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High Spatial Resolution in Distributed Temperature Measurement Sensors

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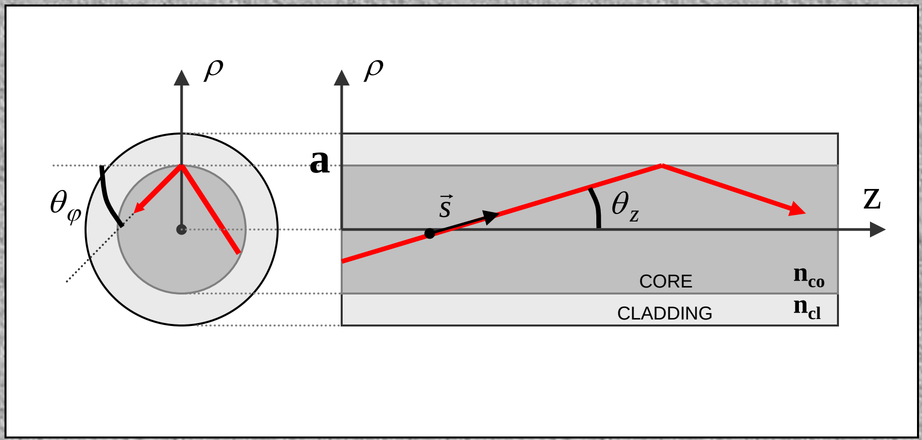
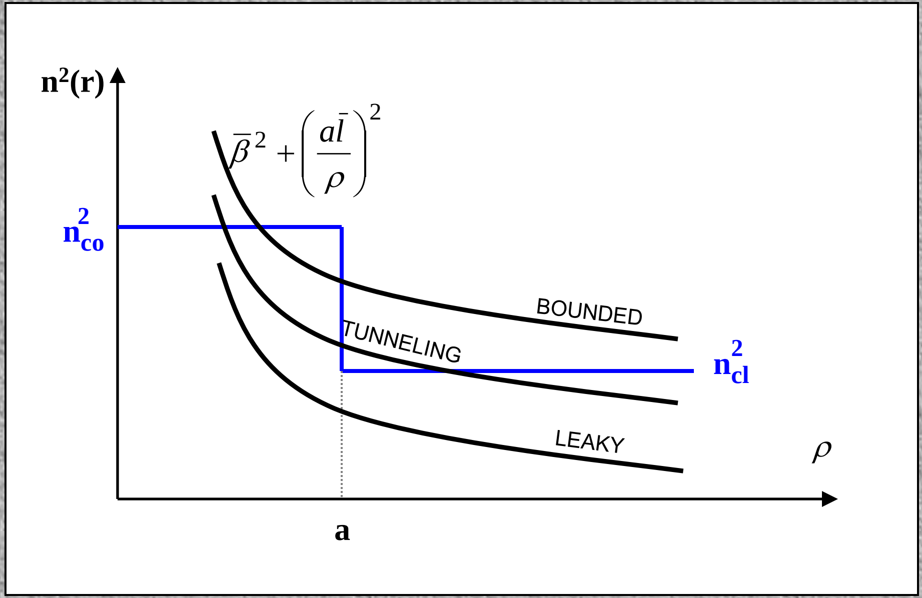
Geometrical optics for step-index fibers





In a step-index optical fiber, if

$$\bar{\beta} = n\frac{dz}{ds} = n(\rho)\cos(\theta_z)$$

$$\bar{l} = \frac{\rho^2 n}{a}\frac{d\varphi}{ds} = \frac{\rho \cdot n(\rho)}{a}\sin(\theta_z)\cos(\theta_\varphi)$$

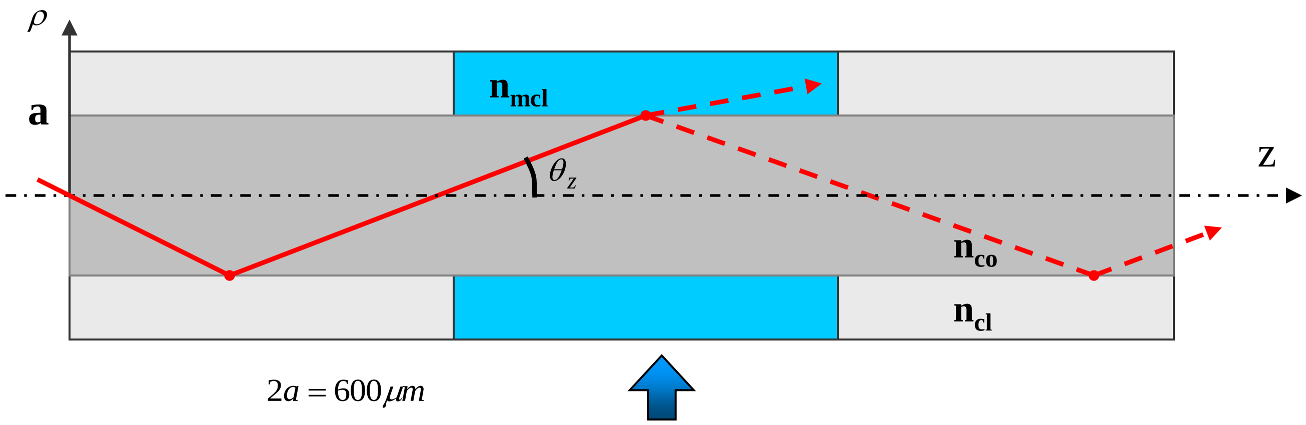
are the ray invariants, a ray has a real trajectory for every ρ such that

$$n^2 > \bar{\beta}^2 + \left(\frac{a\bar{l}}{\rho}\right)^2$$

Thus, the ray is bounded in the core if:

$$\begin{cases} \bar{\beta}^2 + \left(\frac{a\bar{l}}{\rho}\right)^2 < n_{co}^2, & \rho < a \\ \bar{\beta}^2 + \left(\frac{a\bar{l}}{\rho}\right)^2 > n_{cl}^2, & \rho > a \end{cases}$$

The sensor physical principle (i)

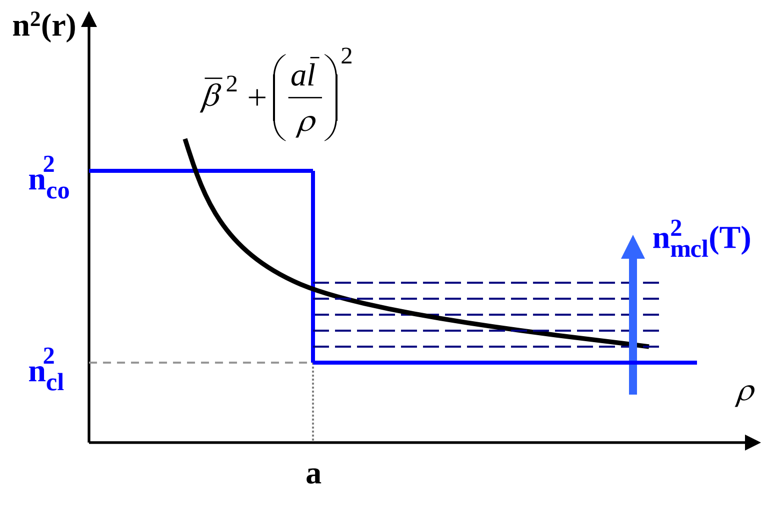


Modified cladding (liquid)

A little portion of the fiber cladding is replaced by a liquid with refractive index $\boldsymbol{n_{mcl}= n_{mcl}(T)}$ depending on temperature.

