HIGH SPATIAL RESOLUTION IN DISTRIBUTED TEMPERATURE MEASUREMENT SENSORS

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Abstract – *A fiber optic reflectometric temperature sensor was set up and characterised. Its reduced dimensions render it suitable for monitoring application whenever a high spatial resolution is required. The metrological performance of the first prototype seems very interesting in terms of accuracy and above all, response time. This performance will be further improved by employing a side-polishing technique for sensor realisation and silver mirroring for its reflective part.*

Keywords - temperature measurement, optical fiber transducers, distributed measurement system

1. INTRODUCTION

Fiber optic sensor technology has experienced a tremendous growth since its early beginnings in the 1970's with early laboratory demonstrations of fiber optic gyros and acoustic sensors and the introduction of the first commercial intensity and spectrally based sensors. These early efforts were followed by a further growth of interest in the 1980's when the number of workers in the field increased from perhaps a few hundred to thousands. The result was the introduction in the 1990's of the first mass produced fiber optic sensors that are being used to support navigation and medical applications. The number of fiber optic sensor products is growing tremendously in these years as rapid progress continues to be made in the related optoelectronic and communication fields.

In particular, several measurement principles have been used for measuring temperature by using optical fibers [1]-[7].

In spectrally based sensors, the lightwave is modulated in wavelength by temperature, as in the “blackbody sensor” where an end of the fiber is placed in a blackbody cavity so that the wavelength profile of the light emitted by the cavity depends on temperature. The performance of this sensor is poor at low temperature (<200°C) due to the low level of the cavity emission with respect to other noise source, like the fiber lead itself [8].

A significant number of other prototypes are based on a typical set-up for time domain measurements, where a pulsed laser output is launched in a sensing fiber. In this case, a variation in the temperature surrounding the fiber, causing a change in the length and/or in the refractive index of the fiber, modifies the pulse propagation time and then the shift between transmitted and reflected pulse peaks. These systems can assure temperature measurements with resolutions on the order of a tenth of °C/m (thus very poor if the length of the sensing element must be kept small), provided accurate and expensive instruments are employed in the time shift measurement [9].

Interferometric sensors, instead, have higher sensitivities, so can provide the most accurate results. However they are generally characterised by a complex structure and are limited in range by the periodicity of the phase, unless the variations of the sum of intensities from two fibers is used in order to extend the measurement range [10].

Finally in the intensity based-sensors, the measurement information is carried by the intensity of the guided wave. Many techniques of this category take advantage of the correspondence between the surrounding temperature and the confinement of the propagating light. In evanescence based sensors the cores of two single mode fibers are placed very close (10-20 μm), thus obtaining the coupling between the evanescent field in the cladding of the first fiber and the core of the second one. The power lost in the coupling depends on the temperature, but also on several other environmental quantities. A major drawback of this approach is that the measurement system must be made insensitive to undesired parameters, like pressure or strain [11].

Among the different field of application, particular interest is in the use of fiber optic temperature sensors for monitoring in distributed environment. Power cable operating conditions can be monitored by embedding suitable fiber optic sensors in the cable itself [12]-[15]. Temperature and its variations with space and time is a key parameter also for the risk assessment in building and fiber optic distributed temperature sensors were successfully used also with this task [16]. Finally, fiber optic sensors were also used for monitoring the temperature within power transformers, indispensable activity for controlling winding insulation ageing [17]-[18].

Starting from their previous experience on fiber optic sensors [19]-[22], at first the authors experimentally verified a novel temperature measurement principle. The change of refractive index of some fluids versus temperature [23] was demonstrated to be useful to make intensity-based fiber optic sensors [24], [25]. Then, on the basis of this principle, two prototypes were realised. The former consists in a multi-fiber probe whose outputs were elaborated by a neural network processing software to provide a single point temperature, with a 0.5 °C accuracy, in a 100 °C range [26]. The latter allows measurement of temperature of the power transformer oil close to the windings, by up to 5 single-fiber probes [18], with a spatial resolution of 0.03 m and about 20 s response time.

