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Designing Modified Cladding Sensors: A Structured Approach

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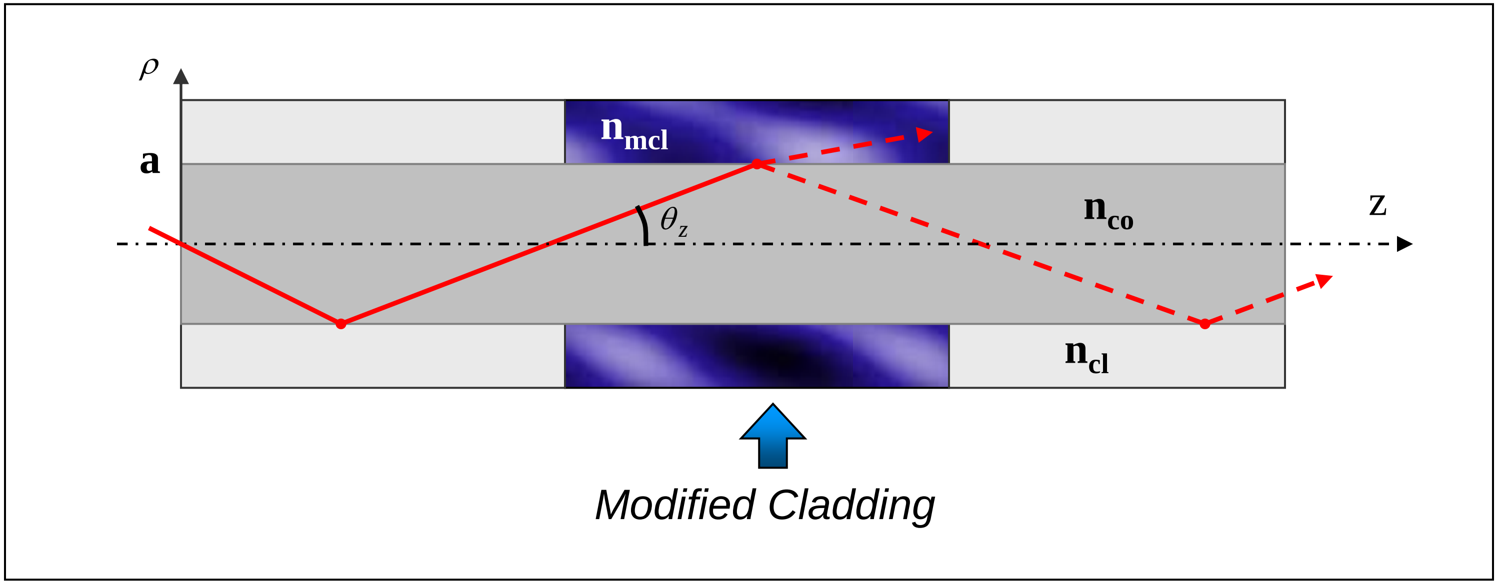
Summary

- A compact and low-cost solution for the realization of reflectometric optical fiber sensors, based on a modified-cladding sensing principle has been developed.

- A prototype of such a sensor, for the measurement of the temperature of liquids, will be described and the experimental results for its characterization will be reported.

Modified-cladding sensors: physical principle



A short length of the *cladding* is replaced by a liquid (the modified cladding), which has a refractive index n_{mcl} that changes with a particular physical quantity (the temperature, for the described prototype).

Basically, when n_{mcl} is greater enough than n_{cl}, the rays are partially refracted from the core into the modified cladding, thus an attenuation of the power guided along the fiber appears.

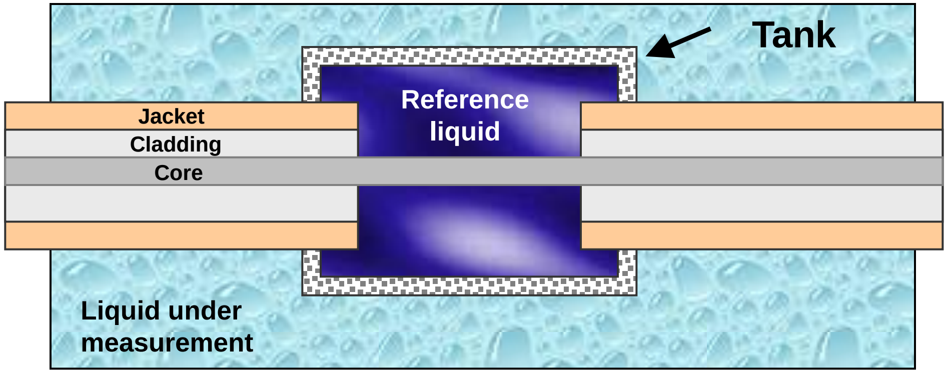
Modified-cladding sensors: the calibration

The power loss ratio depends on the refractive indices $\boldsymbol{n_{co}}$ e $\boldsymbol{n_{mcl}(T)}$ and then from the value of the physical quantity of interest (the temperature $\boldsymbol{T}$).