If $\boldsymbol{n_{mcl}(T) > n_{co}}$, partial transmission of rays in the modified cladding occurs, resulting in a power loss of guided light.

The sensor physical principle (ii)



In the generic case of skew rays, a power loss is expected even when:

$$n_{cl} < n_{mcl}(T) < n_{co}$$

The power loss ratio depends on the difference between n_{co} and $n_{mcl}(T)$ and then on the temperature **T** of the liquid replacing the cladding.

Thus, the liquid temperature **T** would be determined if the function $n_{mcl}(T)$ was known, and if the ray invariants could be computed for each ray known to propagate in the fiber.

The one-off calibration

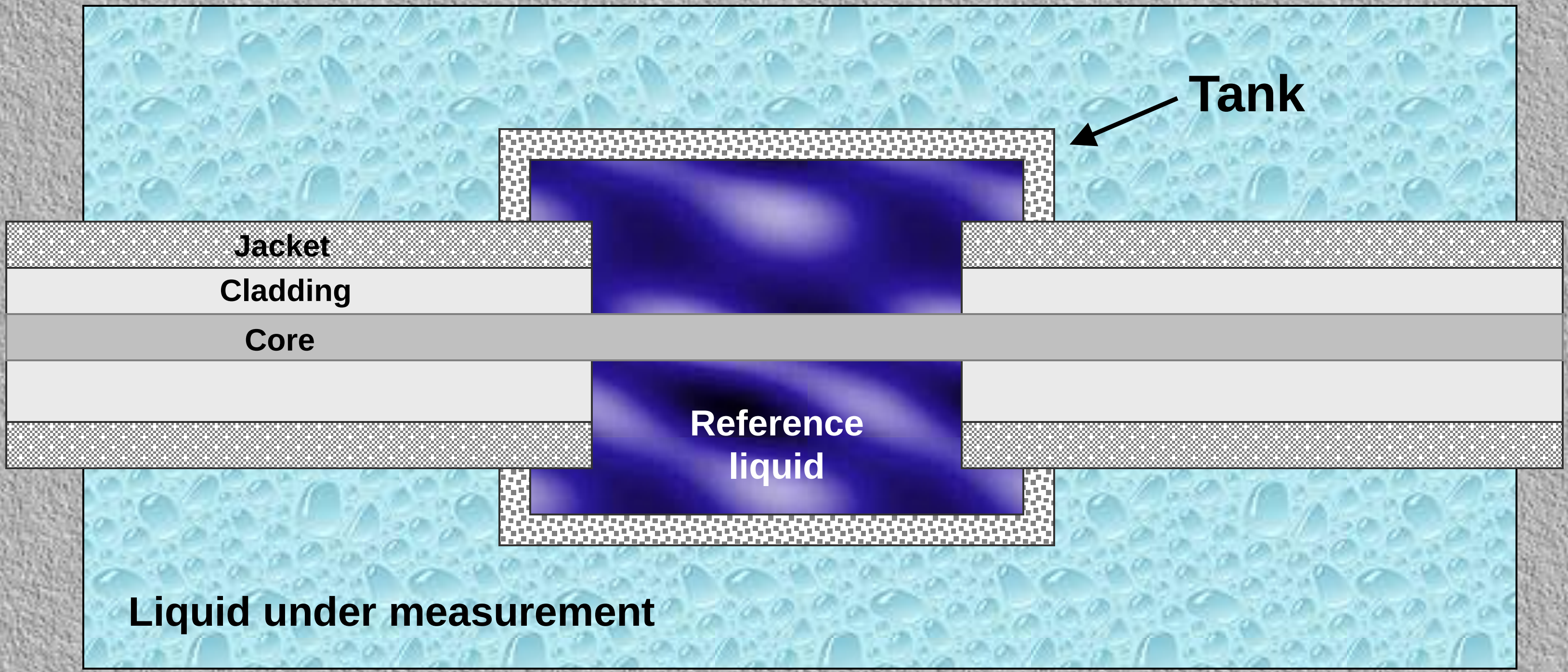
Although the relationship between power loss ratio and temperature of the modified cladding can be numerically determined under defined assumptions, the most accurate evaluation is achieved empirically, through a one-off calibration procedure.

A look-up table of temperature **T** versus power loss ratio values is evaluated during this phase.

In the calibration procedure, a reference termocouple was used.

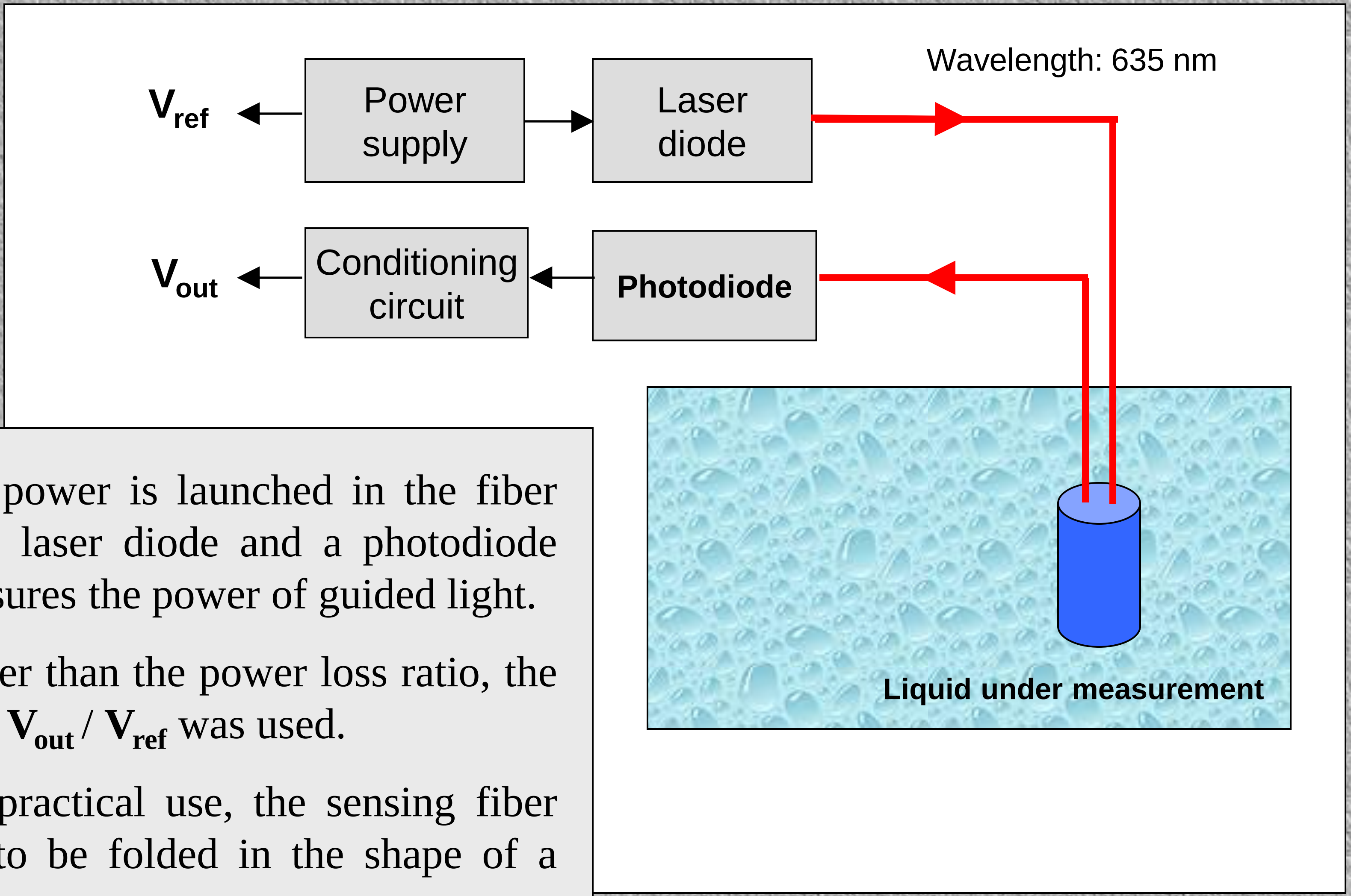
Subsequent temperature measurements will be obtained measuring the power loss ratio and using it as entry in the look-up table.