Even though fully compatible with the aforementioned application, these values of spatial resolution and response time must be improved when volume and mass of the fluid whose temperature has to be measured are comparable with the sensor dimension. This is the case of numerous applications in chemical or electronics manufacturing industrial applications where, moreover, more limited input ranges are required.

In this paper, a new temperature probe is presented which uses the same principle of the previous one but, thanking to its reflectometric structure, assures higher spatial and temperature resolution, and lower response time.

Starting from a brief description of the previous sensor, the reflectometric sensor is described in detail, providing both the theoretical basis of its behaviour, and the experimental performance verification of a prototype.

2. THE PREVIOUS PROTOTYPE

In Fig.1 the schematisation of the temperature probe is reported [24], [26], [18]. If a little portion of the cladding along the optical fiber is replaced by a liquid with a suitable refractive index, a temperature variation of the liquid acts as a localised refractive index change that can be detected at the fiber end by a power measurement. In fact for a given fiber excitation, a localised change of the cladding refractive index modifies the propagation regime along the fiber. To be able to determine the temperature value from such measurements, the relationship between the fiber output power and the temperature of the liquid should be known. Although this relationship can be numerically determined under defined assumptions on the ray propagation, polarisation-dependent effects, etc., the most accurate evaluation comes empirically by a suitable calibration procedure. Obviously, the calibration should be repeated for every liquid whose temperature is to be measured. This problem was overcome by inserting the fiber unclad zone in a little tank, containing a "reference" liquid that should be at the same temperature of the external fluid where the probe is immersed. For a given fiber, the "reference" liquid can be chosen with a refractive index versus temperature characteristic that offers the best fitting with the required values of input range and temperature resolution. This implies that only a one-off calibration of the fiber-"reference liquid" pairing will be required, without specifying or constraining the optical characteristics of the fluid being measured.

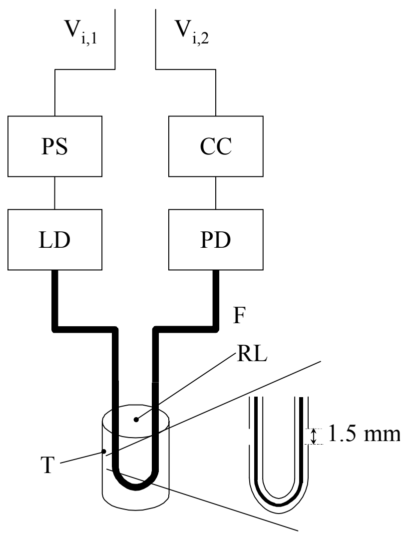

Fig. 1 - The previously realised temperature probe. (CC conditioning cicuit, PD photo diode, PS power supply, LD laser diode, F fibre, RL reference liquid, T tank).

The thickness and dimension of the tank (compared with the external fluid mass) determine:

- the **sensor response time** which depends on the time the "reference" liquid temperature takes to reach the external "unknown" fluid temperature;
- the **sensor spatial resolution**.

In the previous prototype, both these sensor characteristics (about 20 s and 0.03 m respectively) were enough for the specific application. But whereas their significant improving should be necessary the folded structure of the sensor, which also causes a reduction of its mechanical robustness, cannot be kept anymore.

