

- intensity modulation,
- phase modulation,
- polarisation modulation.

Readers can find further information in the wide literature, particularly the reference [1 [Handbook of optical fibre sensing technology]], [2 [Fiber optics sensors]], [3 [Optical Fiber Sensor Technology: Fundamentals]] , and [4 [Optical Fiber Sensors: Principles and Components]] .

1. Intensity modulation sensors: exemples and applications

In this part we will focus on optical fiber sensors which use variation of light intensity induced by the quantity to measure, that is to say the measurand (temperature, strain, pressure...). This approach is by far the easiest to carry out since there are numerous configurations to make an intensity modulation, so almost all the measurands can be detected. Its cheap price is also an asset, since it does not need any special fiber nor complex assembly. It is not very sensitive, compared to other modulation techniques. Please note that the light variations it detects can be due to the measurand effect or to disruptions. This drawback can be a real problem but it can be compensated (see *Mitigation techniques*). The intensity modulation by the measurand can be made by creating leakages during the transmission, that is to say by bringing light out of the optical fiber. There are three basic techniques to create these leakages:

- using periodical microbenders (see "*Periodical micro-curves* ")
- interacting with the evanescent field (see "*Evanescent field* ")
- modifying the coupling between two fibers (see " *Coupling with two fibers* ")

1.1. Periodical microbenders

Figure 1 shows a sensor going by the periodical microbenders' principle. This technique relies on two phenomenons: the first one is creating leakages in an optical fiber as a result of small radius of curvature, the second one is the resonance effect thanks to the periodicity of the microbenders which will make the coupling of two modes possible. The curve will enable the light to come out of the fiber's core and create leakages, either by bringing out a portion of the fundamental mode or by redistributing the intensity each mode carries to the cladding modes or to the leaky mode. The periodic structure will act as a diffraction grating coupling preferentially in a cladding mode. The intensity of the coupling and so of the leakage in the intensity of the transmitted signal will be proportional to the power of these microbenders.

The coupling made through this method has been thoroughly studied in numerous books (cf [5 [-]] and [6 [Optical Waveguide theory]]). To define the period of the microbenders, we can either use the network equation or the coupled mode theory, the results are similar. Then it is easy to determine the pitch as we know the characteristics of the cladding mode and conversely. The formula between the parameters is:

$$\beta_{core} - \beta_{jacket} = \frac{2\pi}{\Lambda}$$

$$math:(1)$$

where β_{core} and β_{jacket} are respectively the constant of propagation of the fundamental mode and of the cladding mode in which the light will be coupled, Λ is the pitch of the microbenders.

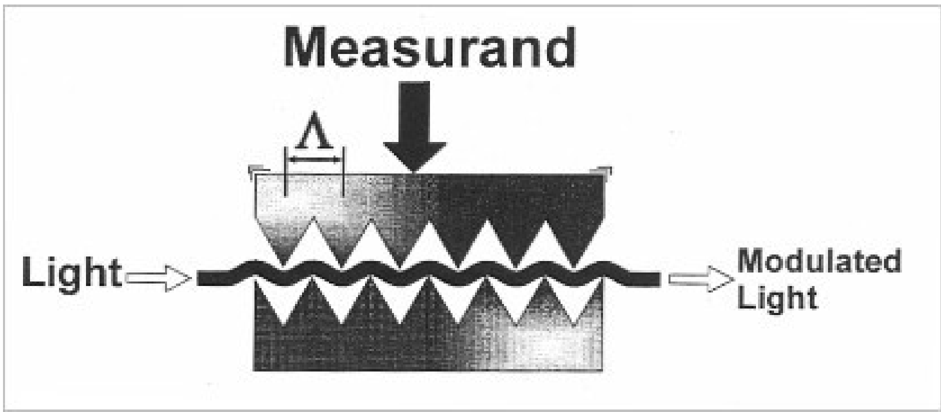

Figure 1 : Transducer going by periodical micro-curves

As it is above-mentioned, it is possible to create propagation leakages just by applying a definite radius of curvature to the fiber; you can use this only effect to make a sensor. Since the leakages generated by coupling to superior modes are low in monomode fibers, you can resort to a multimode fiber in the sensitive area to increase this effect, as shown on Figure 2. This sensor is a hybrid structure formed by a segment of a monomode fiber, a fragment of a multimode fiber and another fragment of a monomode fiber. The injection of the monomode fiber in the multimode fiber will generate an injection in different modes depending on the type of multimode fiber (gradient index or stepped index) and on the positioning of the two fibers. The effect of one or several curves will change the intensity transmitted by each mode. Finally, passing through the monomode fiber will only select the light transmitted by the first modes. As Figure 2 shows, the sensitivity of the hybrid structure is far higher than the sensitivity of the structure which is only made of monomode fiber.

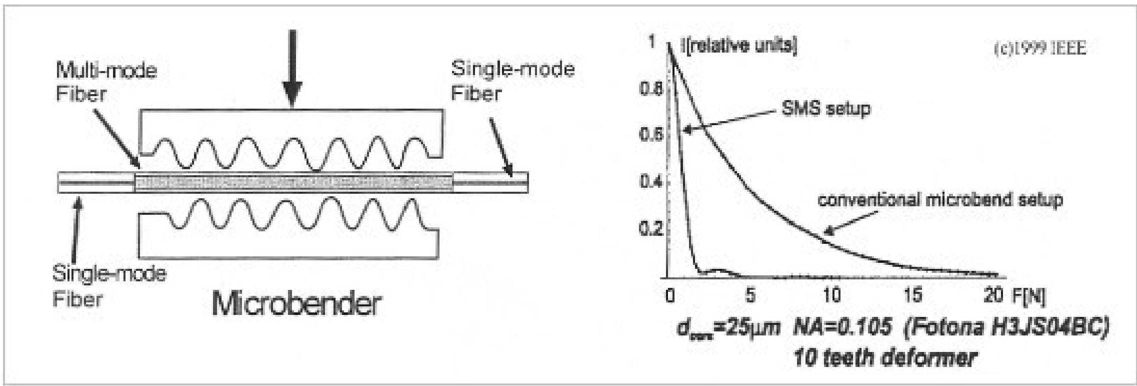

Figure 2 : Transducer composed of multimode fiber microbenders (on the left) and exemple of improving the sensitiviity of a hybrid structure (SMS) and conventional (on the right)

based on [7 [-]]

The sensor made of one or several curves can be used to measure:

- displacement, by letting one of the two blocks free.
- pressure, by using an elastic membrane to let one of the two blocks move [8 [-]].
- strain; several configurations are possible with a single curve and a fiber maintained on the piece to measure, or with microbenders, whose distance between one another depends on the strain to detect [9 [-]], [10 [-]].
- vibration; one of the two blocks is linked up to a mass whose acceleration makes it move [11 [-]].
- temperature, by using the thermal properties of the different materials [12 [Temperature dependence of PCS fiber characteristics]].

1.2. Evanescent field

In this part we will present a method of intensity modulation based on direct interaction of the measurand with the electromagnetic wave. The conventional mono- or multimode fibers guide the way by the well-known phenomenon of total internal reflection. It appears when the Snell-Descartes law is not verified or simply at the interface between a medium with a high refraction index and another medium with a lower refraction index; then the rays which come from definite incidences are totally reflected, however the light will get through the interface and enter farther or closer in the medium with a low refraction index. This part of the electromagnetic field is called evanescent field (see Figure 3-a) and its particularity is to exponentially decrease.

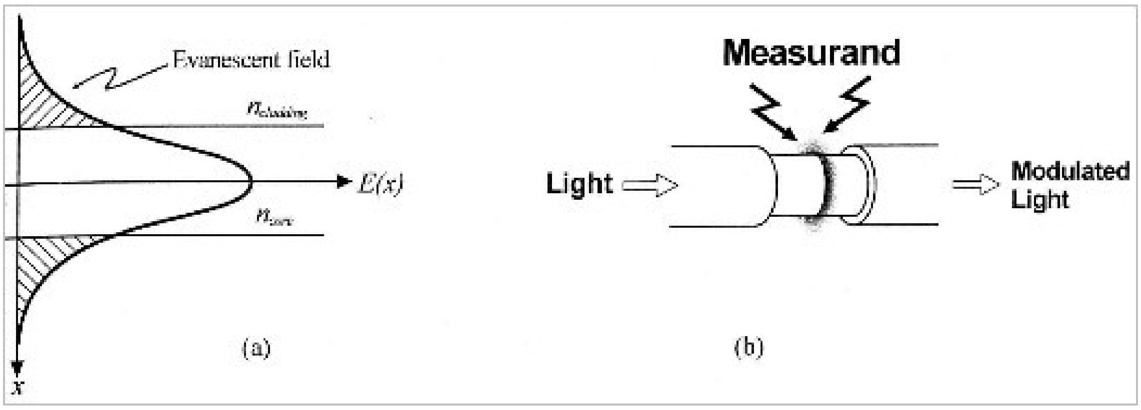

Figure 3-a : Evanescent field in an optical fiber. -b : Principle of the transducer on an evanescent field

The basic principle of the evanescent field sensor (refer to Figure 3-b) is to make the quantity to measure and this part of the electromagnetic field interact. So it is necessary to come as close as possible to the guiding part (i.e. the core) to obtain enough sensitivity.

The main problem of this kind of sensors is the low interaction between the evanescent field and the measurand. For the waveguides, this interaction is proportional with the depth of the penetration in the cladding. This depth is related to the opto-geometrical parameters of the fibers, which are summed up in the normalized frequency V (see the module about the propagation in the optical fibers). To say it simply, the higher V's value is, the deeper the penetration in the evanescent field is.

The easiest configuration of this sensor is shown on Figure 3-b, where the protective plastic jacket of the fiber has been removed and the cladding has been reduced by polishing or by chemical attacks. Then it is simple to detect chemical species or gaz by choosing adequately the wavelength used. The presence of the measurand will be obvious through the absorption of the evanescent wave, creating leakages and modulating the light intensity.

In order to increase the interaction with the evanescent field, it is possible to use special fibers, like D-fibers or micro-structured fibers [13 [-]]. It is also possible to sharpen the fiber by heating it up to its softening temperature and then by stretching it [14 [Use of tapered optical fibers as evanescent field sensors]]. People frequently resort to putting a thiner or larger layer on the cladding, because as its optical characteristics vary depending on the substance to detect, the evanescent wave will also be affected.

Others sensors use the frustration, or the modification of the total internal reflection, as a principle [15 [-]], [16 [-]], either by moving the middle near to the heart (displacement sensors) or by varying the refraction index of the medium (refractometers). A big modulation of the light intensity can be obtained through this technique [44 [-]].

Finally, the evanescent field sensor can be used in numerous configurations, you just have to make the wave interact directly or indirectly with the measurand.

1.3. Coupling between two fibers

In this last part dedicated to intensity modulation we will talk about sensors coupling two fibers or more generally two waveguides. This kind of sensors includes the configurations where the light is extracted from a waveguide, interacts with the measurand and is coupled in another or in the same waveguide. This kind of sensors can have different structures with mono- or multimode fibers. Coupling two fibers can be for transmission or for reflection, as shown on Figure 4.

The main element to get a good coupling sensor is to perfectly know how to couple the two fibers you use. There are lots of articles about this topic, notably [16 [-]], [17 [An introduction to fiber optics]]. These studies were to determine the leakages in the connectors' area. People often use the paraxial approximation to describe the fundamental mode because it makes it possible to simplify calculating and have very good results when using monomode fibers.