The reference liquid



The calibration should be repeated every time the fluid replacing the cladding changes. For this reason, the uncladded region is enclosed in a small plastic tank filled once and for all with a reference fluid.

The previous prototype (i)

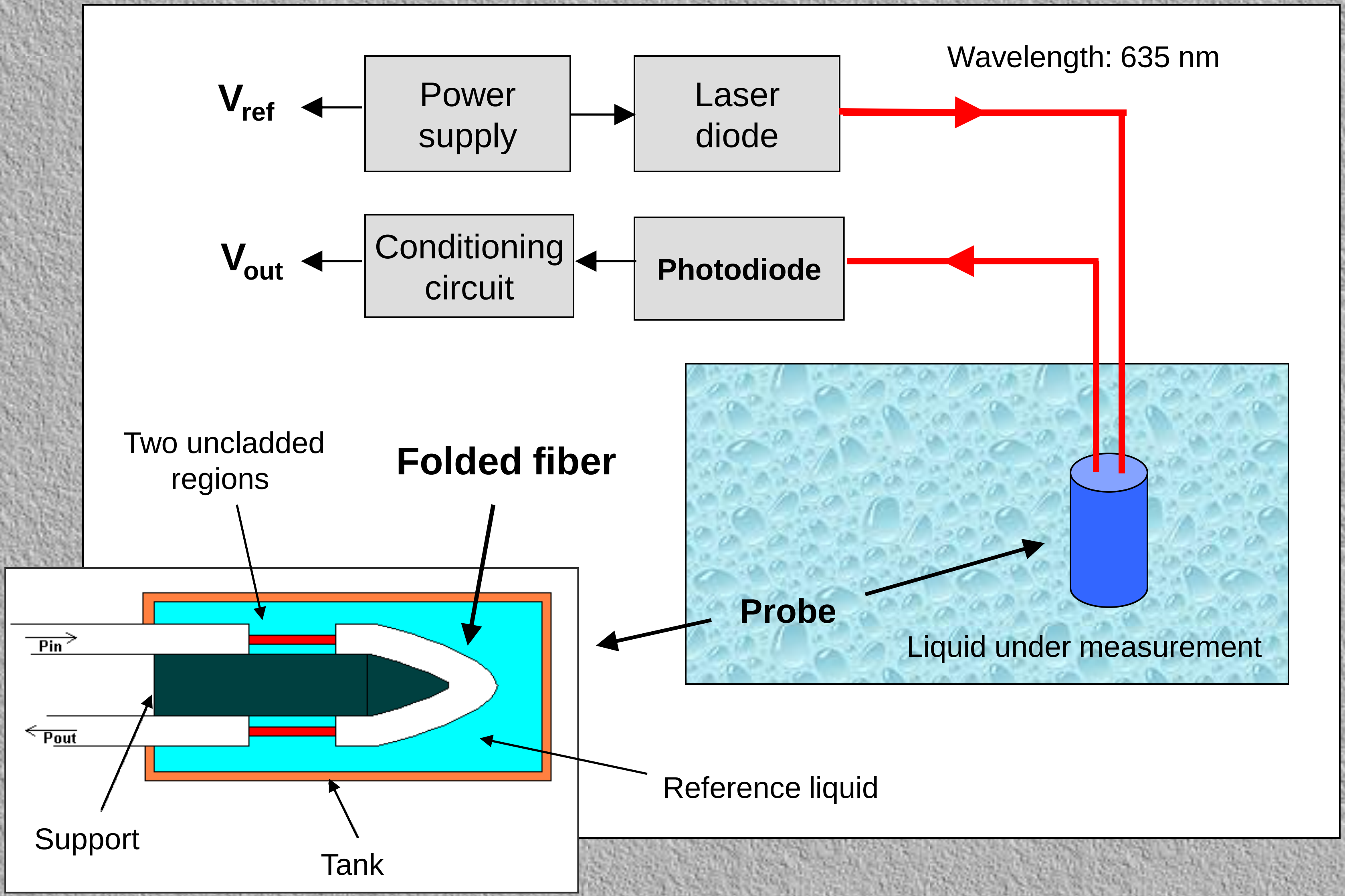


The power is launched in the fiber by a laser diode and a photodiode measures the power of guided light.