3. THE REFLECTOMETRIC TEMPERATURE PROBE

The reflectometric structure of the new temperature probe is schematised in Fig. 2. The probe is made up of a no folded fiber optic. At one extremity, ended with a reflecting layer, there is the unclad zone covered by the reference liquid tank. At the other fiber extremity, a directional coupler allows a fraction of about 50% of the reflected power to be received (V_{out}) on a face different from the one directly coupled to the

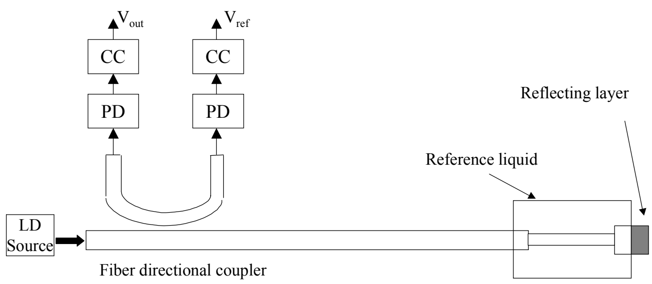

Fig. 2 - The reflectometric temperature probe

light source. The last coupler port outputs power whose intensity directly depends on the light source output power and could be used as input power monitoring (V_{ref}). A 5 mW laser diode (LD) is used as light source, while a photodiode (PD), supplying a current-to-voltage conditioning circuit (CC), is coupled at each directional coupler output port.

Among various possible devices (external beam-splitter, fiber power-splitter, 2x2 fiber coupler), the 2x2 fiber coupler represents the best trade-off between measurement and technological requirements. It was realised on the same fiber of the sensor (to obtain an "all-fiber" sensor) by fusing, for a length of 2 cm, its core with the core of a 20 cm long sample of the same kind of optic fiber. To this end an oxygen-propane microtorch mounted on a motorised translation stage was used, and the uniform power distribution of the input power between the output ports was experimentally verified in both directions.

The silica-silica fiber optic is side-polished with a technique developed as an alternative to other methods reported in the literature like the glass block approach [27], silicon groove substrates [28], or the polishing wheel [29]. This technique can be reported to be a variation of the former: the fiber is carefully embedded into an epoxy resin block, which is later polished. The block serves two purposes, first to shape the fiber with the desired radius of curvature, and second, but not less important, to prevent breaking the fibre during the polishing stage. As it has been mentioned the resin is a commercial epoxy with a curing time of 20 to 24 h.

The polishing is carried out in a commercial lapping machine from BUEHLER with a sample holder specially designed for this purpose, able to hold the fibre ends well protected. Aluminium oxide is used as abrasive, employing powder of decreasing grain size (9, 3.5 and 1 μm) [30], [31].

The fibre ends are mirrored with a layer of evaporated silver. The physical vapour deposition (PVD) is performed in high vacuum (10-6 mbar), using a Pfeiffer Vacuum evaporation chamber. Silver of 99.99% purity was used to charge the boat, which due to Joule effect is heated when applying a voltage by two electrodes. The thickness of the deposited layer is monitored thanks to a quartz oscillator placed inside the chamber that varies its resonance frequency as the metal is deposited.

On the basis of the above mentioned hypothesis a numerical simulation of the sensor was carried out by a ray-tracing technique which, for a step-index fiber, reconstructs the path of rays travelling along the optical fiber by recursive application of the Snell's law at the core/cladding interface. For a given ray congruence, the implemented routine evaluates the location of the ray reflections along the fiber. The power lost in the sensing element is then determined by multiplying, at each reflection point, the incident power with the Fresnel power transmission coefficient. The sensor fiber is a 600-μm optical fiber (n_{co} = 1.457, n_{cl} = 1.368, N.A. = 0.37, critical angle ≅ 20°) 1 m long having a 10 mm sensing element directly placed onto the mirrored fiber end. This allows a **12 mm high and 1mm wide** tank to be realized, thus significantly reducing the sensor spatial resolution. The modified-cladding is mineral oil for

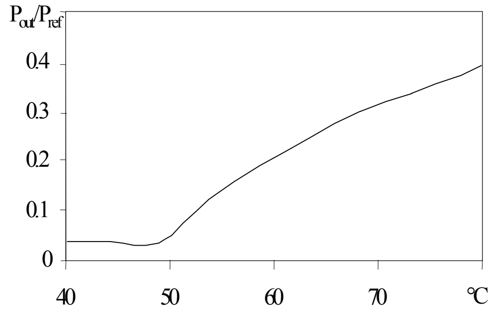

Fig.3 The P_{out}/P_{ref} ratio versus temperature calculated for mineral oil and an unclad zone 20 mm long.