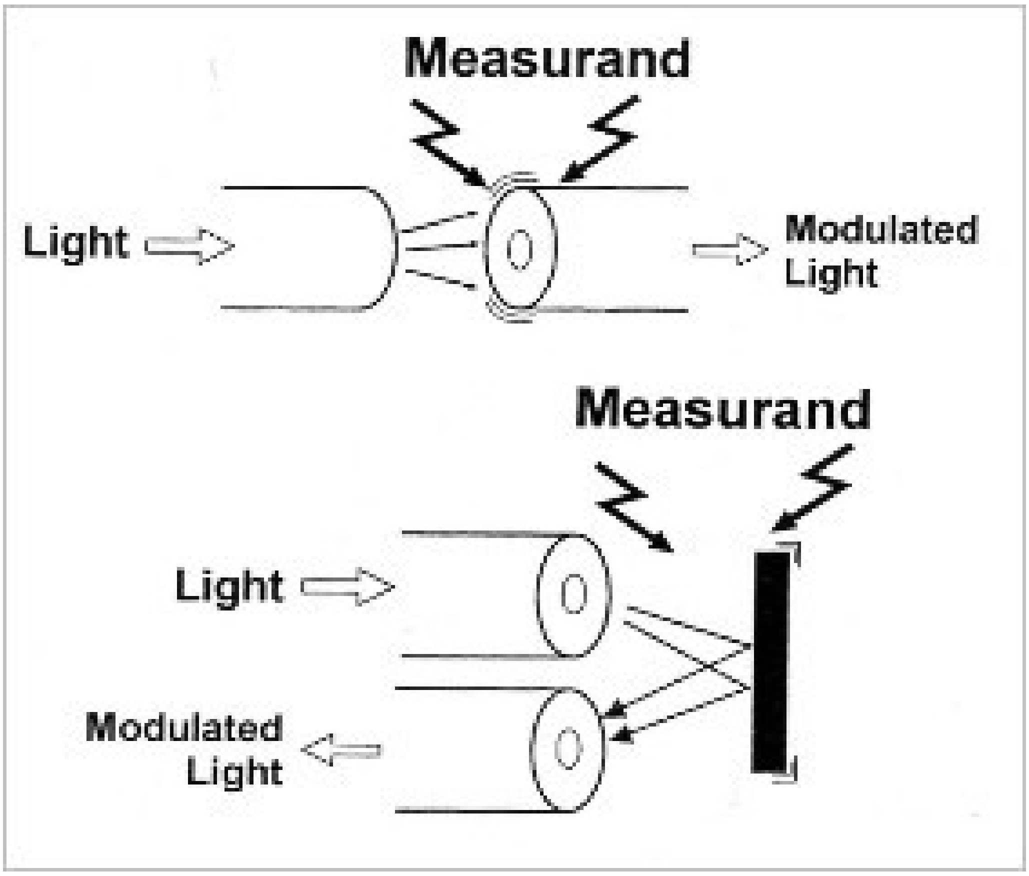

Figure 6 : Example of coupling two transmitting fibers (top) and reflecting ones (bottom)

For the multimode fibers, you have to use more complicated and sophisticated methods to get good predictions. Some models as the ray tracing or the uniform illumination (that is to say assuming that the transmitting fiber uniformly lights the receiving fiber) are often used because they are simple, despite they fail when the two fibers are very unaligned.

These sensors coupling two fibers make it possible to measure:

- displacement
- pressure
- vibration
- positioning
- ...

In order to use this kind of sensors, you just have to design a mechanical assembly which can be moved by the measurand

1.4. Mitigation techniques

When using intensity modulated sensors, variations in optical power are expected to come only from the quantity to be measured. However this is generally not the case, and many unwanted disturbances add up to the signal. Three major sources of error can be identified:

- Fluctuations of temperature which affect the emitting devices, so that the optical output power is not constant.
- Leakages due to curves, connectors, modal interferences, etc.
- Aging of the electronic components, notably for the sources, so that the emitted power decreases.

So it is necessary to resort to mitigation techniques for all sensors whose performances must remain stable. Mitigation techniques are not unique because they depend on the structure of the transducers. They are all based on the principle of adding extra information in the system in order to extract the fluctuations due to measurands. Then we will present some of the most used types of mitigation techniques, even if it is difficult to draw up an exhaustive classification.

a) Spatial division

The signal is divided into at least two and injected into identical fibers. The fibers are introduced at the same place, the light intensity transmitted in each of them will be modulated by disturbances and by the measurand, the signal can be inferred by combining all the measured intensities. Here for example two of the most frequently used equations:

$$Signal = \frac{I_1}{I_2}, \qquad Signal = \frac{I_1 - I_2}{I_1 + I_2}, \qquad math:(1)$$

where I_1 and I_2 are the intensity coming from each fiber. This technique is often used for systems with coupling sensors [18 [-]]. This simple technique depends a lot on the kind of sensors and it is difficult to apply it with intrinsic sensors (i.e. sensors which modulate the light intensity without making it coming out of the fiber).

b) Reference fiber

This technique can be considered as an exceptional case of spatial division. An extra fiber which transmits a light signal follows the same path as the fiber with the sensor. This signal is exposed to the same leakages and external disturbances, so that you can use it as a signal of reference [19 [-]]. The asset of this technique is to make it possible to follow the drift of the light power emitted by the source, which is critical for the intensity modulation sensor.

c) Wavelength of reference

In its simplest configuration, this technique uses two optical sources with thin spectral widths and with two different wavelengths. We can use a source with a large spectral width instead but you will need to use filters in order to assess the information coming from each wavelength. If we assume that the leakages induced by the system are independent of the wavelength but that the amplitude of the measurand we want to detect does depend on it, then it is possible to use the results of the spatial division. Provided that we choose the correct wavelengths, it is sometimes possible to take one of the two wavelengths as a reference.

d) Intrinsic characteristics of the measurand:

If the quantity you have to measure is alternating (for example vibrations), you simply have to make a spectrum analysis on the electric signal coming from the sensor, so that the ratio between the alternating and continued components will directly give the amplitude of the measurand. In other cases, the measurand will be proportional to the continued component. It is also possible to use modulated sources [20 [A modified AC/DC compensation technique for DC mesurands]].

1.5. Summary

We have studied in this chapter the most significant techniques using intensity modulation optical fiber sensors. Here is a summary of the characteristics of the different transducers:

a) The sensors going by microbenders

They are intrinsic sensors (i.e. they modulate light intensity without making it going out of the fiber), they are particularly suited for measuring displacements. Because of their principle they are very sensitive and they have a big amplitude of modulation, however they are not very stable, because of the modal redistribution in the fiber.

b) Evanescent field sensors

They are especially useful for detecting chemical species. Their main disadvantage is the low interaction between the measurand and the light (i.e. the low amplitude of modulation); you can improve the sensitivity by using special fibers.

c) The sensors coupling two fibers

These extrinsic sensors are often used for measuring displacements. There are lots of possible configurations but most often, you have a low rate of coupling, so you have to use multimode fibers or extra optics.

* *
*

We can see that intensity modulation sensors have disadvantages (i.e. low sensitivity and low stability, necessity to use a mitigation technique on the long view) but their big asset is that they are simple to use.

2. Phase modulation sensors and interferometric sensors: examples and applications

Optical interferometry has always been associated with precision metrology. An interferometer is an instrument in which at least two optical waves stack up at the same place. Moreover, if these waves are coherent, the resulting intensity periodically varies depending on the phase difference or on the optical path and the period is equal to the wavelength. The variation of phase difference between the waves is on the scale of the wavelength, so the measure is appreciable.

Using monomode fibers and their components makes it possible to build very sturdy interferometers which can be used in laboratories and anywhere else. Since the optical fibers have first been used, we have realized that their guidance properties were related to the environment (temperature, strain, pressure, etc.). So a difference in the optical path makes it possible to measure any variation of the temperature or of the strain.

This chapter concerns sensors whose principle takes into account the variation of optical path induced by the measurand. With interferometry you can measure the difference of optical path and so infer the measurand.

2.1. Fundamental principles

A sensor can be defined as a component in which the optical signal will be modulated in response to the measurand. Let's take as an example a source whose spectrum is known, and the electric field $E(\lambda)$ of an optical wave, whose wavelength is λ. The electric field $E'(\lambda)$ after the sensor can be written as: :

$$E'(\lambda)=T(X,\lambda)E(\lambda)$$
$$math:(1)$$

where $E'(\lambda)$ *is the transformation matrix of the sensor and* X is the vector which defines its environment, including temperature, strain, etc. The configuration of the sensor will enable you to determine T then you just have to invert the previous equation to get the measurand. In a interferometric sensor, the measurand will modulate the phase of the electromagnetic field, which will result in changing the intensity of the interferometer.

We can take T as the product whose effect is observable on the transmitted beam:

$$T=a\,e^{i\phi}B$$
$$math:(2)$$

where $a$is the scalar transmittance, ϕ is the phase delay and *B* is the birefringent matrix of the component. a, ϕ et B sont depend on λ and on the environment medium. The effects of the matrix B are studied in the next chapter I.2.3.

We can write again the equation (1) with the aid of equation (2) by assuming that the sensor does not modify the polarization of the wave:

$$E'(\lambda)=a\,E(\lambda)e^{i\phi}$$
$$math:(3)$$

The modification of the transmitted wave is obtained with a or ϕ.The transmittance a enerally does not depend much on the environment medium, we can assume that a is constant, it has been studied in the previous chapter. The sensitivity of the fiber to the three magnitudes of the environment (temperature, strain and pressure) can be written as:

$$\frac{\partial\phi}{\partial X}=\frac{2\pi}{\lambda}\left(n\frac{\partial l}{\partial X}+l\frac{\partial n}{\partial X}\right)\text{ with }X=f(T,P,\Delta l)$$
$$math:(4)$$

where l is the length of the fiber and n is the effective index of the fundamental mode of the fiber. The first term of the bracket is the physical extension of the fiber and the second is the variation of the effective index.

Most of the interferometers have two waves (i.e. fibers) in which a fiber is subjected to the measurand and another is isolated from it in order to be used as a reference.

For example, let's take an optical fiber strain sensor. To simplify, we will assume that the sensitive element is an isotropic optical fiber with a cylindrical symmetry. We will also assume that the measurand is purely axial without any transverse component. The application of this strain on the fiber will have three effects:

1. the fiber is physically stretched or squeezed.
2. the refractive index of the core and of the jacket are modified, so the effective index of the fundamental mode varies as well.
3. The rays of the core and of the optical jacket will be affected too, consequently the effective index of the fundamental mode will varies as well.

The first effect is the main one, and if we consider the others are negligible, all we have to do is to make the fiber a wavelength longer or shorter to make a one-period change in the interferometer. However, the second effect is about 20% as big as the first one in melted silica and has an opposite sign, so that its sensitivity is a little lower. The third effect is a little bit more complicated. The effective index of the guided modes of the fiber depends on opto-geometrical parameters, like the refractive index of the core and of the optical jacket, on the rays of the core and of the optical jacket and of the considered wavelength. In practice, the fundamental mode's effective index is almost the same as the core's refractive index. By reducing (or increasing) the core's diameter, you can reduce (or increase) the effective index of the fundamental mode, and so come closer (farther) to the refractive index of the optical jacket. However, the third effect is negligible. When you take into consideration all the elements, the sensitivity to strain of a fiber with $\lambda = 633\ nm$ is $6.5 \times 10^6\ rad/m$ [21 [-]].

A similar study can be carried out concerning the temperature, then the three effects are:

1. 1.fiber lengthening due to the heat
2. modification of the refractive indexes of the fiber because of the thermo-optic effect
3. the rays of the fiber increase due to the heat

In melted silica the thermal expansion coefficient is very low, consequently only the second effect has an impact. When you take into consideration all the elements, the thermal sensitivity of a fiber with $\lambda = 633\ nm$ is $100\ rad/K$ for a sensitive one-meter element [22 [-]].

We can also study the effect of pressure which will reduce the geometrical dimensions (length and diameter) and modify the refractive indexes via the elasto-optic coefficient [23 [-]].

We know that interferograms are periodic with a 2π rad period in terms of phase difference or of optical path length of λ. In order to infer the value of the measurand as precisely as possible, you have to know for sure the optical path length, but this is not easy given the interferogram's periodicity.

2.2. Two-wave interferometers

The most common form of two-wave interferometers is the Mach-Zehnder configuration shown on Figure 7. The source is coupled in a monomode optical fiber, the amplitude is divided into two fibers after being passed in a directional coupler $DC1$. One of the fibers is to be the reference wave (i.e. the reference fiber) whereas the other is the modulated wave (i.e. the signal fiber). Then the fibers are combined again with another directional coupler $DC2$. All you have to do then is plugging a photodetector in one of the outputs of the $DC2$ to get an electrical signal which will be proportional to the incident optical power.