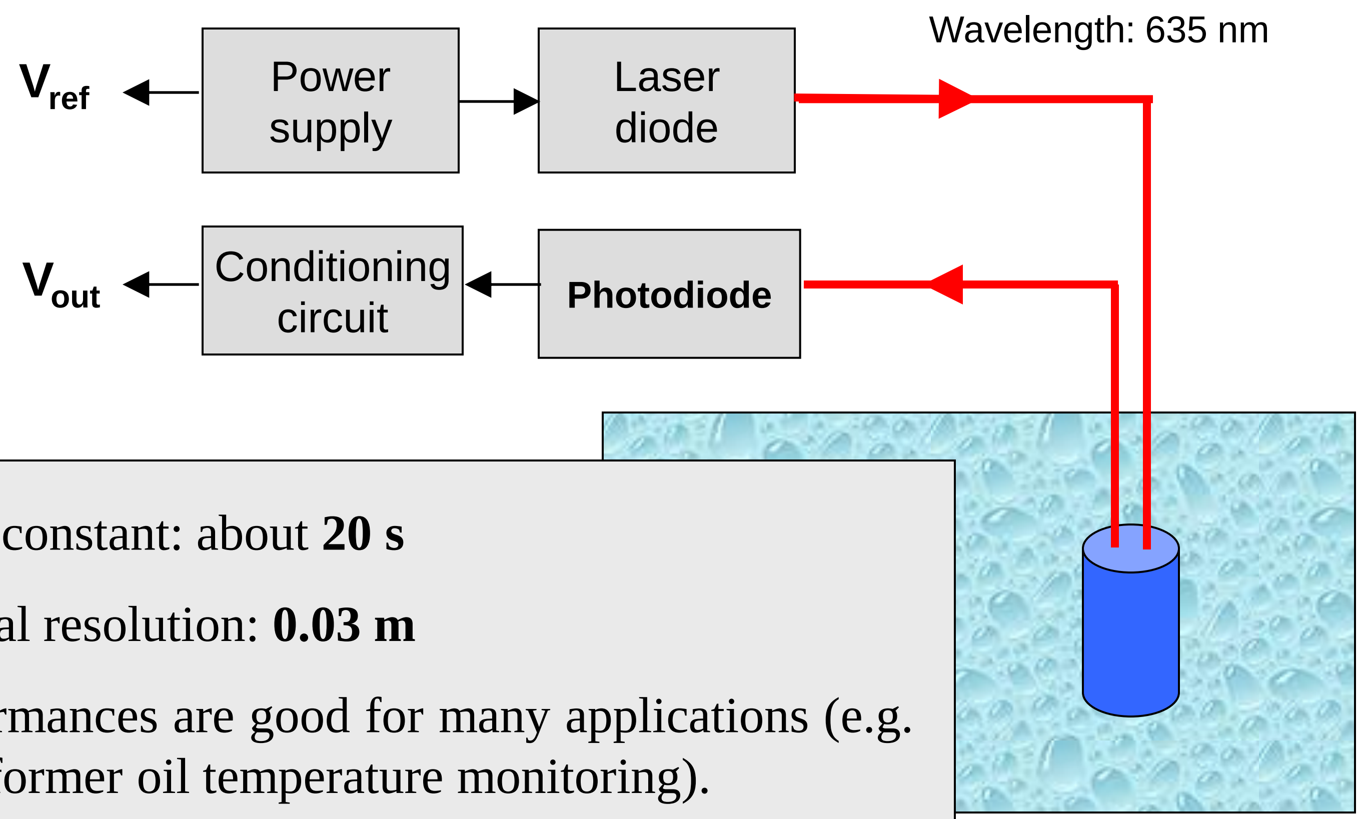
Rather than the power loss ratio, the ratio $\mathbf{V_{out}}$ / $\mathbf{V_{ref}}$ was used.

For practical use, the sensing fiber has to be folded in the shape of a probe.

The previous prototype (ii)



The previous prototype (iii)



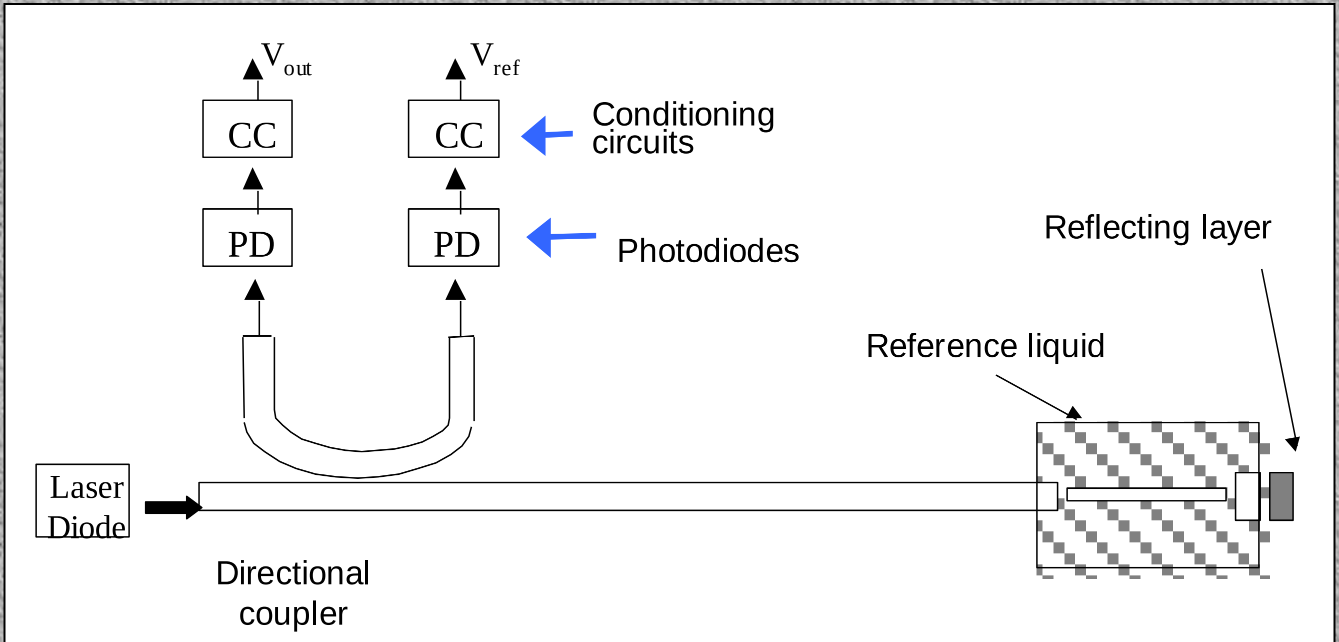
Sensor time constant: about **20 s**

Sensor spatial resolution: **0.03 m**

These performances are good for many applications (e.g. power transformer oil temperature monitoring).

The folded geometry does not allow to further reduce the volume of the tank, and then a smaller time constant cannot be achieved.

The reflectometric temperature probe (i)