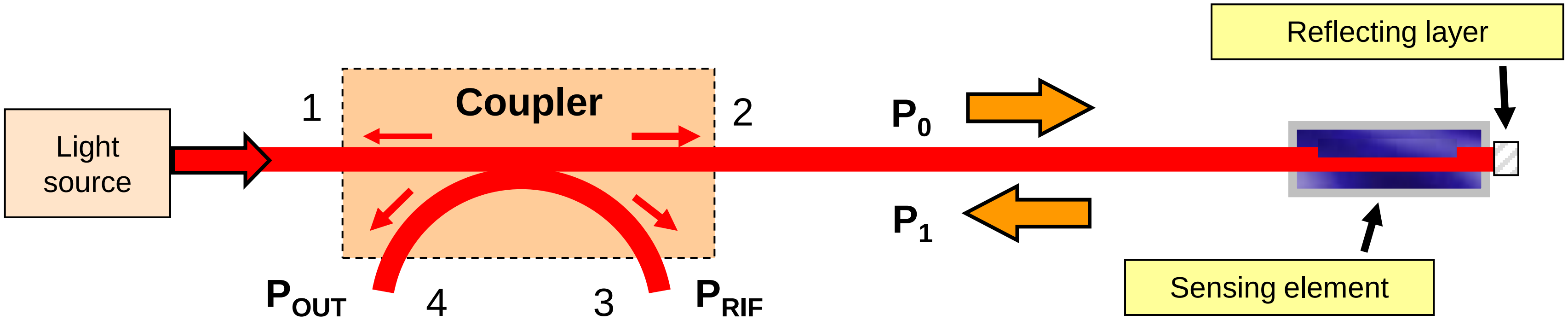
Hence, the value of the physical quantity $\boldsymbol{T}$ could be determined if the relationship between $\boldsymbol{n_{mcl}}$ and $\boldsymbol{T}$ were known, if the refraction coefficient could be determined for all rays propagating along the fiber, and if the distribution of the power among all the rays were known: it is extremely difficult to achieve this knowledge, both analytically or numerically.

Instead, a table of the values of the power loss ratio versus $\boldsymbol{T}$ can be obtained experimentally, during a calibration phase.

A small tank contains the same reference ("calibrated") liquid for the measurement of the temperature of other different liquids.



Previous work



Reflectometric structure: the sensing element can be used as a small probe.

Multimodal fiber with a large core (600 µm): mechanical robustness.

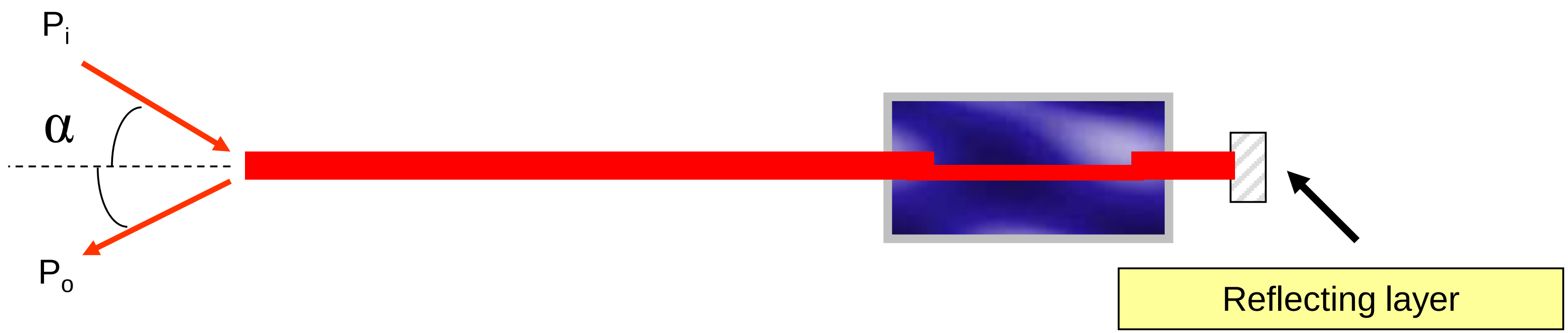
Optical directional coupler: indirect measurement of the power loss through the sensing element.

Reference liquid: **glycol** (input range 15-100°C) or **mineral oil** (30-80°C).

The directional coupler:

- limits the sensitivity of the sensor, since P_{out} is only a fraction of P_1.
- reduces the compactness of the whole system, since it is fragile and bulky.

The idea for a new reflectometric sensor



The coupler could be avoided if the illumination of the fiber and the measurement were made at the same “near” end of the fiber.