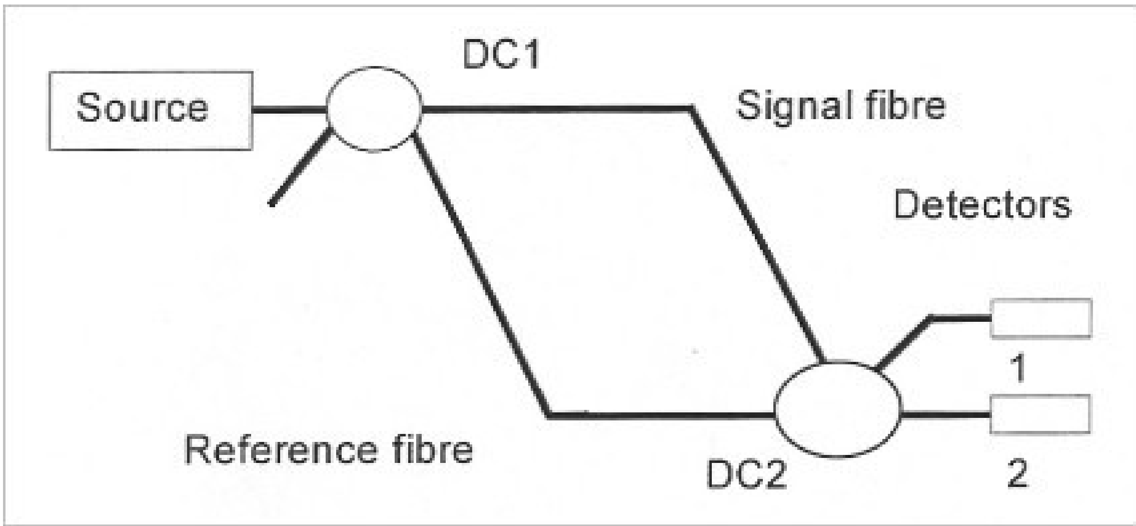

Figure 7 : Mach-Zehnder optical fiber interferometer. DC1 and DC2 are directional couplers.

We can demonstrate [24 [Interferometers in Optical fibre sensors : systems and applications]] that the intensities seen by the photodetectors 1 and 2 can be written as:

$$I_1 = I_0 \left[1 - V \cos\left(\phi_a - \phi_b \right) \right]$$
$$math:(1)$$

and

$$I_2 = I_0 \left[1 + V \cos\left(\phi_a - \phi_b \right) \right]$$
$$math:(2)$$

where ϕ_a and ϕ_b are the phases of the signal and reference waves, $I_0$is the average intensity and V is the interferences' visibility. The visibility depends on the relative intensities of both signal and reference waves. The best visibility can be obtained when the intensities are identical and the difference of optical path between the signal and reference waves is smaller than the length of coherence of the source. Under these circumstances, the visibility is equal to 1. Otherwise, the visibility generally varies between zero and one. It is important to note that the two intensities I_1 and I_2 are in phase opposition and that their sum is constant. The access to both of the outputs can make it possible to mitigate the possible fluctuations of the source.

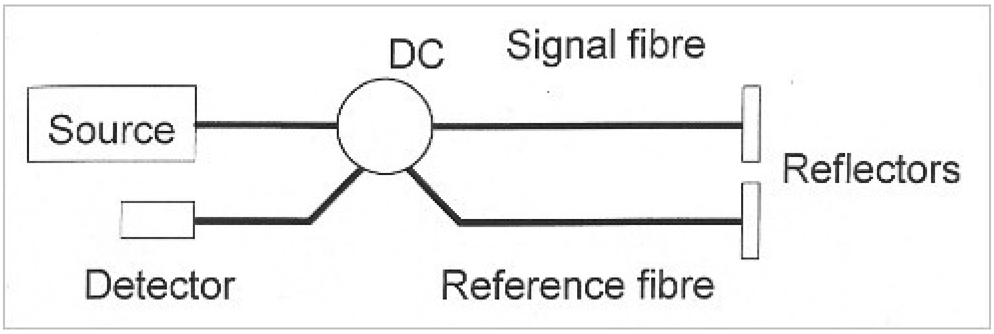

Figure 8 : The Michelson optical fiber interferometer. DC is for "directional coupler"

Figure 8 shows the Michelson interferometer which is a variant of the Mach-Zehnder one. Both reference and signal fibers are ended by reflectors which reflect the light on itself. The directional coupler DC combines and divides the beams at the same time. The sensitivity of this interferometer is twice as high as Mach-Zehnder interferometer's because the signal passes twice in the sensitive area. However, this configuration has an important disadvantage, since it reflects the signal towards the source. It can generate instabilities in the source area [25 [-]] especially when using laser diodes. In practice, in order to avoid this problem, people add an optical isolator just after the source, this device only lets the light pass in one direction, so that it prevents any light coming back to the source. The optical isolators use the Faraday effect to rotate the polarization and a polarizer to block the wave or not. Another disadvantage of this coming back to the source is not being able anymore to access to the intensity in phase opposition and to easily mitigate the fluctuations of the source.

The Sagnac interferometer shown in Figure 9 is another kind of two-wave interferometers. It has essentially been created to measure the angular speed, like in the gyroscope's case [26 [Fibre Optic Gyroscope]].

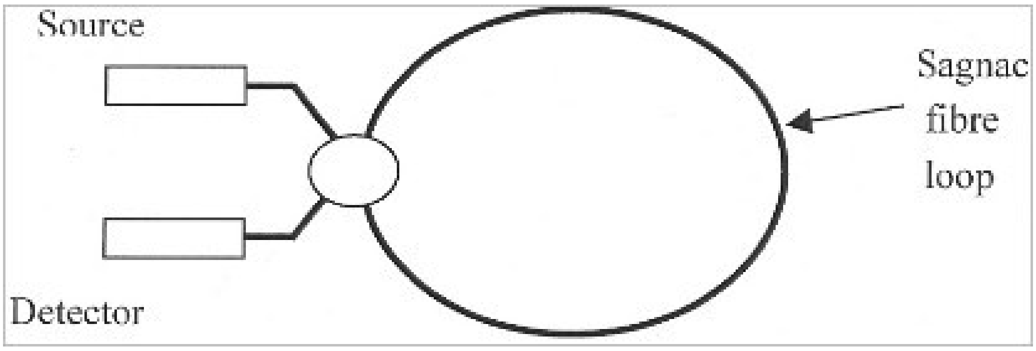

Figure 9 : Sagnac fiber interferometer

The signal and reference waves are propagating in the same fiber and rotate clockwise and anticlockwise into a fiber loop. At first sight, the two waves seem to propagate in the same path and so to always be in phase, and that is true if we have reciprocal effects. However non-reciprocal effects can make phase differences, notably angular speed [27 [Fiber optic gyroscopes : a bibliography of published literature]], a magnetic field [28 [-]] or a dynamic measurand [29 [-]]. Let's take as an example the effect of a dynamic and mechanical strain near one of the tips of the fiber loop. At a given moment, the signal and reference waves coming to the directional coupler to interact will not see the same strain, so that the phase difference will not be null anymore.

2.3. Multibeam interferometers

Until now, we have only talked about two-wave interferometers, but there are also multibeam interferometers.

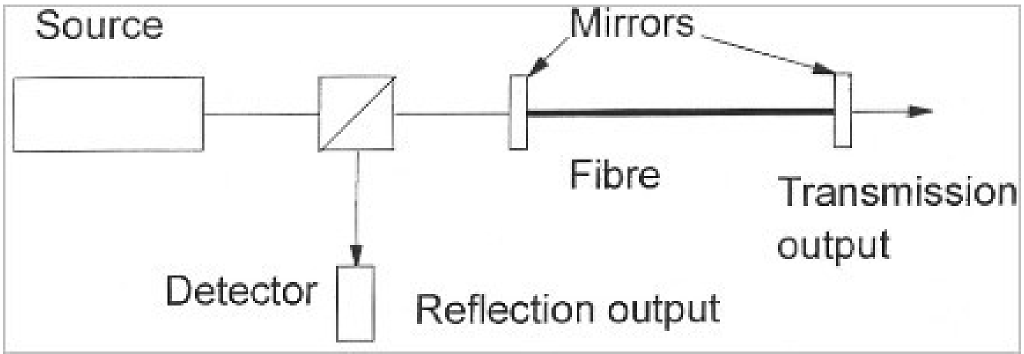

Figure 10 ; Fabry-Pérot interferometer

The quintessence of this kind of interferometers is the Fabry–Pérot interferometer (FP), shown on figure 10. The transfer function of a Fabry-Pérot interferometer is famous [30 [Principles of Optics]]:

$$I = \frac{I_0}{1 + F\sin^2(\phi/2)}$$

$$math:(1)$$

where ϕ is the phase difference of the light after a round-trip in the cavity and F is the finesse characterizing the resolution of the phase difference of the component and it is written as:

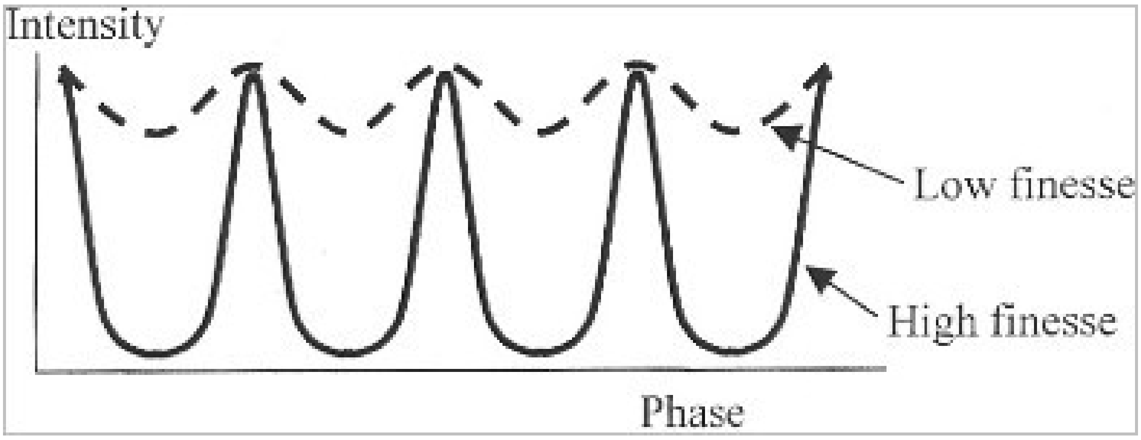

Figure 11 : Transmission of a Fabry-Pérot interferometer according to the phase difference and with two different finesses.

$$F = \frac{4R}{(1-R)^2}$$
$$math:(2)$$

where R is the reflection coefficient of the reflectors.

The free spectral range (i.e. the distance between two consecutive peaks) is another important characteristic of the Fabry-Pérot interferometer:

$$\Delta \nu = \frac{c}{2Ln}$$

where c is the speed of light, L the distance between the reflectors and n is the refractive index of the medium.

The sensitivity of such a device is improved by the numerous round-trips of the co-propagative and counter-propagative waves. The typical reaction of a Fabry-Pérot interferometer for two kinds of finesse is shown in Figure 11. The higher the reflection coefficient of the reflectors is, the more round-trips in the cavity the waves do, and the finer it is.

In practice, it is quite difficult to put high-reflectivity reflectors at the end of fibers, however Stone [31 [-]] has proven it is possible to to realize a finesse of 300. The most common Fabry-Pérot interferometers simply use Fresnel reflection of 4% which happens at each extremity let naked in the air: their transmissions look like the low finesse shown in Figure 9. It is possible to use the Bragg grating as cavity mirrors, like Henderson proved it [32 [-]].

2.4. Two-wavelength interferometry

As we have seen previously, an interferogram is periodic when we superimpose monochromatic waves. In order to widen the range of possible uses, it is possible to make waves which have very similar wavelengths interfere [33 [Cambridge Studies in Modern Optics : Interferometry]]. This technique can also be used with fiber interferometers, like Kersey proved it [34 [-]].