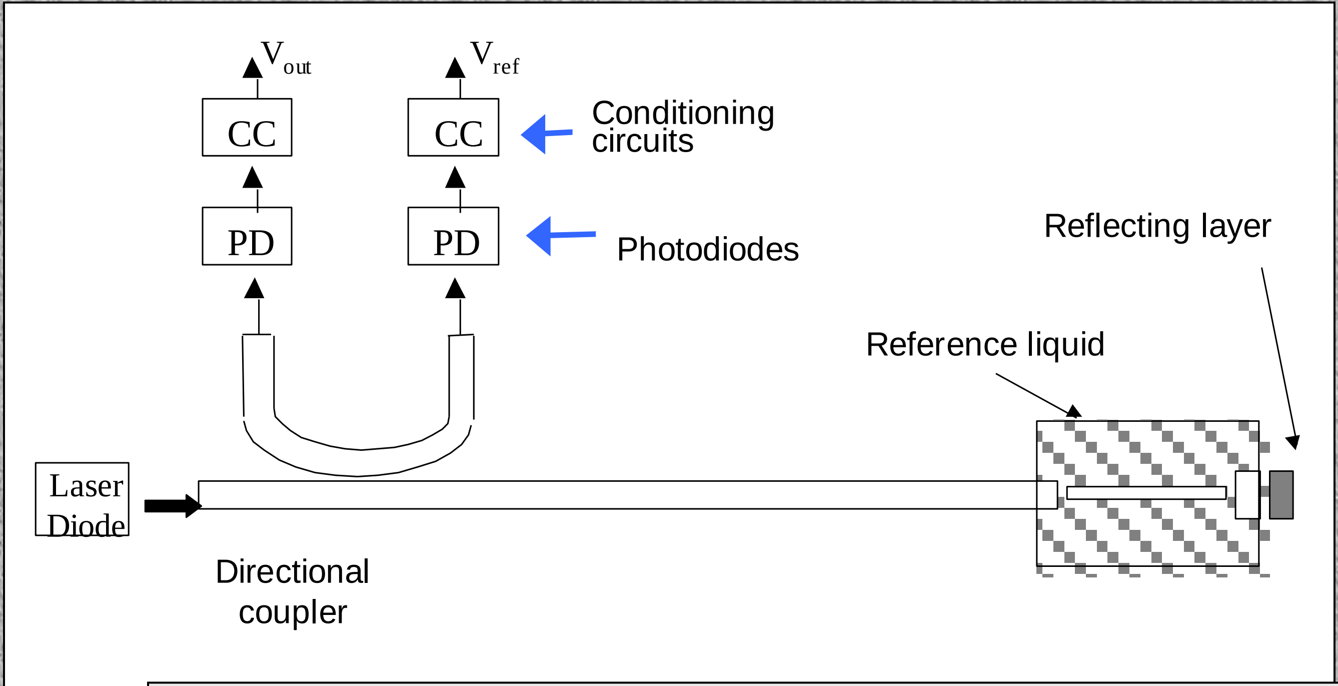


The probe is constituted by a piece of unfolded fiber, with its end deprived of the cladding and enclosed in the tank containing the reference liquid.

The fiber end is mirrored by silver deposition.

The cladding is removed by side-polishing the fiber included in a molding.

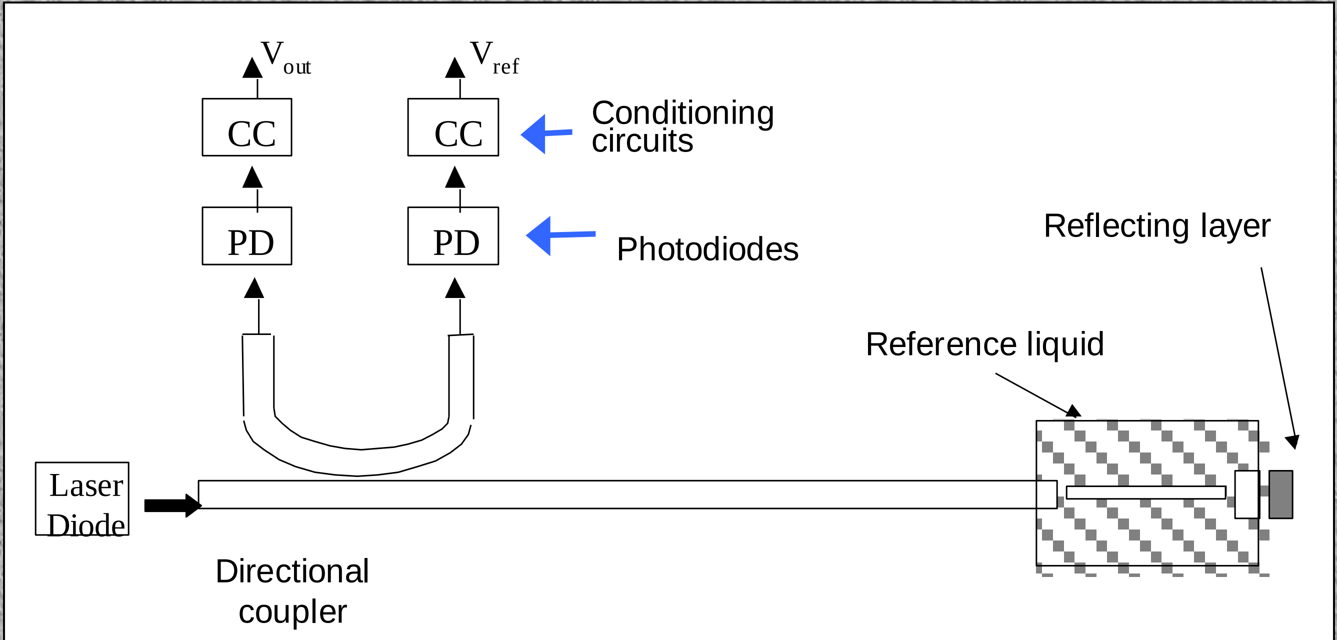
The reflectometric temperature probe (ii)



The probe geometry allows the tank dimensions to be contained within **12 mm** of length and **1 mm** of diameter.

By this way, it was possible to improve both spatial resolution and time constant of the sensor.

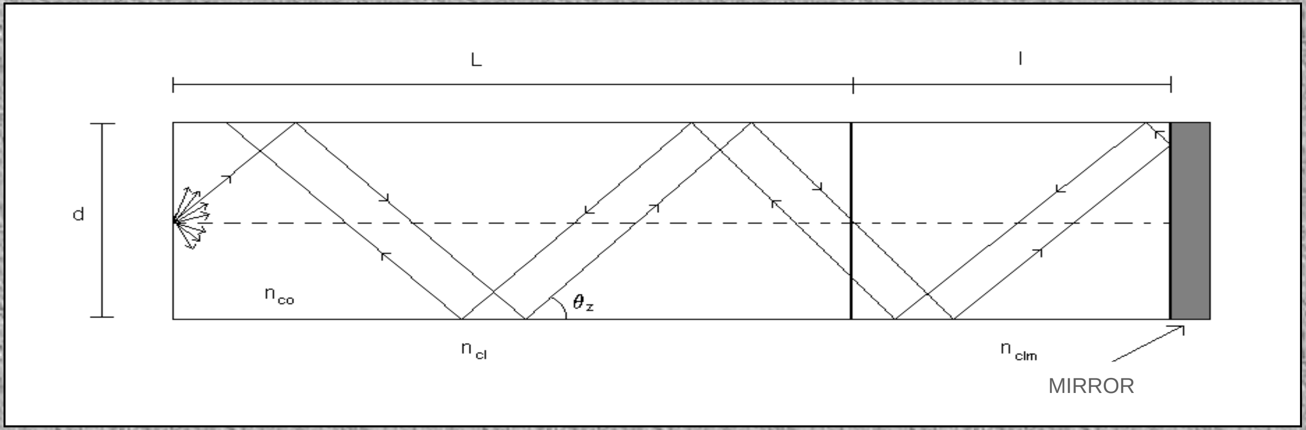
The directional coupler



Close to the power source, a directional coupler, realized by fusion on the fiber itself, allows both the power proportional to the power supplied by the source and the power proportional to the probe output power to be measured.