Some issues have to be investigated:

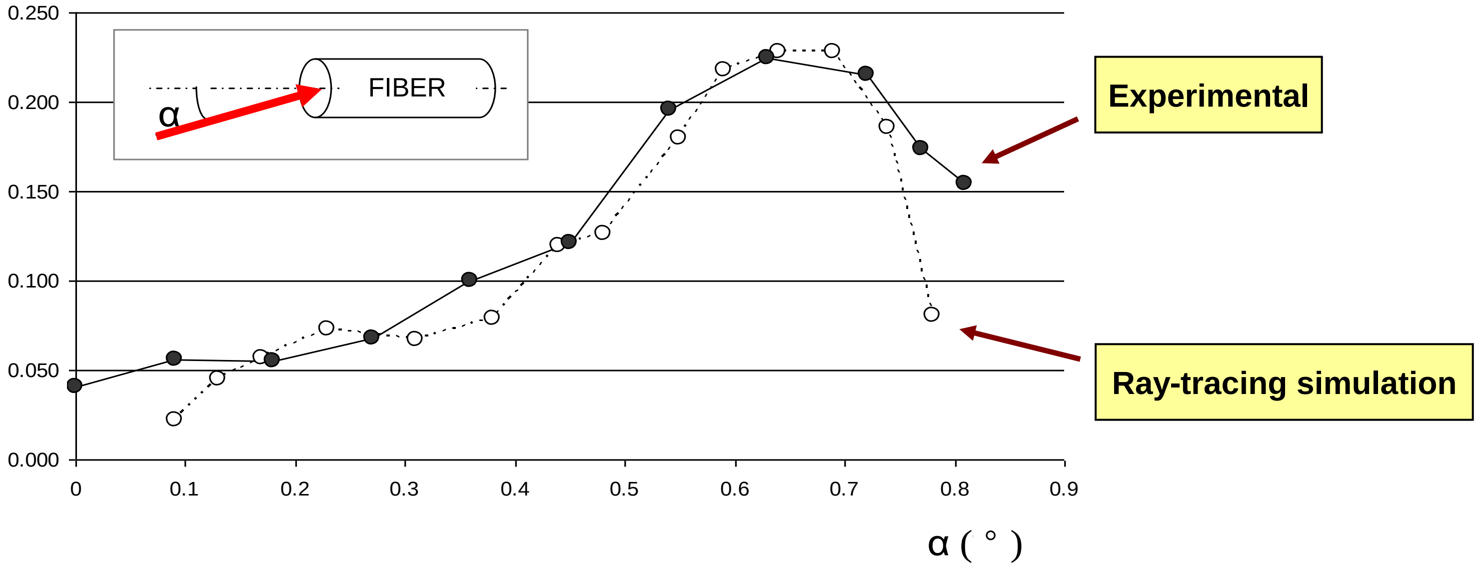
• Does an **off-axis illumination** alter the performances of the sensor?

• How can two discrete components for the illumination and the measurement be placed close enough to the end of the fiber?

Analysis of the launching conditions

$$\Delta P_0 = \frac{P_0(80^\circ C) - P_0(30^\circ C)}{P_0(80^\circ C)}$$

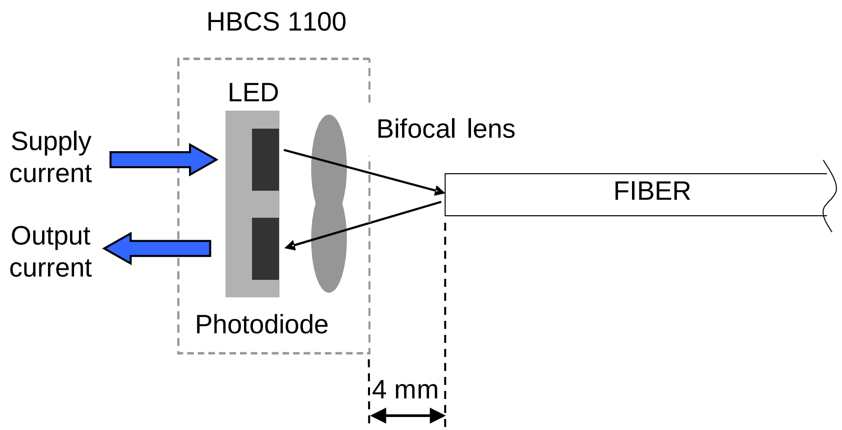
(Relative mean sensitivity between 30°C and 80°C)



Experimental and numerical tests show that an off-axis illumination enhances the sensitivity of the modified-cladding sensor.

This result was already known as Modal Power Distribution technique (MPD).