When a two-wave interferometer is illuminated by two monochromatic sources whose wavelengths are λ_1 and λ_2 each one will make an interferogram with a definite visibility (lets' take one to simplify) and a definite average intensity I_0(identical for λ_1 and λ_2, once again to simplify), so the final intensity is:

$$I = I_0\left[1+\cos\left(\frac{2\pi n l}{\lambda_1}\right)\right]+I_0\left[1+\cos\left(\frac{2\pi n l}{\lambda_2}\right)\right]$$
$$math:(1)$$

This equation can be also written as:

$$I = I_0\left[1+V\cos\left(\pi n l\frac{\lambda_1+\lambda_2}{\lambda_1\lambda_2}\right)\right]$$
$$math:(2)$$

where V is the fringe contrast function and can be written as:

$$V=\cos\left(\pi n l\frac{\lambda_2-\lambda_1}{\lambda_1\lambda_2}\right)$$
$$math:(3)$$

In this configuration the measure is equivalent to a one-wavelength interferometer's measure. On the other hand the range within which the measure is obtained without ambiguity is related to the period of V, so the measure range is increase by a factor $\lambda_2/(\lambda_2-\lambda_1)$.

2.5. Low coherence interferometry

We have already made mention of that at the beginning of the chapter: for the fringes of an interferogram to be visible, the optical path difference between the waves need to be shorter than the coherence length of the source $l_c$which is equal to:

$$l_c=\lambda^2/\Delta\lambda$$
$$math:(1)$$

where $\lambda$is the central wavelength and $\Delta\lambda$ is the spectral width of the source.

Generally laser diodes' coherence lengths are within dozens of centimeters and meters, whereas LED's (Light Emitting Diodes) ones vary from dozens to several hundreds of micrometers. Consequently, by illuminating an interferometer with a low coherence source, it is possible to determine the position for which the optical path difference is null: you have to find the position where the fringes have the best visibility. You can use this technique to resolve the ambiguity related to fringes order (i.e. the real displacement of the fringe system) which is a recurrent problem in interferometry. Then the measure range is widened.

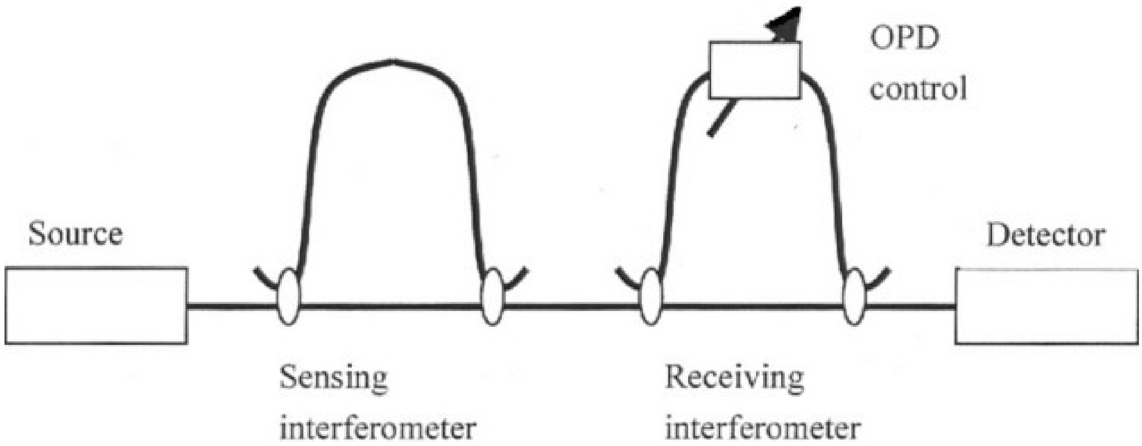

Figure 12 : Double fiber interferometer. The optical path difference (OPD) makes it possible to control the optical path difference of the second interferometer

It is possible to measure the optical path difference of an interferometer by using the configuration shown on Figure 12. This assembly is made of a double interferometer, one which is used in sensing and the other which is receiving and which OPD we can control. For a better understanding of the second interferometer's role, let's study the influence of the second interferometer's control OPD on the intensity seen by the detector. If the OPD is near zero, fringes are visible. When the OPD is increased beyond the coherence length of the source, the fringes disappear. If you increase even more its OPD so that it comes closer to the sensing interferometer's OPD, interferences can appear again. These interferences are obtained between the two next waves if their phase difference is smaller than the coherence length of the source:

- **Wave 1**: the wave which takes the longer path in the sensing interferometer and the shorter path in the receiving
- **Wave 2:** the wave which takes the shorter path in the sensing interferometer and the longer path in the receiving

Consequently, the fringe visibility shows a local maximum, as shown on Figure 13, when both measuring and receiving interferometers have equal OPD. When the OPD is defined, you immediately get the measurand.

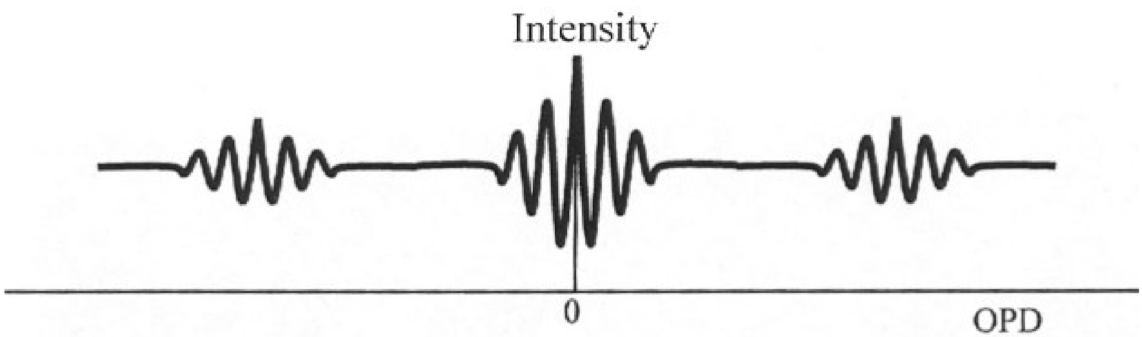

Figure 13 : Schematic representation of the interference fringes of a double interferometer according to the OPD

In practice, there are different ways to make an interferometer's OPD vary. The simplest methods are based on the displacement of a reflector which is put on a motorized linear stage so that you can make the length of the interferometer's arms vary [35 [-]]. This method is simple and has a wide range of possible variations, but its drawback is its being in open space. So you have to bring the light out of the fiber to inject it back, so that you create leakages. Furthermore, you need to be extremely precise when positioning the opto-mechanical elements. Nevertheless it is possible to accomplish a length variation without bringing the light out of the fiber: you have to stick the fiber on a piezoelectrical element which dilates or reduces according to the electrical signal you give to it. But this technique has a very limited range of variation.

2.6. Determinating the phase

In a interferometric assembly, the key to determine the measurand is measuring without ambiguity and with enough sensitivity the phase difference. The intensity of the assemblies we have seen previously varies according to equations [1] and [2].

If we assume that the phase of the signal wave (ϕ_a) is composed of a continuous term and of a harmonic of low amplitude, determinating the measurand will need the interferometer to be configured as on Figure 14, and the best sensitivity will be obtained in Q position. In that case, we say that the (signal and reference) waves are in quadrature.

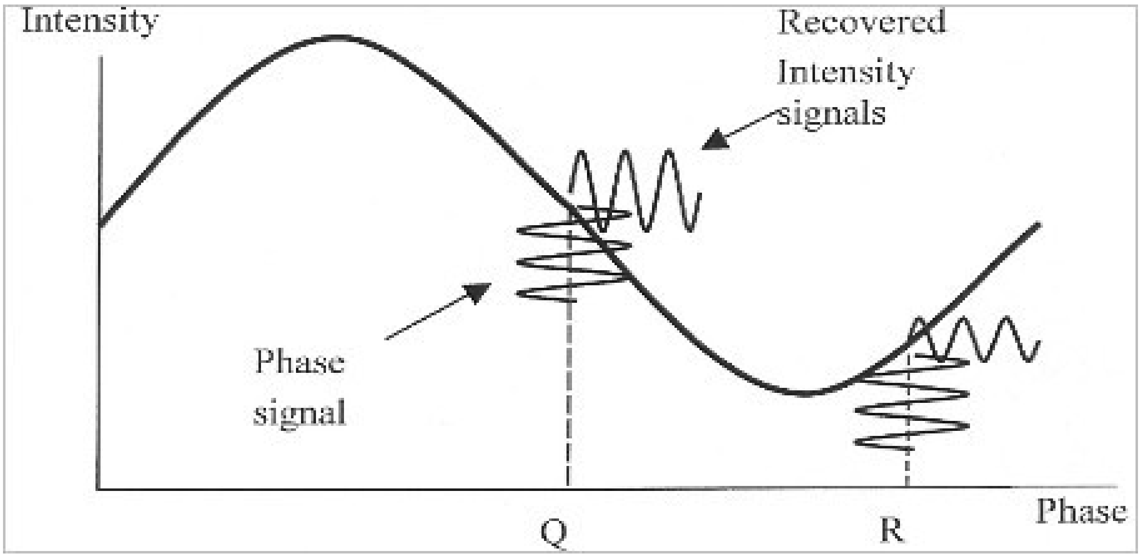

Figure 14 : Determinating the phase for two particular points

This position is obtained when the phase difference is:

$$\phi_a - \phi_b = \frac{\pi}{4} + N\,\pi$$
$$math:(1)$$

Some techniques go by adjusting ϕ_b (i.e. the phase of the reference wave) to maintain the interferometer in quadrature:)

- you can vary the length of the fiber by the aid of the piezoelectrical element [36 [-]].
- or vary the wavelength of the laser diode by controlling the injection current or the temperature [37 [-]].

Some passive techniques are also possible, they use predetermined sequences of the reference wave's phase difference. As an example, if you create a $\pi/2$ rads phase difference, the output intensity is:

$$I_i = I_0\left[1 + V\cos(\phi + i\frac{\pi}{2})\right]$$
$$math:(1)$$

with i varying from 1 to 4.

A combination of the four intensities gives as a phase difference:

$$\tan(\phi) = \frac{I_3 - I_1}{I_4 - I_2}$$
$$math:(2)$$

Finally, we can mention the method based on adding an alternative discrepancy of ϕ_b, which resembles the phase modulation of the carrier. The intensity can be written as:

$$I = I_0 [1 + V \cos(\phi_a - \phi_b - \omega_m t)]$$
$$math:(3)$$

With techniques of phase-locked loop well known in electronics, you can get the demodulation.

2.7. Summary and conclusion

Interferometric sensors are often used for detecting diverse measurands. The most common and simplest one is probably the strain sensor that makes it possible to watch how the structure evolves. For example it can easily be placed in a part made of composite material. The small size of the fiber makes it possible not to adulterate the characteristics of the part. Configurations with a very long sensitive area are also possible but people most often use distributed sensors. In order to watch infrastructures (like bridges and dams...) the most common method is using Bragg gratings, however interferometry can turn out to be more appropriate: using a double interferometer can be useful to watch the sensitive areas (via the OPD's control). These areas are generally air cavities positioned along the infrastructure [38 [-]].

It is also possible to measure transversal strains, but they induce birefringence in the fiber, so sensors using polarization modulation are better to detect them (cf next chapter).

All the measurands making a strain on the sensitive area are easily detectable, others quantities also are measurable like electric and magnetic fields via magneto- and electro-optic effects [39 [Electric and Magnetic field Seinsing for High Voltage Applications]].

Interferometric techniques enable fine and sensitive measuring but they are limited by the methods you need to resort to in order to get the phase difference without ambiguity. That is why Bragg gratings are still most often used.

Optical fiber's intrinsic sensitivity to temperature is one of its main drawbacks; you have to use discriminatory techniques to distinguish between the measurands. Of course, this effect is very useful for producing a thermometer.

3. Polarization modulation sensors: examples and aplications

Sensors using polarization modulation are based on the changes of state of the polarization of the light which is propagating in the optical fiber ; these changes are induced by the measurand. In this chapter, we will present the fundamentals of the physicals properties and the techniques used to make a polarimetric sensor, and their limitations.

3.1. Fundamental principles

Before going into more detail about sensors using polarization modulation, here is a brief summary about the properties of the waves propagating in fibers with a particular interest on polarization.

The state of polarization of an electromagnetic wave propagating according to a z-axis can be described by the extremity of the electric field vector $\vec{E}$ in the xOy plane. Figure 15 shows an example of elliptical polarization. Three states can be defined: linear, circular and elliptical.