A pair of conditioning circuits yield two voltages proportional to these powers, and a one-off calibration is still used to determine temperature.

Numerical simulation

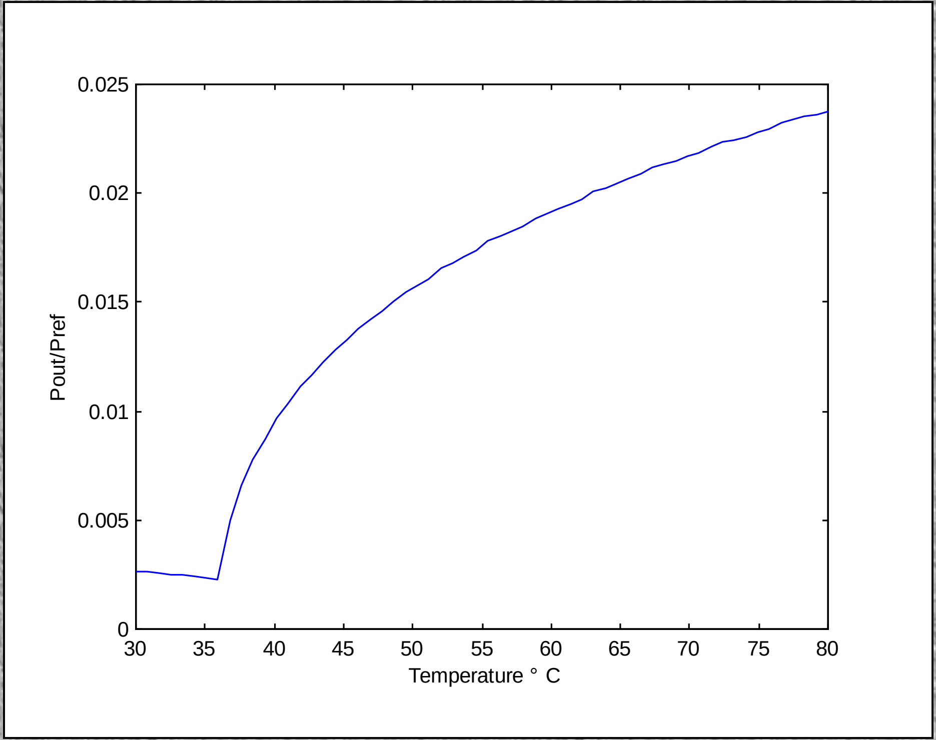


A ray-tracing technique was used in order to numerically evaluate the power ratio dependance from temperature, consisting in a recursive application of Snell's law at core-cladding interface, and in the evaluation of power loss at each reflection.

• 100 ray source points equally spaced along a diameter;

• From each source point, 1600 rays were considered within a cone having half aperture equal to fiber critical angle.

Numerical simulation results

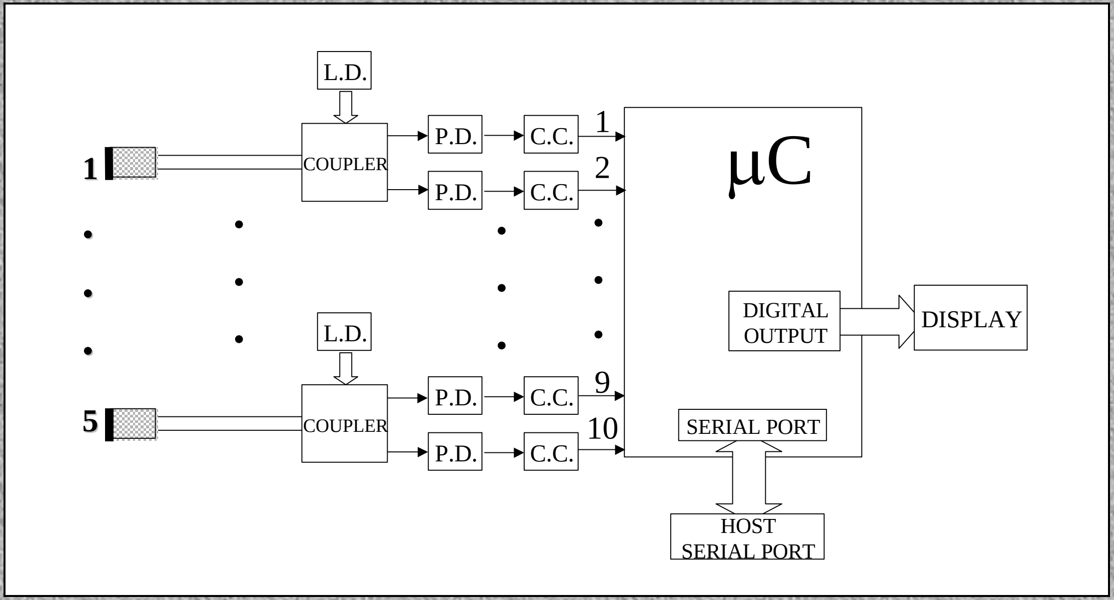


- Fiber length: **2 m**
- Core diameter: **600 μm**
- n_{co} = **1.457**
- n_{co} = **1.368**
- N.A.= **0.37**
- Fiber critical angle: about **20°**
- Modified cladding **2 cm** long and **100 μm** thick

Mineral oil was considered as reference liquid, for which:

$$\boldsymbol{n_{mcl}(T) = 1.463 - 0.00037\,(T - 20°C)}$$

A system for distributed temperature measurements



A system, based on an Intel™ MCS96 microcontroller, has been realised in order to execute contemporary temperature measurements in different points.

With its 10 channel multiplexer, up to 5 temperature probes can be employed.

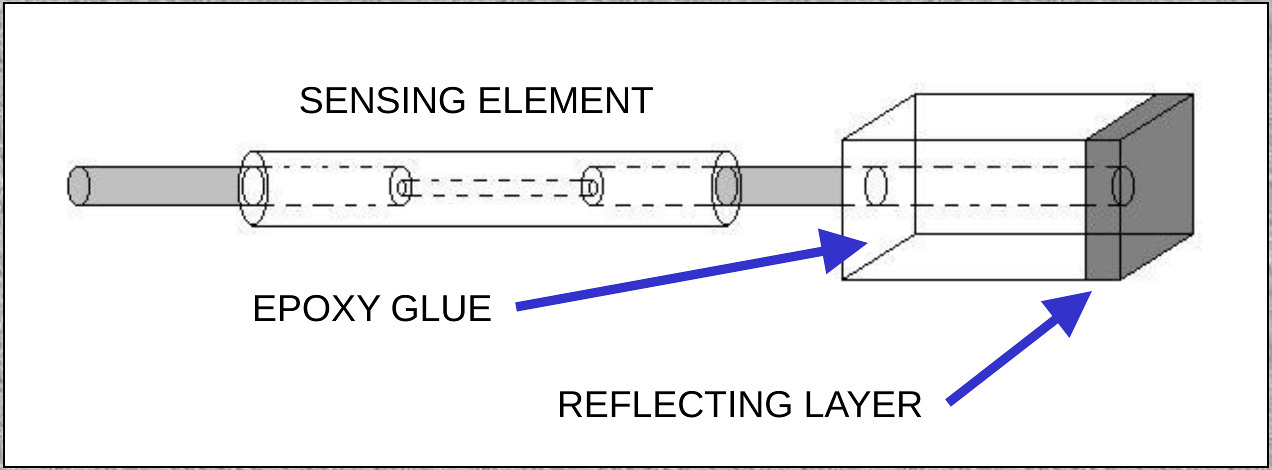
By averaging ten 10-bit samples, higher resolution can be achieved (11.5 equivalent bits).