The component for the illumination and the measurement



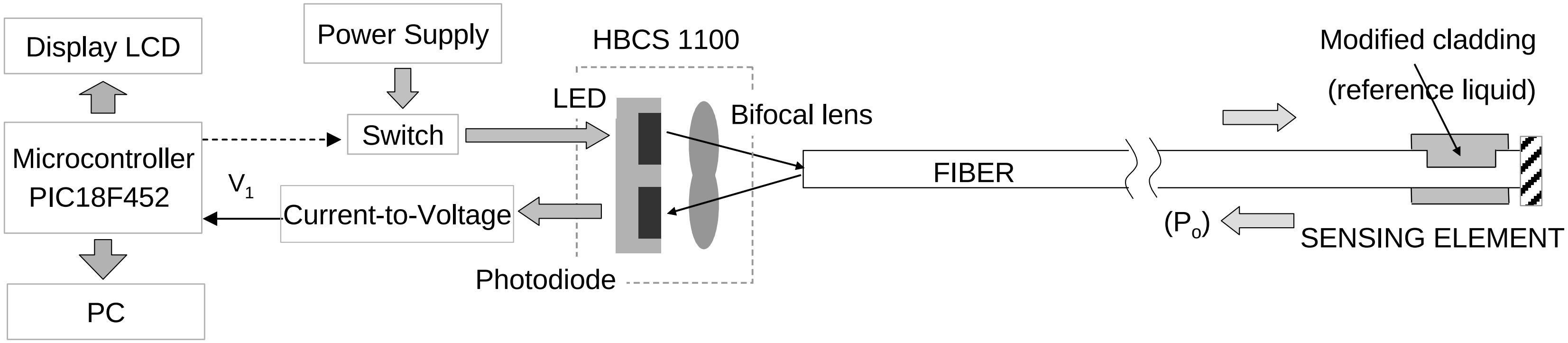
• Instead of two discrete components, a device including both a light source (LED, λ=700 nm) and a photodetector on the same package has been used (HBCS 1100 by Agilent).

• A bifurcated lens images the active areas of the source and of the photodetector to a single spot on the end surface of the fiber.

• The output current of the photodetector can be used in the indirect measurement of the light power exiting the sensing element and propagating backwards.

• This device is available on the market for applications such as bar code readers.