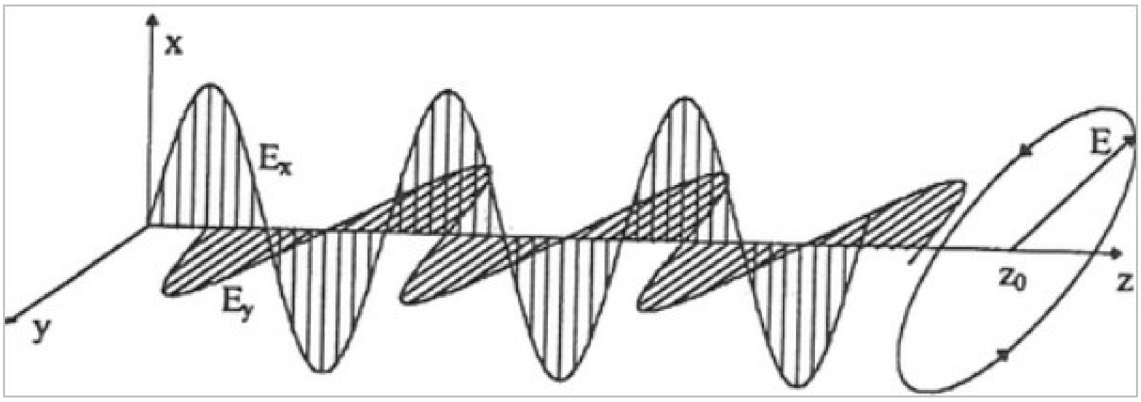

Figure 15 : Example of a polarization of an electromagnetic wave

Only the electric field $\vec{E}$ is shown.

a) Linear polarization

Linear polarization's state is characterized by an oscillation of the electric field vector which runs on a straight line. Should the wave travel in the z-direction, the straight line drawn by $\vec{E}$ belongs to the xOy plane . The components od E_x and E_y have a phase difference of $\delta\phi = \phi_y - \phi_x = m\pi$ Ifd m is nil or an even whole number, the components are said to be in phase. If m is an odd whole number, the polarization line is orthogonally oriented compared to the previous one (cf Figure 16).

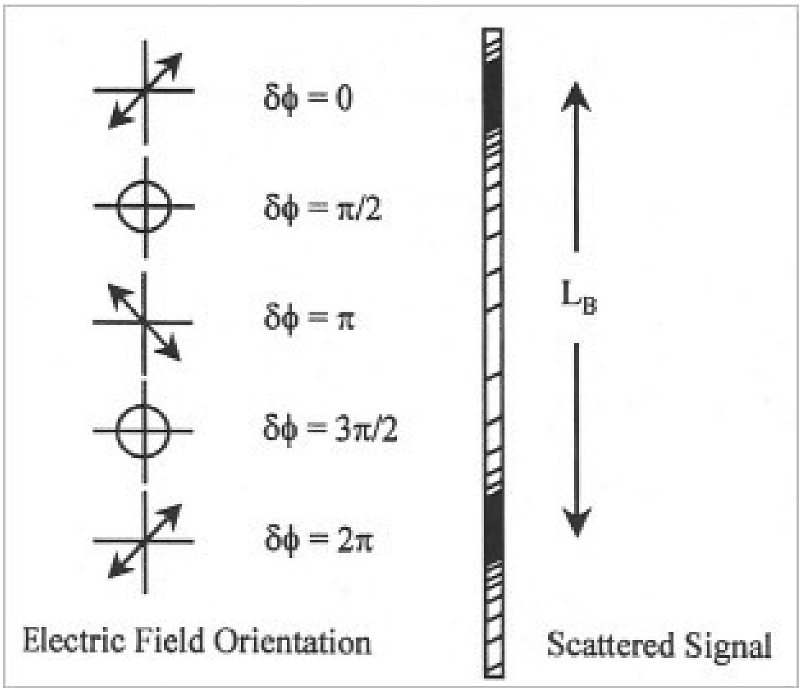

Figure 16 : States of polarization for diverse phase differences

b) Circular polarization

Circular polarization's state is characterized by its two components E_x and E_y having an identical amplitude and a phase difference as:

$$\delta\phi=\phi_y-\phi_x=\pm\frac{\pi}{2}$$

Under these circumstances, the extremity of the electric field vector traces a circle either clockwise or anticlockwise-wise. You can determine the way the rotation moves by watching the wave coming. A right-hand circular polarization (i.e. when $\vec{E}$ rotates clockwise) is obtained when

$$\delta\phi=\frac{-\pi}{2}+2m\pi$$

where

$$m=0,\ \pm1,\ \pm2,\ \ldots$$

By analogy, a phase difference of

$$\delta\phi=\frac{\pi}{2}+2m\pi$$

where

$$m=0,\ \pm1,\ \pm2,\ \ldots$$

will give a left-hand circular polarization, $\vec{E}$ will rotate in the anticlockwise direction.

A circular polarization can be only specified by its amplitude and by which way (left or right) $\vec{E}$ rotates.

c) Elliptical polarization

In any other circumstances, the extremity of the electric field clockwise or anticlockwise traces an ellipse in the xOy plane when rotating (cf Figure 9). The amplitude of the components E_x and E_y is not identical and their phase difference has not characteristic value. Linear and circular polarizations are specific cases of elliptical polarization.

There are several formal representations of the polarization and of the modeling of the transmission of light which has been polarized through a polarizing medium, like birefringent mediums. The most common method is Jones' method, that we will tell in detail later.

d) Jones' matrices

Jones' matrices formalism gives us information about light polarization which travels in a complex medium. The state of polarization can be estimated by using matrix algebra [40 [Optics]]. The state of polarization of a wave is represented by two components which are complex numbers as:

$$a=\begin{bmatrix} E_x e^{j\phi_x} \\ E_y e^{j\phi_y} \end{bmatrix}$$
$$math:(1)$$

where E_x and E_y are the amplitudes and ϕ_x and ϕ_y are the phases of components of $\vec{E}$ in the xOy plane.

The previous equation describes the general case of an elliptically polarized wave travelling in z -direction. In the case of a linear polarization which makes an angle $\theta$with the x - axis , the Jones matrix becomes:

$$a=\begin{bmatrix} E_x\cos(\theta) \\ E_x\sin(\theta) \end{bmatrix}$$
$$math:(2)$$

A circular polarization will be described as:

$$a=\begin{bmatrix} E\cos(\omega t)+i\sin(\omega t) \\ -E\sin(\omega t)+i\cos(\omega t) \end{bmatrix}$$
$$math:(3)$$

If you take the real numbers out of each component of the wave you find:

$$E_x=E\cos(\omega t)$$
$$E_y=-E\sin(\omega t)$$
$$math:(4)$$

When $t=0$, the electric field vector, is given by $E_x=E$ and $E_y=0$, so if t increases, E_x decreases but remains positive and E_y increases but remains negative. Consequently $\vec{E}$ clockwise traces a circle._

Now let's study the matrices which describe the diverse mediums through which light passes. The simplest example is a Jones matrix in an isotropic absorbing medium, which weakens the transmission but does not modify the state of polarization. Such a medium is represented by the matrix:

$$\mathrm{A}=\begin{bmatrix} \alpha & 0 \\ 0 & \alpha \end{bmatrix}$$
$$math:(5)$$

where α*is the weakening of the medium.*

An ideal polarizer will only let one direction of the electric field go out and will stop the others. A polarizer oriented according to the x - axis will have as a matrix:

$$\mathrm{A}=\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$
$$math:(6)$$

and a wave polarized in an unparticular way will have no more component on the y-axis after having passed through the polarizer:

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} E_x \\ E_y \end{bmatrix}=\begin{bmatrix} E_x \\ 0 \end{bmatrix}$$
$$math:(7)$$

Generally, the matrix of a polarizer whose transmitting axis has a θangle with the x -axis in the xOy plan can be written as:

$$P=\begin{bmatrix} \cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \cos(\theta)\sin(\theta) & \sin^2(\theta) \end{bmatrix}$$
$$math:(8)$$

The state of polarization when coming out of a system made of several elements is obtained by multiplying the state of polarization when entering the system by the series of individual matrices of the diverse elements encountered all along the optical path. The matrix multiplication is not commutative, so be careful with the matrices' order.

e) Optical retarder: Quarter-wave plates and half-wave plates

An optical retardant is a component made of a birefringent material and is used to change the state of polarization of any incident wave. When entering the device, the wave be divided according to the main axes of the medium, which are called *ordinary axis* and *extraordinary axis*. The two components will propagate with different speeds characterized by the ordinary refractive index $n_o$and the extraordinary refractive index n_e. When coming out of the device, the components have not the same phase differences anymore and so they have not the same states of polarization as before entering anymore too.

The relative phase difference $\Delta\phi$between the ordinary and extraordinary axes is given by the equation:

$$\Delta\phi=\frac{2\pi}{\lambda}d\left|n_e-n_o\right|$$
$$math:(1)$$

where d is the thickness of the material and $\lambda$is the wavelength.

The thickness of the birefringent material d is chosen in order to produce the expected phase difference. The most famous optical retarders are the half-wave plates and the quarter-wave plates. A half-wave plate makes the direction of a linear polarization rotate by 90. A quarter-wave plate makes a $\pi/2$phase difference between the components of the light travelling on the ordinary and extraordinary axes.

A quarter-wave plate makes a circular polarization out of a linear polarization which was 45-oriented at its main axes. Otherwise, a circular polarization will give a linear polarization which is 45-oriented at the main axes of the plate.

3.2. Birefringent optical fiber

For measuring based on the principle of polarization modulation, one of the essential conditions is using fibers which make it possible to preserve the waves' states of polarization while they propagate. In theory, standard fibers should preserve the state of polarization but in practice, a wave which enters with a definite state of polarization will come out after having been through some centimeters with a completely random state of polarization, notably because of micro-disturbances which appear during the making. That is why people use birefringent optical fibers which have two main axes. These axes are called fast axis and slow axis, depending on how fast the waves propagate on each one. A guided polarized wave travelling on the axis which has a high refractive index (i.e. slow axis) will run more slowly than a guided polarized wave running on the other axis (i.e. fast axis).

The birefringence of a fiber is given by the difference between the refractive indexes of the two axes:

$$B = n_s - n_f$$
$$math:(1)$$

where $n_s$and $n_f$are respectively the refractive indexes of the fast and fast axes. The birefringence is generally defined as the beat time and L_B, represents the length of fiber necessary for the phase difference between the two orthogonal axes to be 2π:

$$L_B = \frac{\lambda}{n_s - n_f} = \frac{\lambda}{B}$$
$$math:(2)$$

If the fiber is subjected to mechanical disturbances whose periods are similar to L_B,then there will be a strong coupling between both orthogonal polarizations. When making those fibers, such disturbances can appear that is why manufacturers pay a particular attention to it in order to avoid the fiber being curved or twisted while stretching it. The polarization will be maintained if the length of the beat time is shorter than about ten centimeters. If the light coming in have its polarization aligned on one of the main axes, it will be guided without any variation of its state of polarization.

There are two main methods to get birefringence in optical fibers:

1. 1.You can modify the core's guidance characteristics by adultering its geometry, for example by breaking its circular symmetry. We can mention the elliptical core fiber (cf Figure 14) which have some millimeters-long beat time length [41 [-]].
2. 1.Another possibility is to apply an asymmetrical strain on the core of the fiber, to get at the same time an asymmetry of the index profile. You can accomplish it by introducing highly doped areas around the core (cf Figure 15).