A first prototype

Tests were carried out on a prototype, having:

• Unclad zone hand made with a scalpel under microscope control;

• Reflecting layer realized with a mirror cemented to the fiber end face by a suitable expoxy glue.



The prototype specifications

The fiber used is multimodal, with $Ø_{co}$= **600 µm**, n_{co} = **1.457**, n_{cl} = **1.368**, NA = **0.37**, critical angle ~ **20°**, cladding in **TECS™** with $Ø_{clad}$ = **630 µm.**

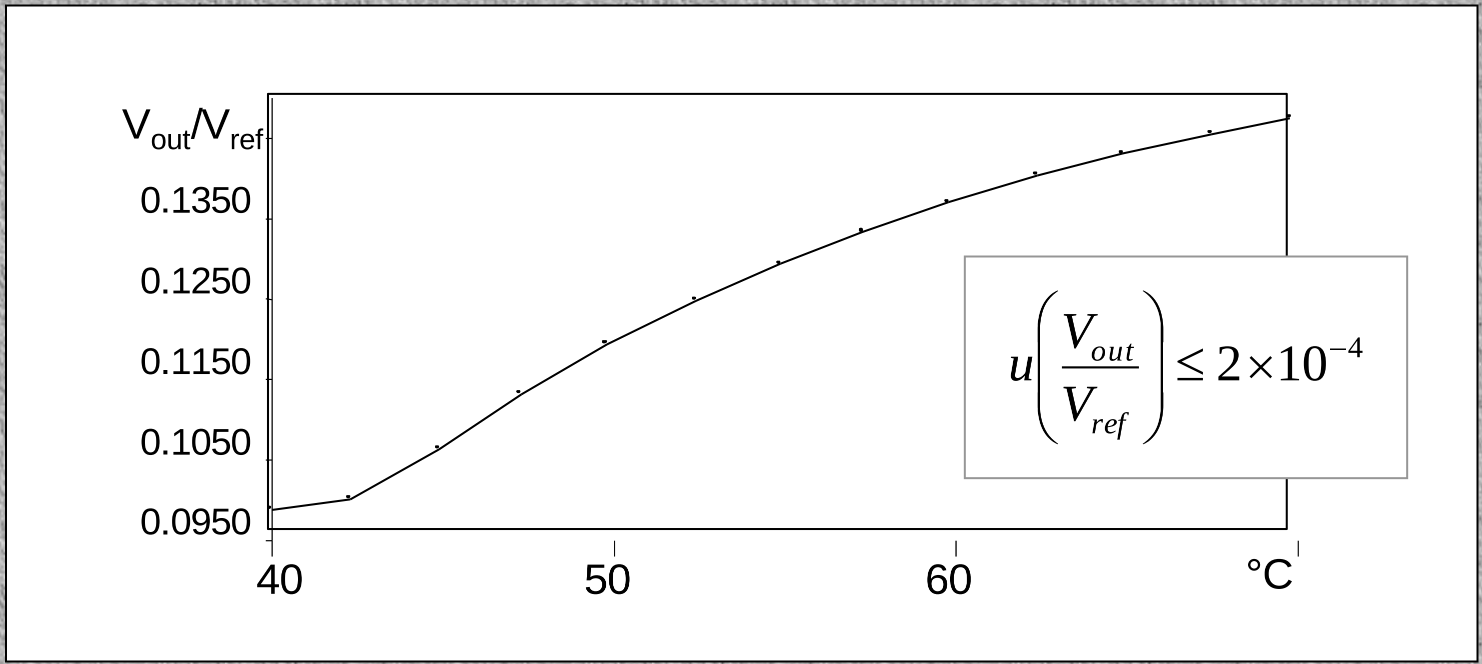
The light source is a **5 mW** laser diode, with a wavelength of **635 nm**.

The realized directional coupler has a coupling length of about **20 mm**, an excess loss of **5 dB** and a coupling ratio of about **3 dB**.

The reference liquid is mineral oil.

System resolution is **0.1°C** in the range [40°C,70°C].

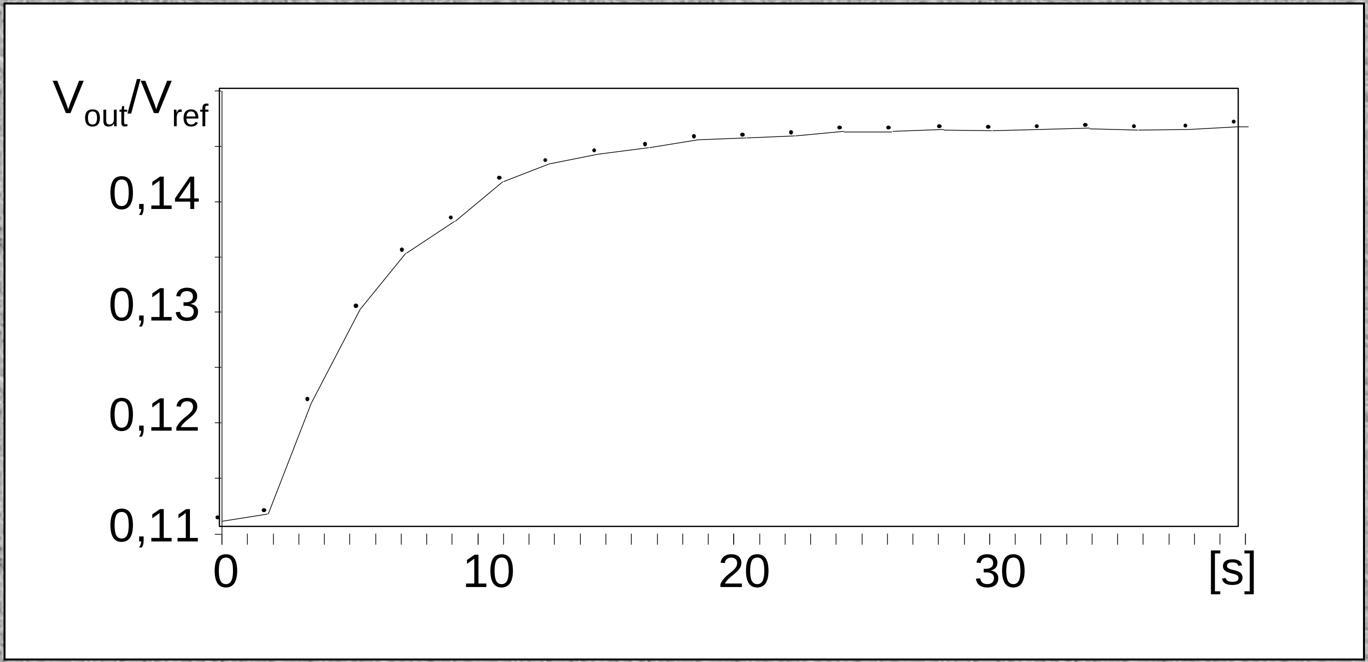
The static characterisation



The static characteristic of the sensor was obtained by averaging 30 measurements of Vout/Vref, acquired in temperature steady-state conditions, with temperature step of about 2.5°C.