which the following relation between the refractive index and temperature T was used:

$$n_{mcl} = 1.468 - 0.00037(T - 25) \quad (1)$$

Due to the involved cylindrical symmetry, analysis was carried out by considering 100 equally spaced source points (i.e. the starting points of the rays) displaced along a single diameter of the input section of the fiber. From each point 1600 rays, uniformly distributed (angular spacing of the inclination angle = 0.5°) within a cone of angular half-aperture equal to the critical angle of the fiber, were considered. The input power was assumed to be uniformly distributed among all considered rays: the result expressed in P_{out}/P_{ref} versus temperature is reported in fig.3 in the range 40 °C - 80 °C.

4. A SYSTEM FOR DISTRIBUTED TEMPERATURE MEASUREMENTS

Several applications require that temperature be contemporary measured in more than one point, maybe also in different fluids. To this aim the measurement system of Fig. 4 has been designed and realised. It is based on an INTEL™ MCS96 microcontroller (μC) which acquires signals by its acquisition section (composed by a 10 channel multiplexer and a 10 bit Analog to Digital Converter), executes measurement software and sends results to the digital display (Display) by its digital output port. The microcontoller is also interfaced via serial port to receive commands from and to send data to a remote control unit. Since each temperature probe requires two

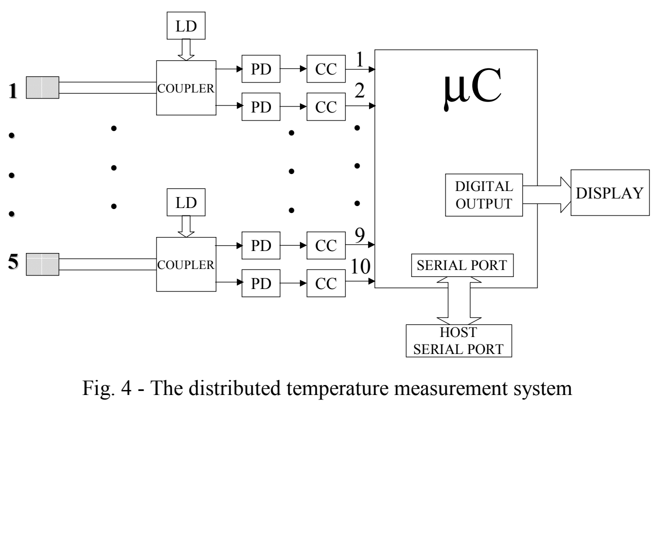

Fig. 4 - The distributed temperature measurement system

analog input channels, up to five probes can be contemporary connected to the μC.

i) The measurement software is composed of: i) Data Acquisition Interrupt Service Routine, ii) External Command Interrupt Service Routine, iii) Main Program. This routine serves a software interrupt every 100 ms by sending the A/D conversion command to the ten channels and reading their output. The ten A/D conversions are executed in sequence (1.7 ms each); consequently, the whole interrupt service routine takes about 20 ms.

ii) This routine serves the interrupt generated whenever the full duplex serial port is accessed by the external control unit for either initialising the transducer or requiring the last temperature measurement value.

iii) After the boot-strap, the microcontroller continuously executes the main program. Ten subsequent interrupt routines provide ten samples for each channel which are averaged in order to obtain higher resolution (hi-res) samples (11.5 equivalent bit), and a further increase of the signal to noise ratio. Each temperature probe provides two voltage signals (V_{out} and V_{ref}): the former directly depends on the temperature, while the latter is only proportional to the laser diode output power. This allows each probe input/output characteristic curve to be given as V_{out}/V_{ref} versus temperature. As a consequence, five voltage ratios V_{out}/V_{ref} are then evaluated and each one is used as entry point in the look-up table of the probe, where the voltage ratio-temperature characteristic in the range [40 °C, 70 °C] is stored with a resolution of 0.1 °C.