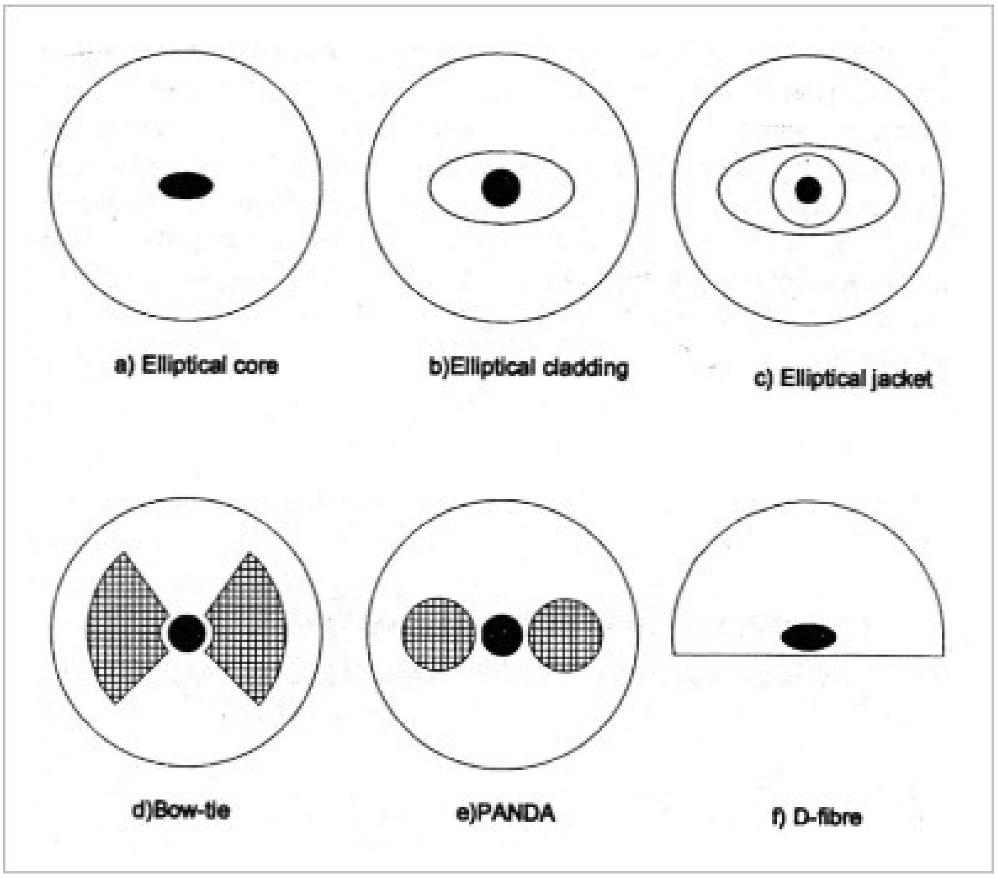

Figure 17 : Examples of highly birefringent optical fibers. Black areas are the core and grey ones are the highly doped areas

The bow-tie fiber has the higher birefringence value with $0.5\,mm$. Recently with the development of microstructured fibers, new birefringent fibers have appeared with more or less possibilities regarding the birefringence values and especially the guidance characteristics (unimodality area, dispersion curve...).

3.3. Polarimetric sensors

In most cases, polarimetric sensors use a linearly polarized source which is injected at a 45 angle from the main axes of the birefringent fiber so that the two propagating ways (slow and fast) should be similarly excited.

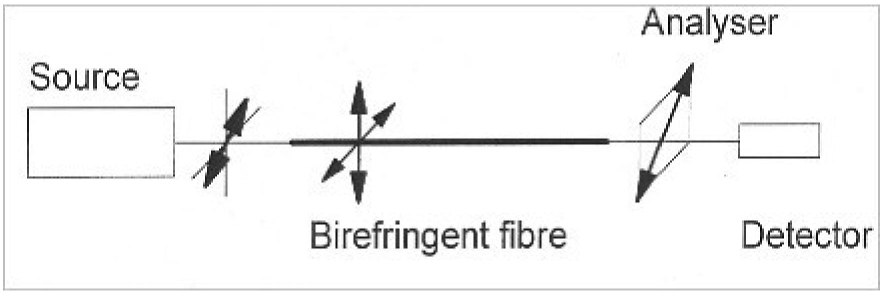

Figure 18 : Schematic representation of a polarimetric sensor

Using a half-wave plate can simplify a lot adjusting the orientation of the input polarization. At the output of the birefringent fiber, an analyzer (i.e. a polarizer) is placed in front of the detector to determine the state of polarization (cf Figure 15). The measurand will make the polarization rotate, so the intensity seen by the detector will vary. This assembly's drawback is its sensitiveness to the intensity variations of the source or of the injection. Using a Wollatson prism which separates the light into two orthogonally polarized beams enables you to avoid this problem, by using techniques like the ones detailed in the *Periodical Micro-curves* chapter and in the *Evanescent field* chapter. However bringing the prism into the line of the two detectors and of the main axes of the fiber is quite tricky.

We will now use Jones matrices to analyze the component. As we have already mentioned it, the two birefringent fiber's propagating modes which are orthogonally polarized are similarly excited. In this case, the electric field can be written as:

$$E_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$math:(1)$$

The electric field which is incident on the detector can be described as:

$$E = ABE_0$$

$$math:(2)$$

where A and B are respectively the Jones matrix of the analyzer and of the birefringent fiber. The fiber can be seen as the phase plate which modifies the phase difference between the two polarizations. The B matrix can be described as:

$$B = \begin{bmatrix} e^{j\left(\phi_m + \frac{\Delta\phi}{2}\right)} & 0 \\ 0 & e^{j\left(\phi_m - \frac{\Delta\phi}{2}\right)} \end{bmatrix}$$

$$math:(3)$$

where ϕ_m is the average phase difference and $\Delta\phi$is the phase difference between the two polarizations. This phase difference is produced by the propagation of light through the fiber.

In the specific case of an analyzer at a 45 angle from the fiber's main axes, the A matrix is written as:

$$A = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

$$math:(4)$$

The intensity after the analyzer will be:

$$I = E^2 = \frac{I_0}{2} \left[1 + \cos(\Delta\phi) \right]$$

$$math:(5)$$

where $I_0$is the total output power. Consequently, as the previous equation shows, changing the state of polarization will modify the intensity seen by the detector and make a sinusoidal signal. The previous equation is similar to the equations (1) and (2) which describe two-wave interferometry. Some measuring techniques can be transposed to improve the sensitivity.

3.4. Phase modification: how does it works?

The sensitivity of the sensor depends on the rotation degree of the polarization induced by the measurand and on the minimal detectable rotation. The influence of the measurand on the state of polarization can determined as follows: the phase of a wave guided by a fiber whose length is called L is :

$$\phi = \beta L = n_{eff} k_0 L$$
$$math:(1)$$

where β is the propagation constant of the mode, n_{eff} is its effective index and $k_0 = \frac{2\pi}{\lambda_0}$ is the wave vector with λ_0 as wavelength. The phase difference between two modes guided by the fiber after a L is :

$$\Delta \phi = \Delta \beta L = \Delta n_{eff} k_0 L$$
$$math:(2)$$

where Δn_{eff} est la différence entre les indices effectifs des deux modes de polarisation.

a) Effect of mechanical strain

Let's assume that the fiber be subjected to an external mechanical strain called ϵ. The phase difference produced by ϵ is proportional to the fiber's length which is subected to this strain. So it is important to consider the answer of the detector unit of length after unit. Then we have :

$$\frac{1}{L}\frac{\partial(\Delta\phi)}{\partial\varepsilon} = k_0 \frac{\partial(\Delta n_{eff})}{\partial n}\frac{\partial n}{\partial \varepsilon} + k_0 \frac{\partial(\Delta n_{eff})}{\partial D}\frac{\partial D}{\partial \varepsilon} + k \Delta n_{eff} \frac{1}{L}\frac{\partial L}{\partial \varepsilon}$$
$$math:(3)$$

where D and n are respectively the transverse dimension and the index profile of the fiber.

The first term of equation (3) describes the photoelastic effect, that is to say the variation of the refractive index of a material according to the mechanical strain. In the case of normal circular fiber, this variation can be calculated with:

$$\frac{\partial n}{\partial \varepsilon} = -\frac{n^3}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right]$$
$$math:(4)$$

where $\nu$is the Poisson's ratio of silica which is supposed to be identical for the core and the cladding layer, and p_{11}, p_{12} are the elasto-optic coefficient of silica [42 [Damage detection in composite structures using polarimetric low coherence i,]].

The second term of equation (3) is related to the variation of the fiber's portion when it is subjected to a mechanical strain. This modification of the section will affect the effective indexes of the modes and so their differences as well (i.e. Δn_{eff}). It has been proven that it does not affect the phase difference's variation much, so that in practice, it is negligible.

The last term of equation (3) describes the variation of the fiber's length due to the mechanical strain.

b) Effect of temperature

We can do a study similar to the previous one in order to describe the modifications induced by temperature. The variation of the phase difference due to temperature (*T*) can be obtained with:

$$\frac{1}{L}\frac{\partial(\Delta\phi)}{\partial T}=k_0\frac{\partial(\Delta n_{eff})}{\partial n}\frac{\partial n}{\partial T}+k_0\frac{\partial(\Delta n_{eff})}{\partial D}\frac{\partial D}{\partial T}+k\,\Delta n_{eff}\frac{1}{L}\frac{\partial L}{\partial T}$$

$math:(5)$

Equation (5) has the same first two terms as equation (3), they are related to the modifications of the fiber's opto-geometrical parameters (n and D) which induce a variation of Δn_{eff} . The variations of the refractive index are due to the termo-optic effect. The third term represents here the compression of the thermal expansion, which is:

$$\frac{\partial L}{\partial T}=\alpha L$$

$math:(6)$

where $\alpha$is the thermal dilatation coefficient.

The variation of the phase difference is essentially due to the modification of the refractive index according to temperature.

Equations (3) and (5) are used to calculate the mechanical and thermal sensitivity of circular fibers. As for birefringent fibers, calculating it is more complicated since the forms and the material which make up the fiber are more complex. So people often have to experimentally determine the sensitivity of the most exotic fibers.

3.5. Summary and conclusion

Polarimetric sensors can be used to detect different measurands. If the quantity you have to measure has no or few impact on the wave's polarization, you need to imagine a mechanical device to increase it, like with intensity modulation sensors and with phase modulation sensors.

Nevertheless, polarimetric sensors are more complicated to use and more expensive than intensity modulation sensors and phase modulation sensors, because you need to use birefringent fibers which are expensive; furthermore carrying out the assembly, especially lining up and orienting all the components is tricky.

These sensors are essentially used for measuring electric magnitudes.

III.Etude de cas

Here we will study the case of a polarimetric current sensor. This kind of sensors can be used for measuring classic measurands (like temperature, mechanical strain or pressure), however their field of expertise is currents or tensions measuring.

1. Polarimetric current sensors

Here we will study the case of a polarimetric current sensor. This kind of sensors can be used for measuring classic measurands (like temperature, mechanical strain or pressure), however their field of expertise is currents or tensions measuring.

The aim when using these sensors is to assess the intensity of the current passing in a conductor by measuring the density of the magnetic flux created around the conductor by the charges' displacements.

The density of the magnetic flux is given by the rotation of the polarization state of the light wave travelling in the fiber or in the magneto-optical material. This rotation is due to the magneto-optical effect which is proportional to the length of interaction (*L*) and to the Verdet constant (V, $radsT^{-1}m^{-1}$) of the material used for making the sensor. The angular rotation θ (in degrees) of the polarization of the wave travelling in the component is given by:

$$\theta = VBL$$
$$math:(1)$$

where B is the magnetic induction (Tesla) which is a function of the current travelling in the conductor and of its geometry.