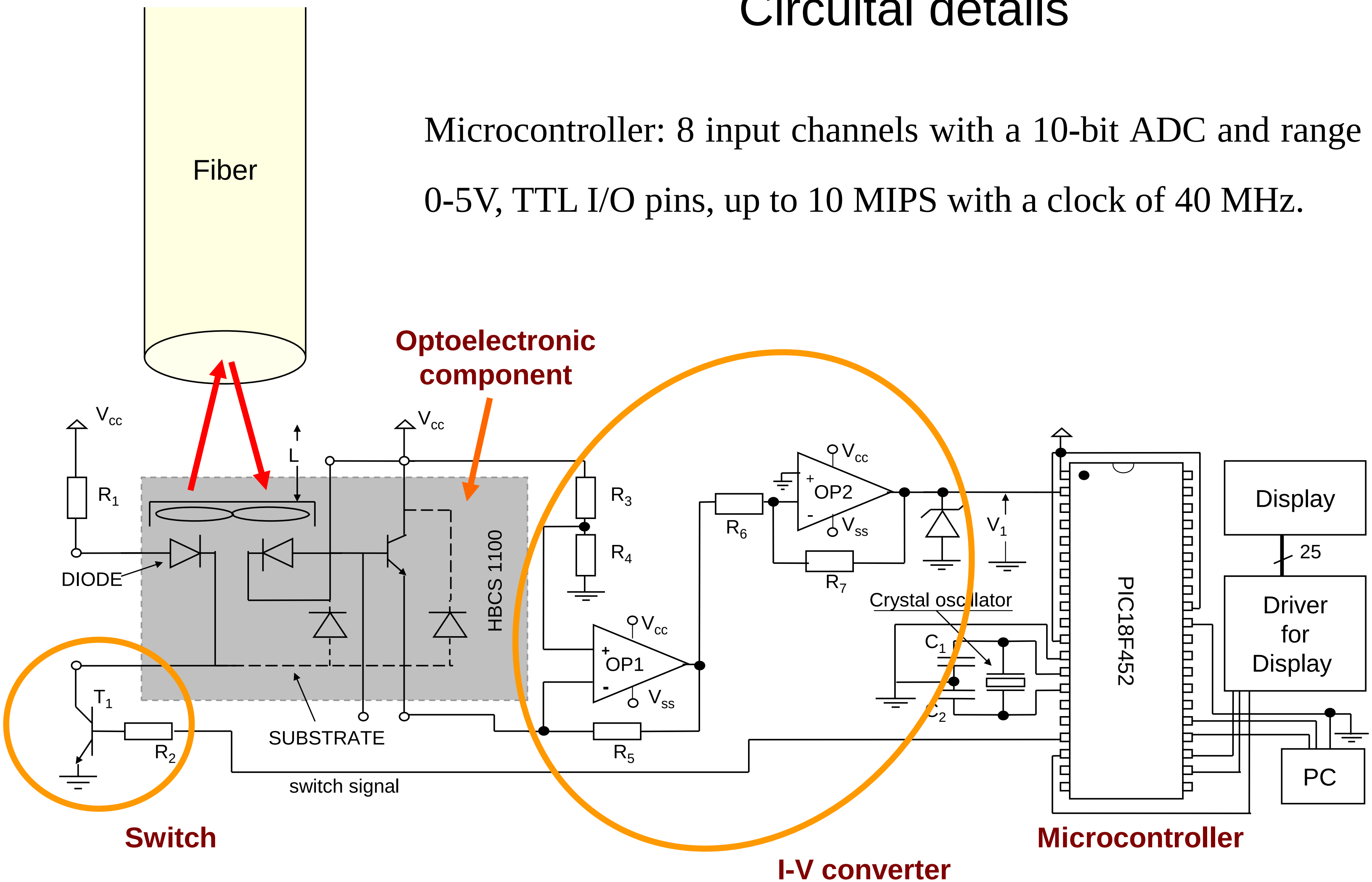
The proposed solution



- A conditioning circuit converts the current given by the photodetector into a voltage V_1, compatible with the input range of the ADC of the microcontroller.
- A microcontroller:
  - Reads V_1 and runs a processing algorithm that returns the measurement of T.
  - Controls a switch in order to turn on and off the light source with a given timing.
  - Sends the measurement results to a 7-segment display and/or to a PC via RS232.
- The optical components (fiber, sensing element) have not been changed since the previous prototype.

Circuital details

Microcontroller: 8 input channels with a 10-bit ADC and range 0-5V, TTL I/O pins, up to 10 MIPS with a clock of 40 MHz.

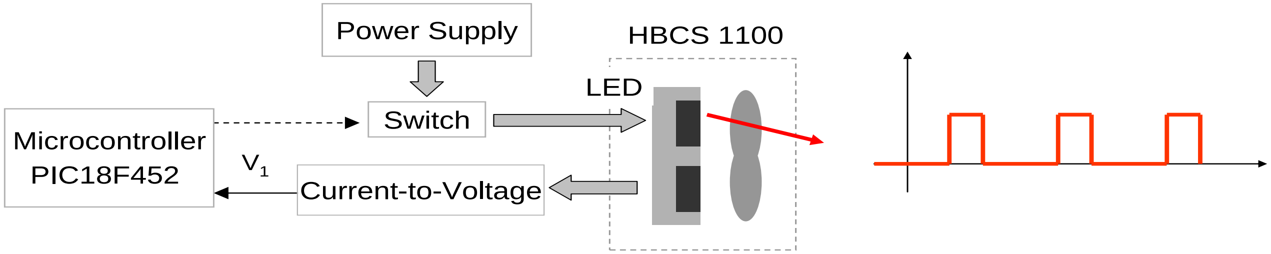


The illumination timing

If a significant optical power is applied to the photodetector of the HBCS for a long time interval, a relevant recovery time appears when the input light decreases or is switched off.

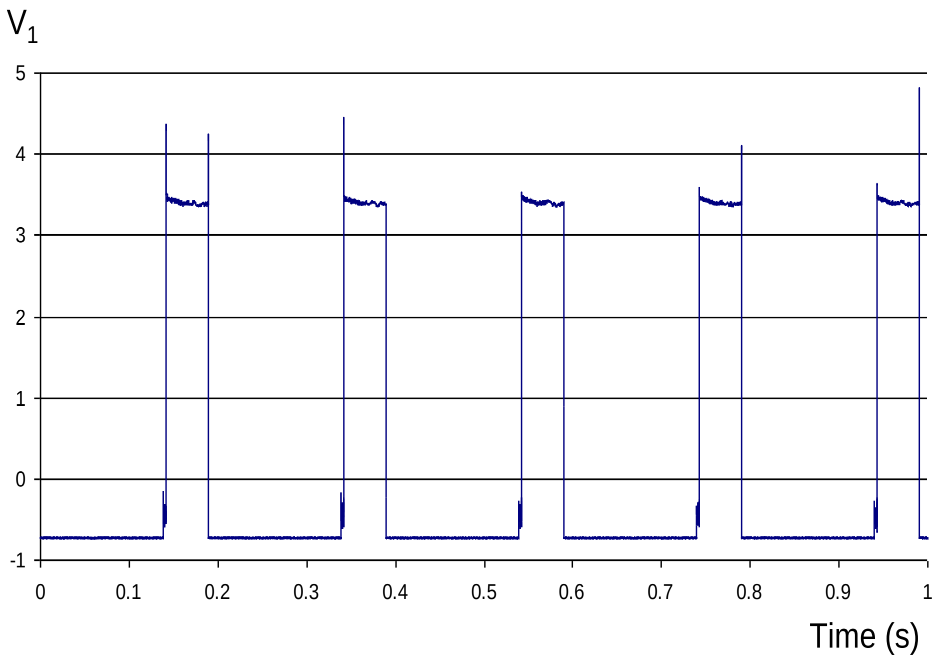
For that reason, a square signal with a duty cycle of about 25% and a period of 200 ms has been used as the stimulus signal.