5. METROLOGICAL CHARACTERISATION

Each look-up table comes from the static characterisation of the temperature probe. Hereinafter, the given results of both static and dynamic characterisation tests concern a probe prototype whose unclad zone was hand made with a cutter (under microscope control) and the reflecting layer is constituted by a mirror fixed to the fiber end face through a suitable coupling gel. Fiber optic, tank and reference liquid are those supposed in simulation.

The static characteristic curve (see Fig. 5) was obtained by applying the following procedure at different temperature values ranging from 40 °C to 70 °C, with steps of about 2.5 °C: a reference thermocouple was immersed, very close to the prototype, in a bath equipped with a thermostatic control. Once the temperature steady state was reached, a sample of N=30 values of the voltage ratio was measured

Table 1 – Results of the sensor static characterization

Temperature (°C)	*Voltage Ratio R*	*u[R]*
40.1	0.0982	2.E-04
42.4	0.0996	1.E-04
45	0.1057	2.E-04
47.4	0.1127	2.E-04
49.9	0.1188	1.E-04
52.5	0.1243	2.E-04
55	0.1289	1.E-04
57.4	0.1328	2.E-04
59.9	0.1365	2.E-04
62.5	0.1399	1.E-04
65	0.1425	1.E-04
67.6	0.1450	2.E-04
69.9	0.1470	2.E-04

and, according to [32], the uncertainty of the voltage ratio values was estimated as equal to the standard deviation. Table I shows a detail of the obtained results, pointing out that the uncertainty is always lower than $0.2x10^{-3}$.

The measured relationship between the power ratio and the temperature is clearly in agreement with the simulation results. The difference in the absolute values depends on: i) the mismatching between the used mineral oil and the model adopted in simulation (1); ii) the actual efficiency of the realised directional coupler.

The dynamic characterisation was carried out by applying a temperature step obtained immersing the sensor, previously maintained at 45°C, in the bath at a temperature of 70°C. The step response of the sensor (reported in Fig. 6) allowed the determination of the response time that is of about 4.5 s.

6. CONCLUSIONS

Without any decrement of the already acceptable static performance typical of the previous prototypes, the new sensing element is characterised by smaller dimension of the reference liquid tank, thus assuring noticeable improvements in both dynamic performance and spatial resolution.

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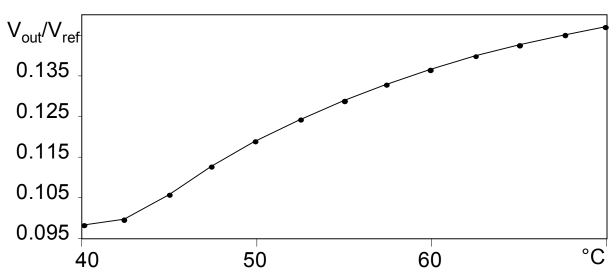

Fig. 5 – Static characteristic curve of the realised prototype

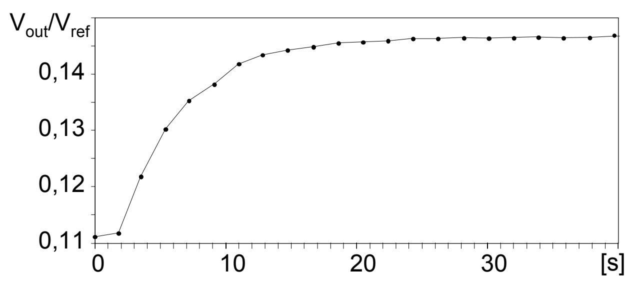

Fig. 6 – Step response of the realised prototype

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