Different methods can be used to measure the angle θ. The basic method is, first, to make the depolarized light pass through the polarizer. Then this polarized wave is modified by the influence of the magnetic field and eventually this rotation is converted into a modification of the intensity by the analyzer placed in front of the detector (see Figure 19):

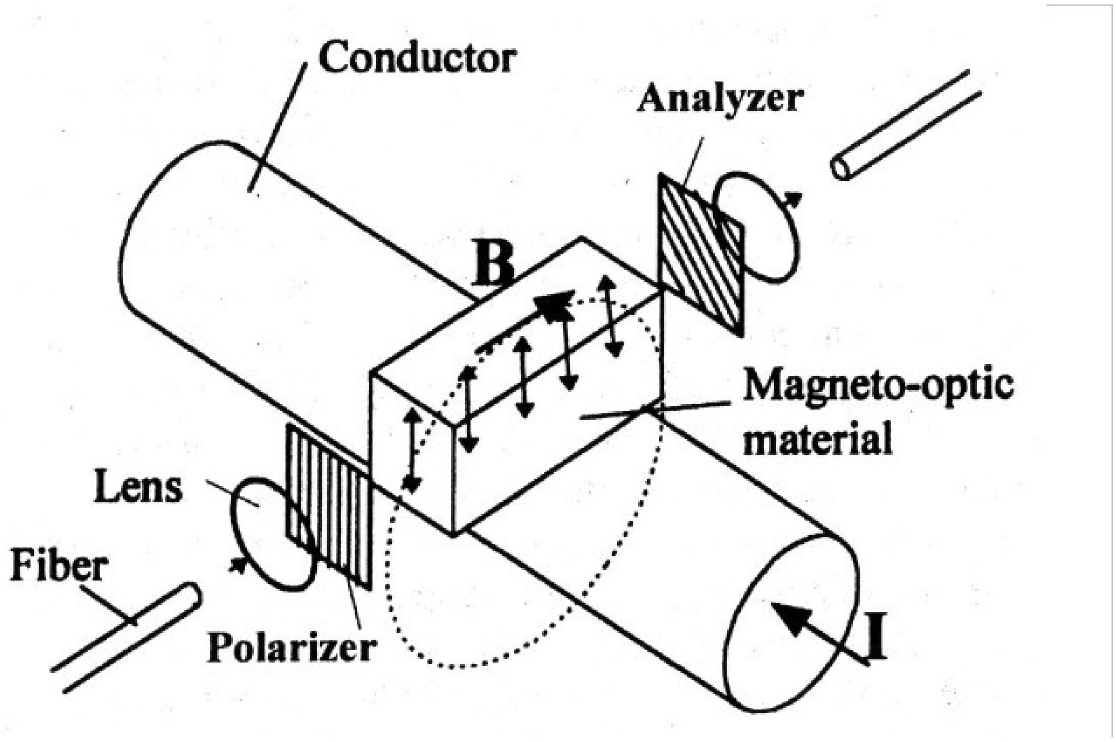

Figure 19 : Outline of an optical current sensor

The emitted intensity can be described as:

$$I = I_0 \frac{(1+\sin(2\theta))}{2}$$
$$math:(2)$$

where I_0 is the source's intensity.

The easiest way to insert an optical fiber current sensor is shown on Figure 20:

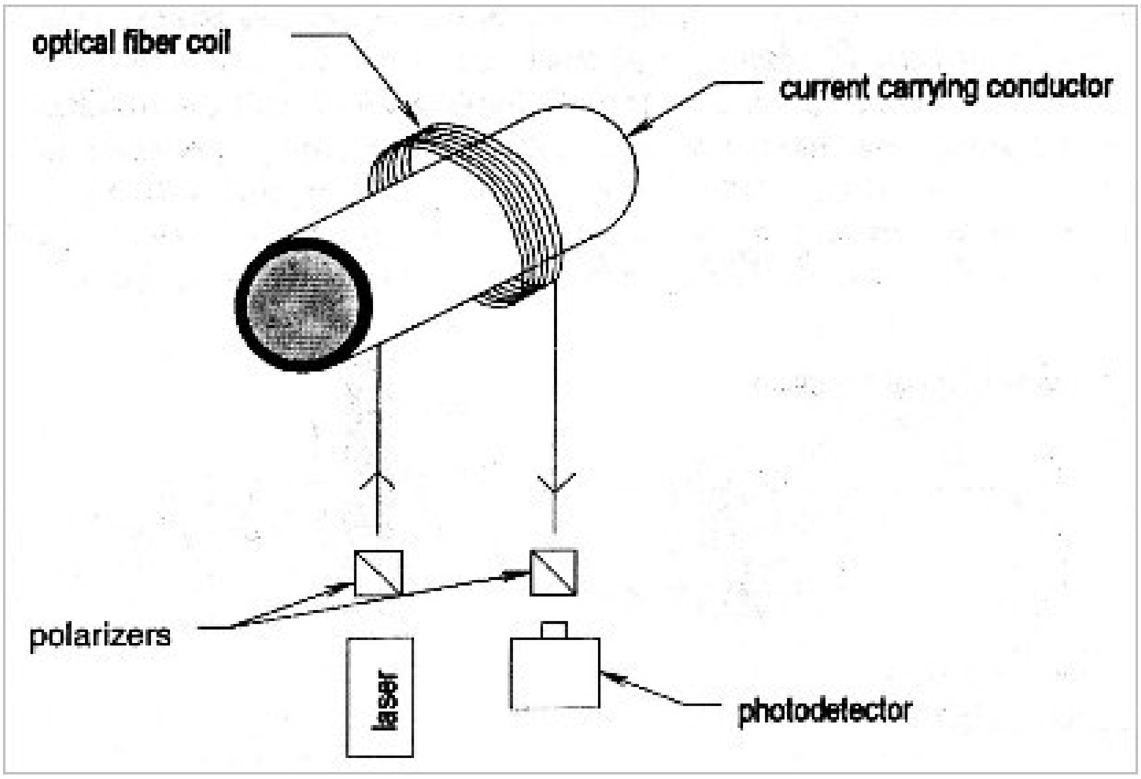

Figure 20 : Optical fiber current sensor

The magneto-optical material used here is the optical fiber itself. This solution is very easy to perform and very cheap. The main drawback is the low Verdet constant of the silica fiber ($\simeq 8\times 10^{-6}\ rad/A$) which is significantly lower than other commonly used crystalline materials' ones. It is possible to slightly increase the sensitiveness of this configuration by performing a round-trip in the area where the magnetic field is, either by adding a mirror at the fiber's extremity, or by using a configuration similar to a Sagnac interferometer's. Of course adding a coupler is necessary. Another possibility is to use a material which has a high Verdet constant like in Figure 21:

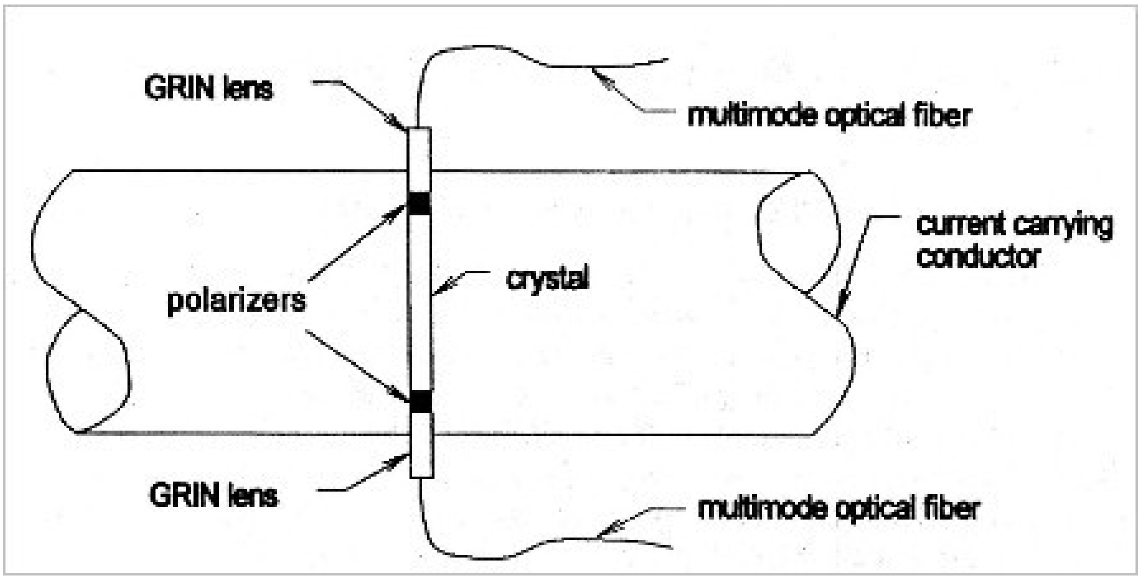

Figure 21 : Optical fiber sensor with a magneto-optical crystal

The optical sensors' sensitivity to variations of temperature and to vibrations has lead researchers to design more complex assemblies. One of the possible assemblies for mitigating disturbances is shown on Figure 22:

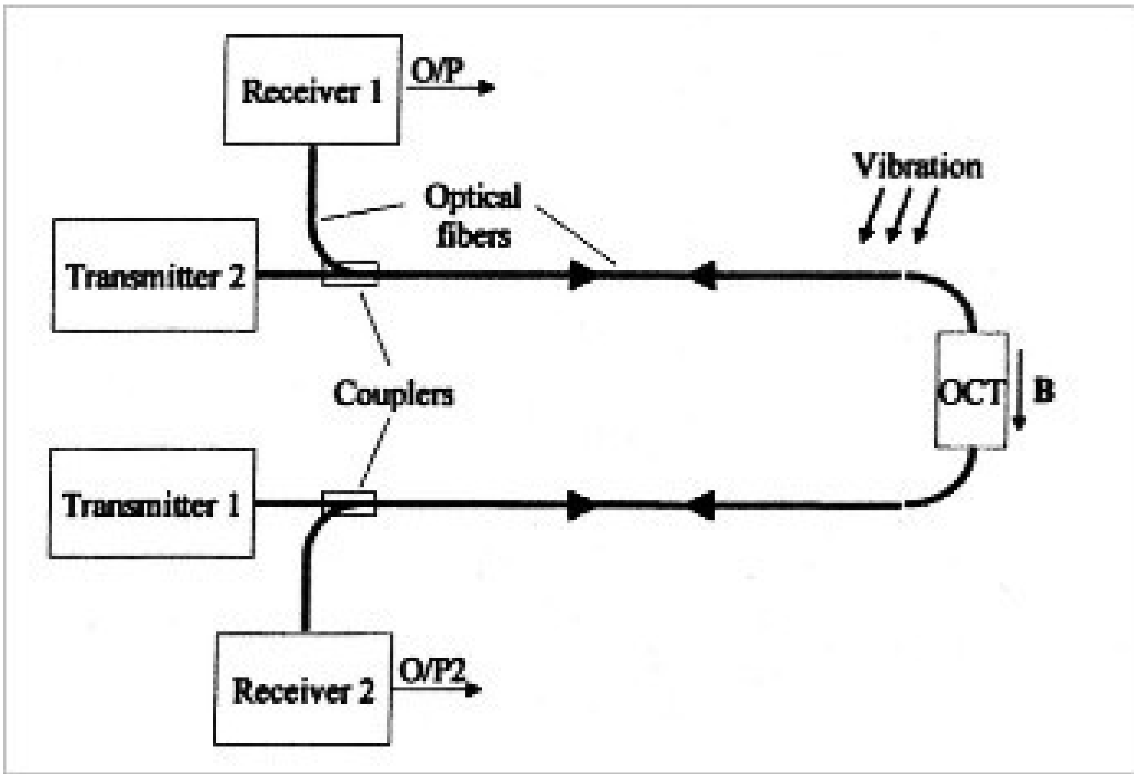

Figure 22 : Optical fiber sensor with compensated vibrations. OCT (Optical current transducer) is the active part of the sensor.

Two independent light sources are injected and travel in opposite directions. The rotation of the polarization state depends on the way the wave travels in the sensor, however the intensity of the two sources is not affected. Consequently, we can use signals to correct the vibration measured as shown on Figure 23. We can see that mitigating significantly improves the measuring of low current, but for high intensities it is not really necessary.