This signal has been generated by properly switching the current that supplies the LED.



The processing algorithm

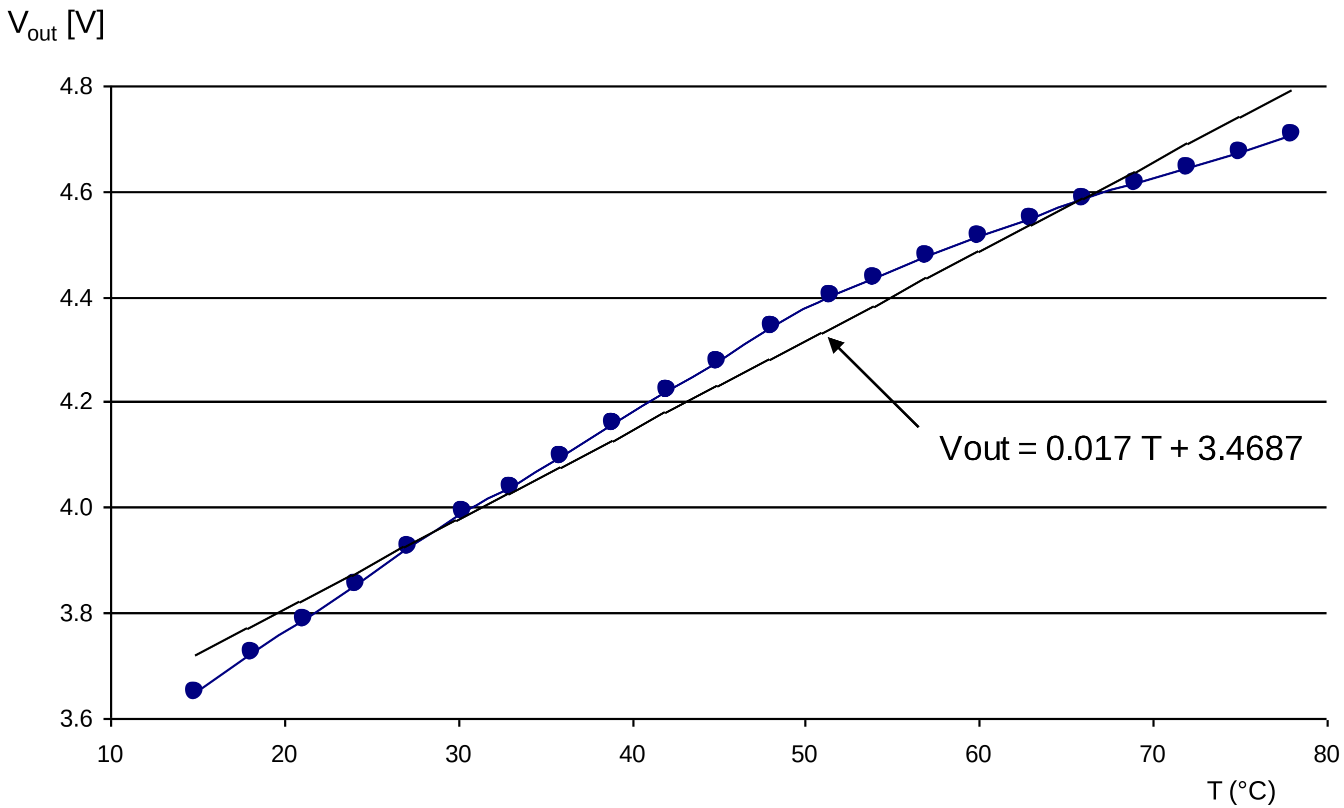
1. The signal is sampled at 10 kHz.
2. A fixed number of samples (50) taken during the "on" intervals are selected, skipping possible overshoots.
3. For each "on" interval, these points are averaged into V_{out}.
4. A table (V_{out},T) built during the calibration is entered (a fitting polynomial is used), and the value of T associated with the observed V_{out} is determined.



- During the calibration, the V_{out} is evaluated with the same algorithm, and a calibration bath is used in order to know the values of T.

- Due to the illumination timing, a measure of temperature is returned each 200 ms.