A bath with termostatic control and a reference termocouple were used.

The dynamic characterisation



The dynamic characterization was carried by applying a 25°C temperature step. The measured time constant is now equal to about **4.5 s**.

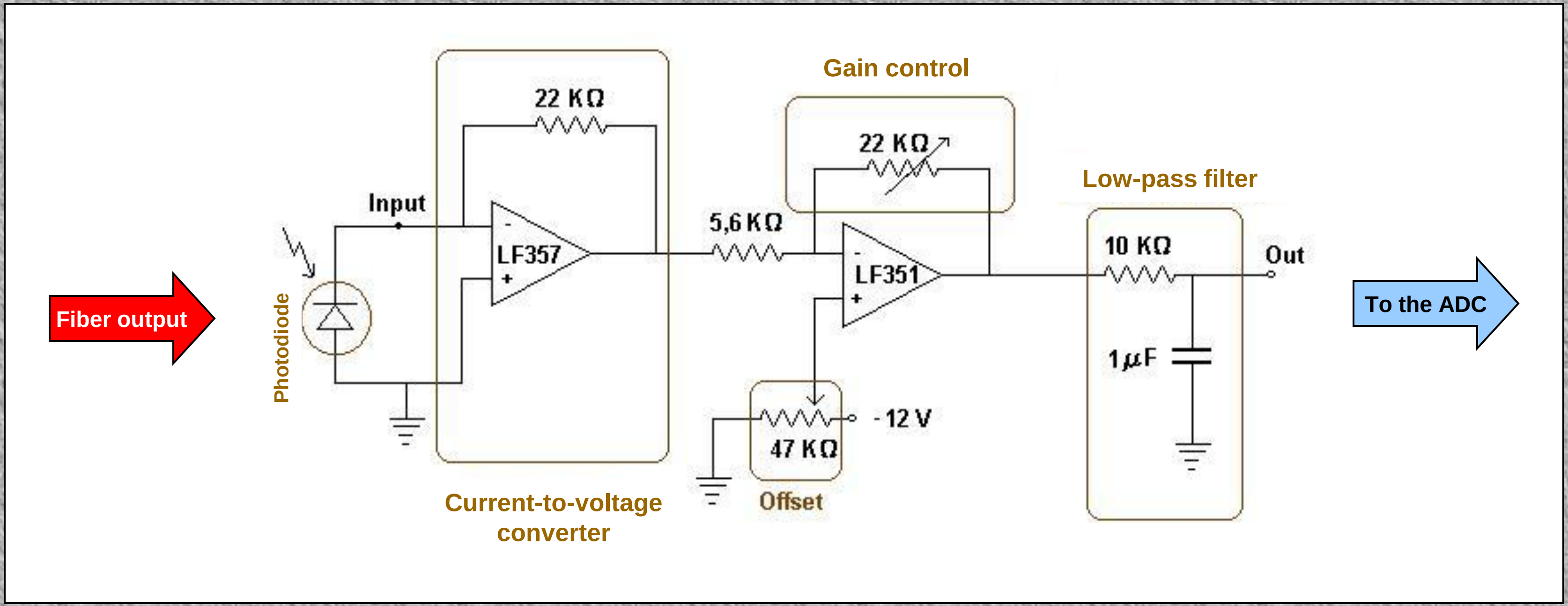
Concluding remarks

An optical fiber temperature measurement system was realized, having:

- Modified cladding sensing element;
- An unfolded fiber architecture, with a reflecting layer and a directional coupler;
- A microcontroller based acquisition system, able to connect up to 5 temperature probe.

A prototype was realized and metrological characterised. With respect to previous folded architectures, it showed an improvement in both dynamic performance and spatial resolution, without any decrement in the static performance.

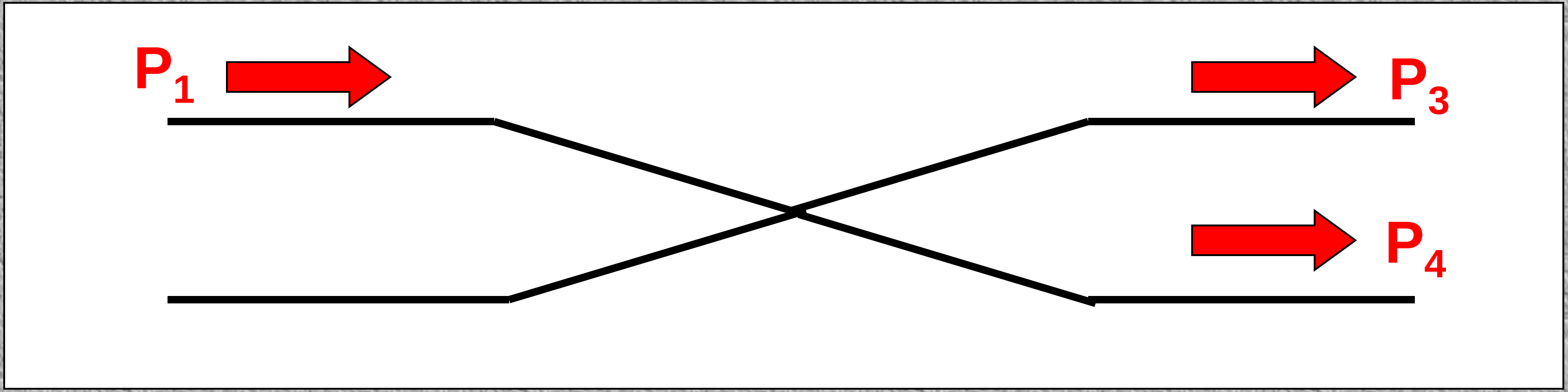
The conditioning circuit



The output current of the photodiode is transduced in a voltage proportional to the power level exiting from the fiber.

The second stage works as a voltage amplifier: the input signal is inverted and amplified in order to cover the input range of the microcontroller ADC. Offset and gain can be adjusted by setting two trimmers.

Directional coupler: definitions



Excess loss dB: $$XL = -10\log\left(\frac{P_3 + P_4}{P_1}\right)$$

Coupling ratio dB: $$CR = 10\log\left(\frac{P_4}{P_3 + P_4}\right)$$