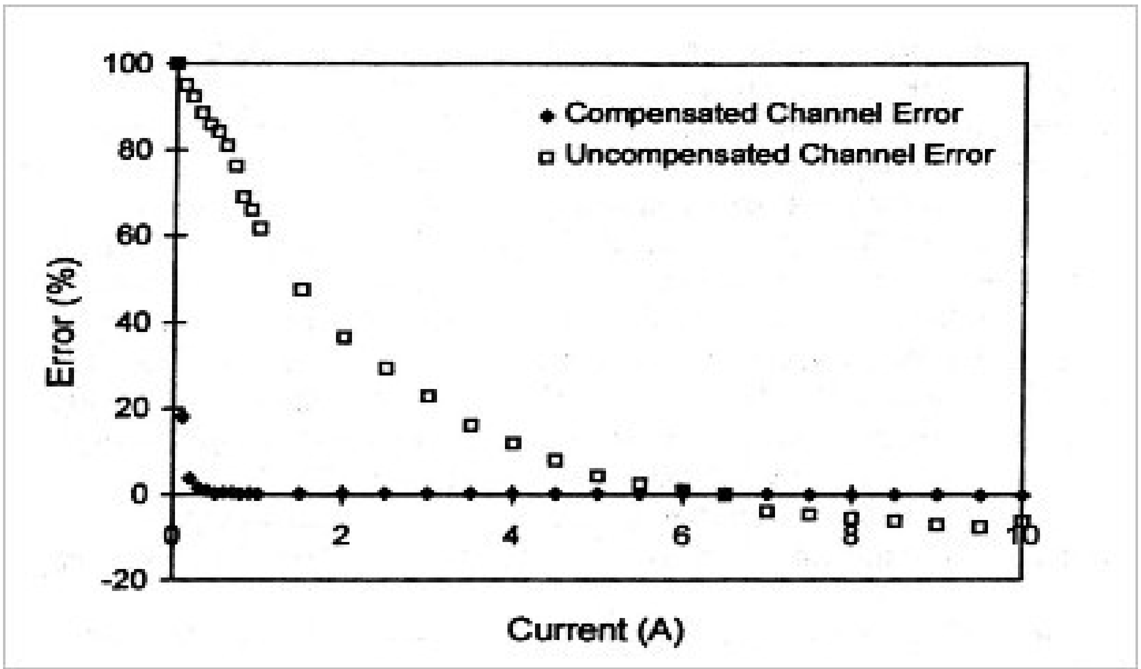

Figure 23 : Effect of the compensation of vibrations on a optical current sensor

(according to [2 [Fiber optics sensors]])

The errors due to temperature come, most of the time, from the materials' big variations of the Verdet constant, as the curves of Figure 24 show.

In Figure 24 we can see that both materials FR5 (Faraday Rotator 5 glass) and TGG (Terbium Galium Grenat) are very sensitive to temperature. Nevertheless, this sensitiveness can be reduced by using an appropriate wavelength. If we want to make an optical current sensor with a low sensitiveness to temperature, FR5 material is right provided that we keep $\lambda = 850\ nm$even if its Verdet constant is lower than TGG's one.

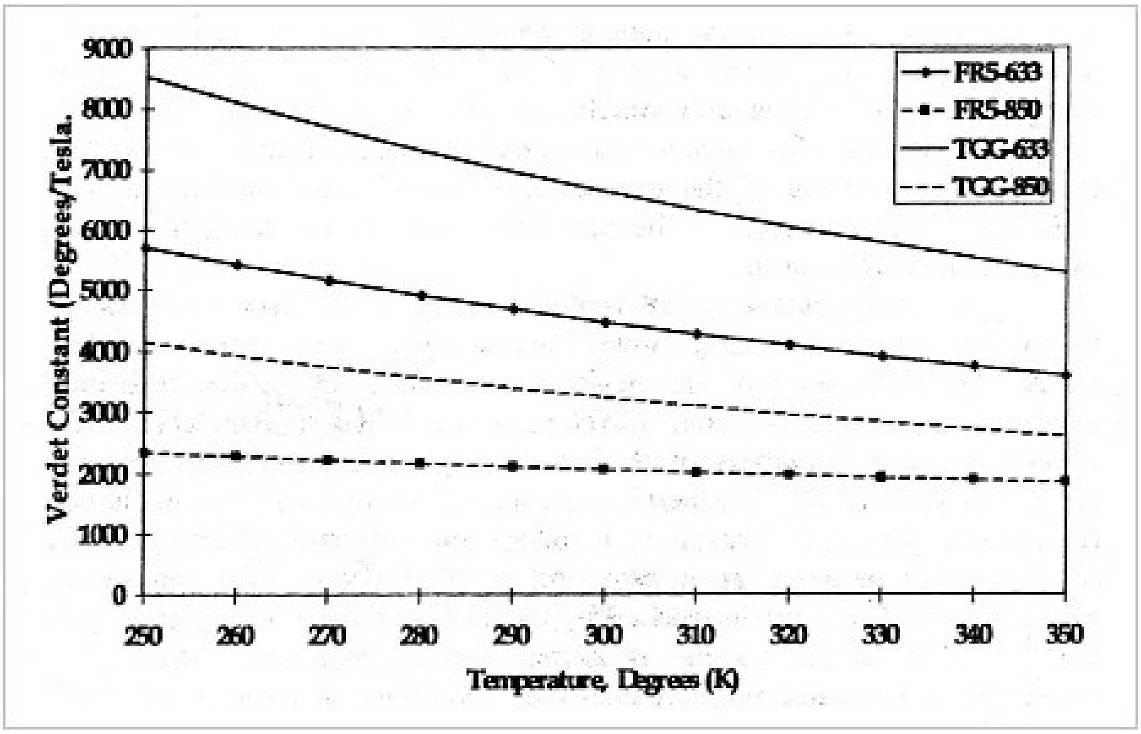

Figure 24 : Verdet constant's variation curves according to temperature (for two materials and two wavelengths : 633 and 850mm). FR5 (Faraday Rotator 5) is made of glass and TGG is made of Terbium Gallium Grenat.

If we know how the material used for the transducer reacts to temperature variations, it is easy to compensate the measuring. In the reference [1] the authors decided to use a Bragg grating temperature sensor and discovered a compensation range from $20C$ to $120C$, as it is shown on Figure 25:

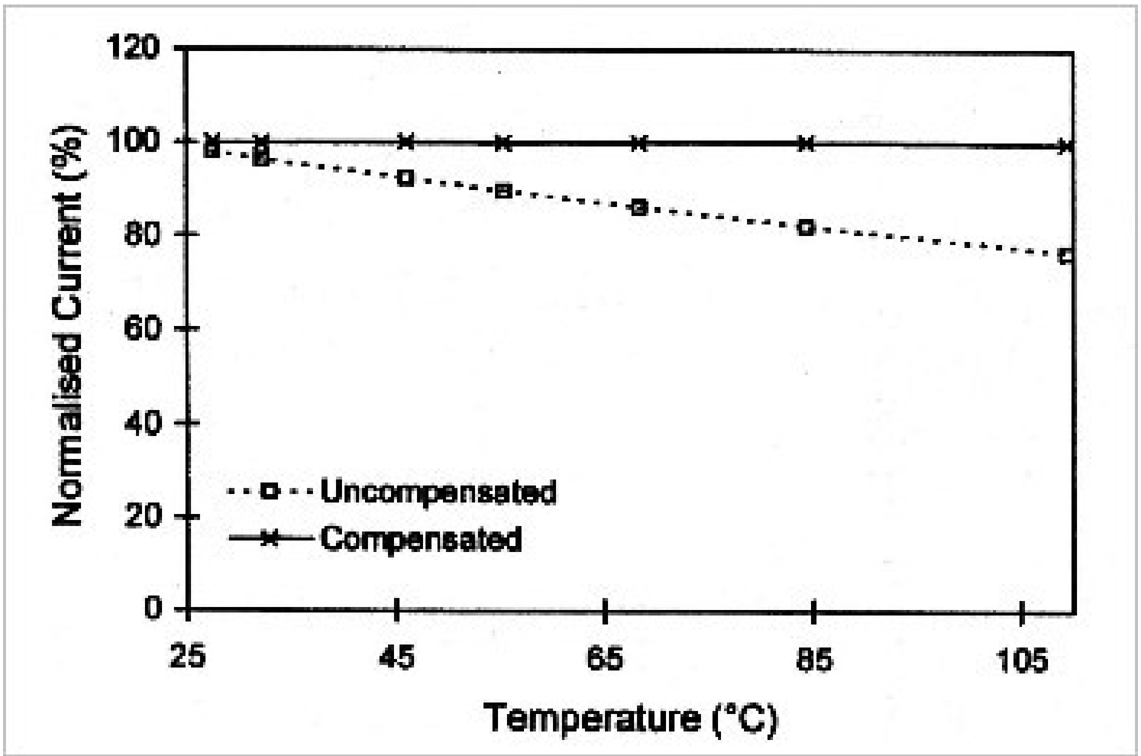

Figure 25 : Temperature-compensated optical current sensor

(according to [43 [-]])

IV.Exercices

1. Exercice 1

We want to make an intensity modulation sensor going by periodical micro curves, with an unimodal fiber, whose characteristics with $\lambda = 1.55\ \mu m$ are :

$$\rho_{core} = 4.5\ \mu m \qquad n_{core} = 1{,}4489$$
$$\rho_{jacket} = 62.5\ \mu m \qquad n_{jacket} = 1{,}4444$$

Question 1

[Solution n°1 p 37]

What should be the period of the micro curves for coupling the core's light in the jacket with $\lambda = 1.55\ \mu m$? You will take approximate values for the effective indexes of the core and the cladding modes.

Question 2

[Solution n°2 p 37]

How can we increase the sensitiveness of the sensor ?

2. Exercice 2

Here is a fiber thermometer with a Fabry-Pérot cavity (FP) placed at the extremity of the fiber as shown on the Figure below. The cavity's mirrors are supposed to all have the same reflection coefficient and to be insensitive to temperature's variations.

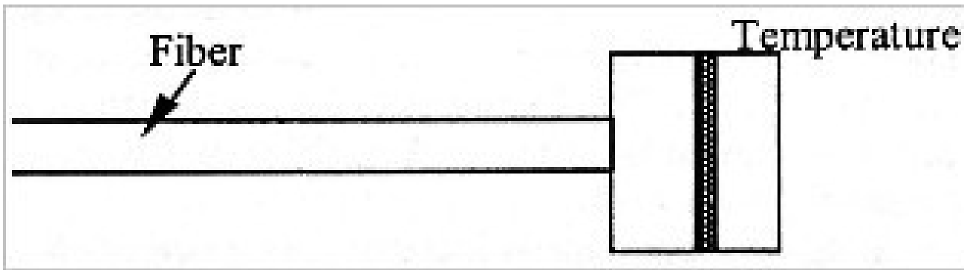

Figure 24 : Fiber thermometer

Question 1

[Solution n°3 p 37]

If we assume that the FP cavity is filled up with a material whose index is called *n* and that the cavity length is L, define the phase difference ϕ inserted in the cavity.

Question 2

[Solution n°4 p 37]

What impact has a variation of temperature on the answer of the FP ?

Question 3

[Solution n°5 p 37]

How does the finesse vary according to the refractive index of the liquid ?

Solution des exercices

>Solution n°1 *(exercice p. 36)*

We could say that the effective index of the core mode is approximately equal to the refraction index of the core, so that $neff_{core} = n_{core}$ and that the effective index of the jacket mode is almost equal to the index of the jacket, that is to say $neff_{jacket} = n_{jacket}$. With the first equation, we can calculate that:

$$\beta_{core} = \frac{2\pi}{1.55\,\mu m} neff_{core} \quad , \quad \beta_{jacket} = \frac{2\pi}{1.55\,\mu m} neff_{core}$$

$$Equation\ 1 \Rightarrow \Lambda = \frac{2\pi}{\beta_{core} - \beta_{jacket}}$$

$$\Lambda \approx 344\,\mu m$$

>Solution n°2 *(exercice p. 36)*

In order to increase the sensitiveness of the sensor, we can insert a piece of multimode fiber where the micro curves are. The structure is then made up of a section of a multimode fiber, another section of monomode fiber and eventually another section of multimode fiber. The multimode fiber will make it possible to increase the coupling between the fundamental mode and the higher order modes. Nothing but the fundamental mode will be transmitted during the reinjection in the monomode fiber, consequently total leakages of the sensor will increased.

>Solution n°3 *(exercice p. 36)*

The phase difference is obtained between the waves reflected by the first mirror and the waves reflected by the second one. Consequently, the phase difference is equal to a round-trip in the cavity and twice as long as the optical path between the mirrors:

$$\phi = \frac{2\pi}{\lambda} 2nL \Leftrightarrow \phi = \frac{4\pi n L}{\lambda}$$

>Solution n°4 *(exercice p. 36)*

Temperature will modify the cavity's index and its length. Then the phase difference will vary too and consequently the distance between two consecutive peaks (i.e. the free spectral range) will change.

>Solution n°5 *(exercice p. 36)*

The finesse only depends on the mirrors' reflection coefficients. The latter are supposed to be identical and insensitive to temperature, consequently the finesse remains the same under any circumstances.

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