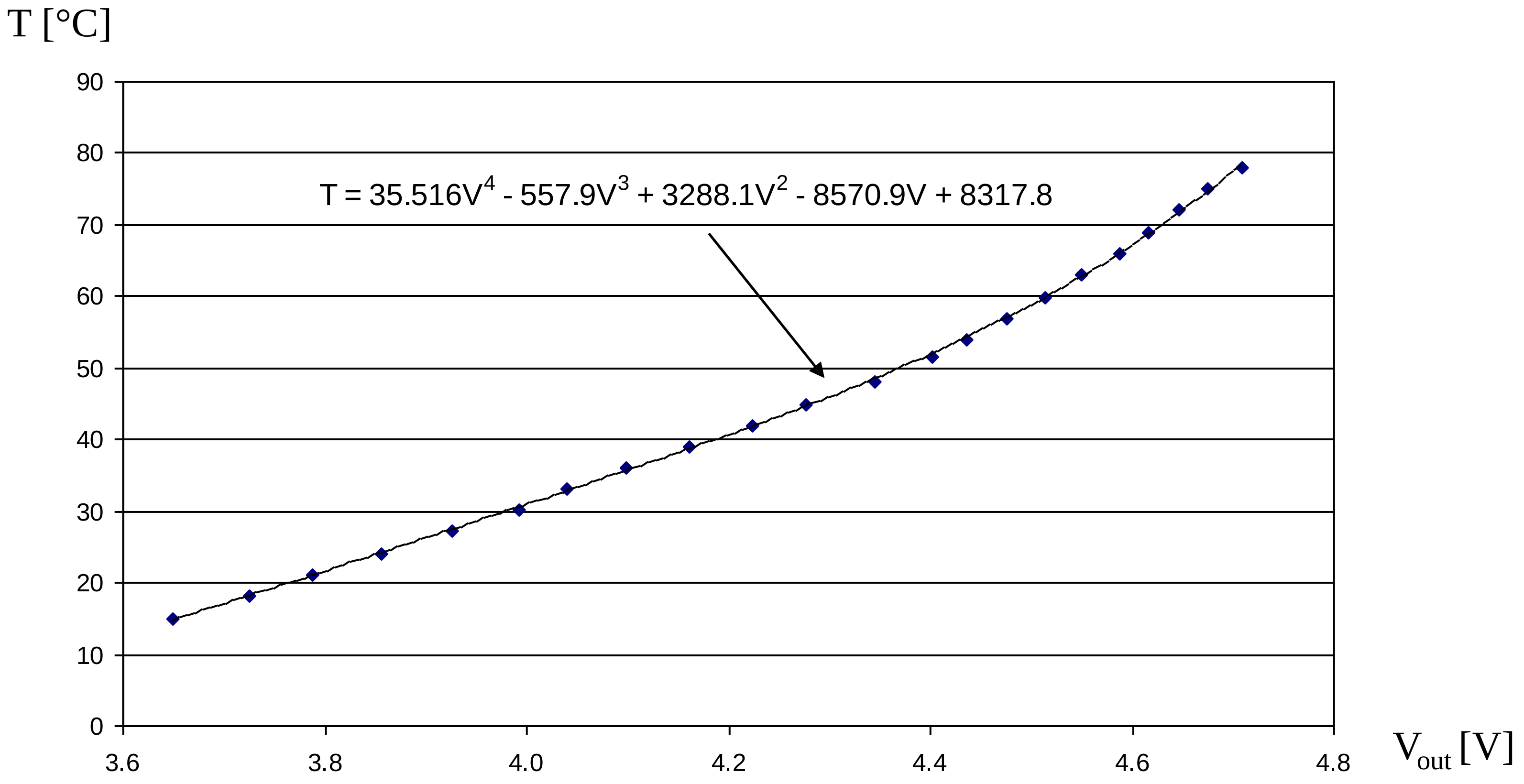
Static characterization of the prototype



Input range 15 - 80°C

With a linear least-square fitting: the **sensitivity** is about 17 mV/°C, the maximum **non-linearity error** is about 80 mV (4.7°C).

The fitting polynomial



A 4th order polynomial is used as a trade-off between complexity and accuracy.

This function is applied by the microcontroller in order to determine the temperature.

The maximum error in this case is about 0.5°C.

Static characterization of the prototype

In the tests for the static characterization, the standard deviation s(*Vout*) of samples of 30 measures of V_{out} resulted of the order of 16 mV.

Tests have been devoted to the evaluation of the **repeatability**, which resulted of about the same order of magnitude of s(*Vout*).

The **hysteresis** has resulted negligible.

The uncertainty contribution u_{fit} due to the approximation of the fitting polynomial has to be considered in the evaluation of the uncertainty.

Considering also the accuracy of the calibration bath as a source of uncertainty, the **standard uncertainty** of V_{out} can be estimated as:

$$u_V = s(V_{out}) / S_m = 16\, mV / 17\, mV °C^{-1} \cong 0.9 °C$$

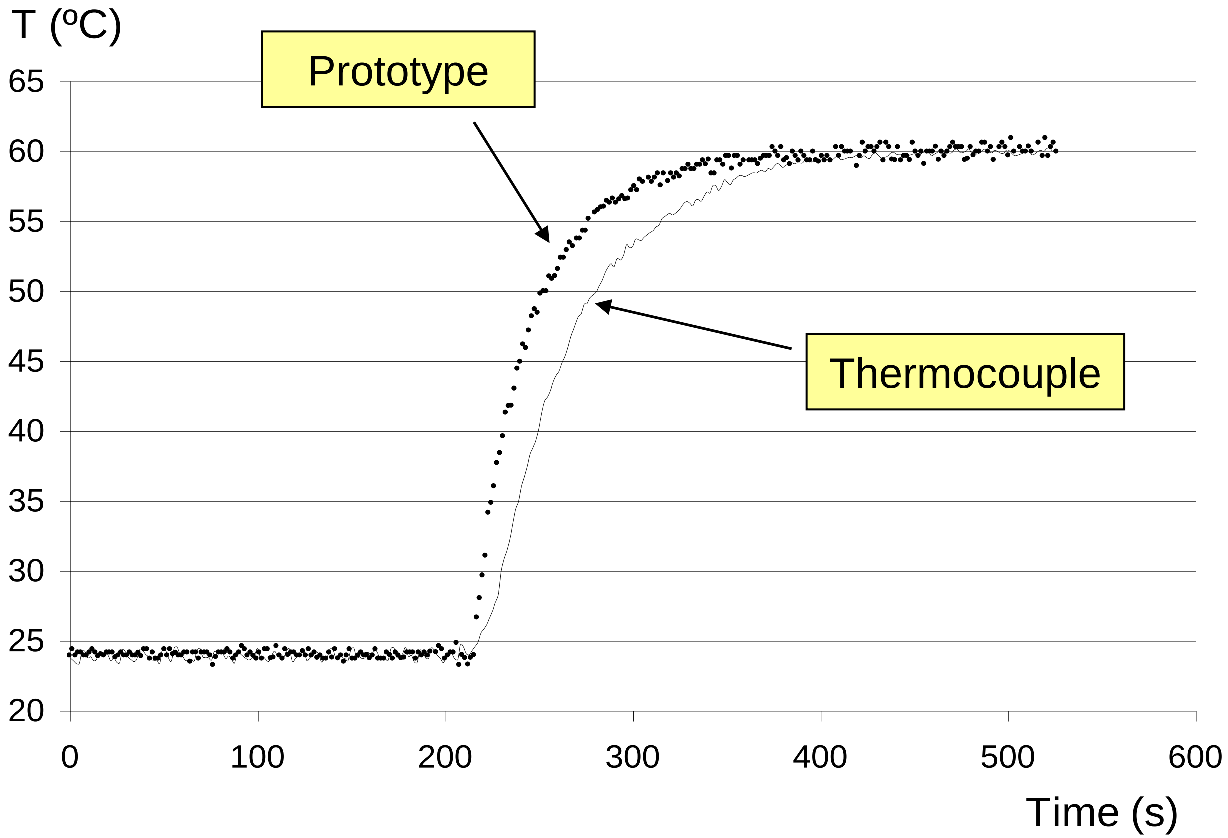
$$u_{fit} = 0.5 °C / \sqrt{3}; \qquad u_{cal} = 0.5 °C / \sqrt{3}$$

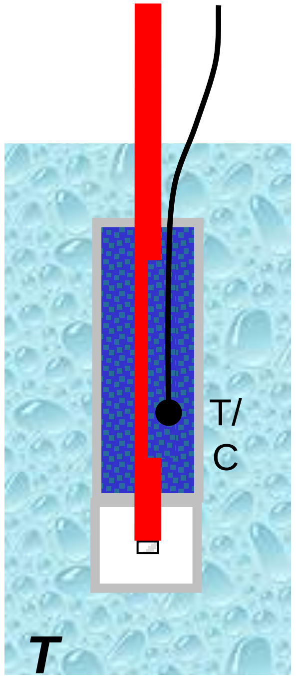
$$u(T) = \sqrt{u_{cal}^2 + u_{fit}^2 + u_V^2} \cong 1 °C$$

Dynamic characterization of the prototype

The prototype has been compared with a K-type thermocouple, when the temperature to be measured rises abruptly.

This test does not consider the thermal inertia of the tank.





Tests made with the previous prototype showed that the overall time constant of this kind of sensing element is about **5 s**.

Concluding remarks

- A compact and low-cost solution for the realization of reflectometric optical fiber sensors, based on a modified-cladding sensing principle, has been developed.

- A prototype for the measurement of the temperature of liquids has been characterized.

- The architecture could be extended to the measurement of other physical quantities, since other materials are known in literature to have optical properties depending on certain physical quantities, only substituting the reference liquid.

- The system could be easily extended to multi-point measurements, exploiting the 8 input channels of the microcontroller.