A DUAL-WAVELENGTH PASSIVE HOMODYNE DETECTION UNIT FOR FIBER-COUPLED WHITE-LIGHT INTERFEROMETERS

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ABSTRACT

This paper is devoted to the description of a prototype Emission/Detection Unit, the ACCORD® Module, developed for the accurate demodulation of fiber optic sensors using spectral modulation encoding techniques. This prototype contains a static polarimetric interferometer with 4 ports to provide the four phase signals needed by the passive homodyne scheme, and uses a dual-wavelength arrangement to extend the measurement range by removing the 2π ambiguity in the phase determination. Resolution as high as $\lambda/40000$ has been achieved with 1 Hz bandwith and Optical Path Difference mismatch in a 20 microns range.

1. INTRODUCTION

In some industrial areas, like petroleum industry (pressure and temperature monitoring for down-hole applications), aeronautics (Fly-By-Light systems), or energy (temperature, voltage and current survey in harsh environment), the use of passive fiber optic sensors allows to achieve measurement of critical parameters by turning to account some advantages of optical methods, as intrinsic safety, galvanic insulation or parallelism. However, these very applications require other specifications for the sensing principle and the coding scheme, namely :

- resolution (10^{-4} of the Full Scale (FS) is a standard value),
- accuracy (the short- and long-term drifts will be less than 0.1% FS),
- down-lead insensitivity (a change in the fiber optic link does not induce any modification of the parameter value provided by the sensor, in its accuracy range),
- multiplexing ability (pointed out applications need sometimes multisensor information or multiparameter sensors on a single optical link).

To fulfil all these requirements, two main sensing and coding principles can be used : the first method is the Time Division Multiplexing of Digital informations (Digital TDM), which has been widely studied by various teams[1], especially for Fly-By-Light applications, and which needs grey-code plates, fiber optic delay lines and high detection bandwith[2]. The multiplexing capacity of such a method is quite low, the manufacturing of the optical sensing head, and especially its miniaturization, remains a critical point and the sensitivity of the sensor to environment (humidity, grease, dust) seems hard to eliminate. The second method uses bulk interferometers connected through multimode optical fibers and illuminated by a broadband source : correlation effects between channeled spectrum provided by each interferometer (sensing and receiving) allow to select and interrogate each sensor without cross-talk[3-7]. Spectral modulation encoding techniques join the simplicity and the reliability of incoherent systems and the sensitivity of interferometric methods together.

2. GENERAL PRESENTATION

A schematic description of this spectral modulation encoding technique is presented at the Figure 1, for two distinct bearings of the problem : the parameter encoding and the sensor multiplexing. For the encoding, we use a BroadBand Source (BBS), with a smooth wavelength dependent intensity distribution; the sensor is designed to produce a periodic spectral modulation of the BBS, at a frequency directly related to the value of the physical parameter X. Hence, when this value is varying, the frequency f of the spectral modulation is modified in the same way. The detection system achieves a FOURIER Transform of the resulting spectrum by optical means, in order to determine the value of the spectral modulation frequency and thus, after calibration, the value of the physical parameter. To separate in the FOURIER space the zero-component and the f-component of the signal, the frequency of the modulation must be high compared with the width of each of these components. Otherwise, to multiplex several sensors illuminated by the same source, it is sufficient to use different spectral modulation frequencies, which have values gaps meeting the same requirements as before.

The use of fiber optics leads to choose a Light Emitting Diode (LED) as BBS, for reliability and simplicity reasons (direct driving by the current); the spectral intensity distribution $P(\sigma)$ of such an emitter is besides quite regular, while it can be described in first approximation by a gaussian function :

$$P(\sigma) = \frac{P_0}{\sqrt{\pi}\,\delta\sigma}\, e^{-\left[\frac{\sigma-\sigma_0}{\delta\sigma}\right]^2}$$

where σ_0 is the central wavenumber of the LED, $\delta\sigma$ its spectral bandwith and P_0 the total output power launched into the fiber core. Moreover, the coherence length of the source l_c is in inverse proportion to its spectral bandwith :

$$l_c \approx \frac{1}{\delta\sigma} \approx \frac{\lambda_0^2}{\Delta\lambda}$$

For a LED emitting around 850 nm, the spectral bandwith FWHM is typically less than 50 nm, and the coherence length of the optical radiation is therefore less than 15 μm.

The sensor is a two beam interferometer (Michelson or polarimeter), which provides an Optical Path Difference (OPD) $\Delta_s(X)$ function of the parameter X with values much greater than the coherence length of the source. As a first assumption, if we neglect the spectral dependence of the OPD, the behaviour of this sensor can be described by the following relation :

$$P_s(\sigma) = T_1\, T_s\, P_0(\sigma)\, \{\, 1 + m_s \cos 2\pi\sigma\Delta_s(X) \}$$

where T_1 is the transmission of the forward fiber link, T_s the transmission of the sensor and m_s the visibility of the interference phenomena. The mean value of the OPD (which corresponds to the center of the parameter range) is called $\Delta_s(0)$. With the same approach, we can write, for the interferometric receiver :

$$P_d(\sigma) = T_2\, T_d\, P_c(\sigma)\, \{\, 1 + m_d \cos 2\pi\sigma\Delta_d \}$$

where Δ_d is the **fixed OPD** provided by the detector, close to $\Delta_s(0)$, T_d (resp. m_d) its transmission (resp. visibility) and T_2 the transmission of the return fiber link.

The total amount of light, detected at the output of the interferometric detector, is thus calculated by integrating the previous equation over all the wavenumbers :

$$S = \int_{\sigma} P_d(\sigma)\, d\sigma$$

If the source has a gaussian spectral distribution, we finally obtain :

$$S = T_1\, T_2\, T_s\, T_d\, P_0 \left\{ 1 + \frac{1}{2}\, m_s\, m_d\, e^{-[\pi\delta\sigma(\Delta_s - \Delta_d)]^2} \cos 2\pi\sigma_0(\Delta_s - \Delta_d) \right\}$$

and the resulting parameter S appears as a damped sine signal with a phase dependent visibility. We can observe that the system presents the classical Multiplex advantage of a FOURIER transform spectrometer (signal proportional to the total output power) and that its visibility at the matching point ($\Delta_d = \Delta_S(0)$) cannot exceed .5 (detection of a beat frequency).

3. DETECTION SCHEME

In the previous relation, the resulting signal S actually contains the searched information $\Delta_S(X)$, closely related to the value of the X parameter, but the recovery of this physical quantity involves some difficulties because of the variation of the modulation amplitude with various items, as the OPD mismatch, the spectral bandwith of the source or the efficiency of the sensor itself (m_S, T_S).

Otherwise, the definition of an optimized and powerfull detection system needs to fulfil some basical requirements, as stability and reliability : accordingly, the detection module should not include any moving parts or mechanisms, which generally offer poor reliability features. Therefore, the system must be absolutely static, this static behaviour providing furthermore a large adaptability of the choice of the detection bandwith.

To meet these specifications, we have chosen to use a dual-wavelength passive homodyne scheme in a polarimetric configuration. Indeed, in this method, the recovery of the phase information involves to record simultaneously four different signals ($\pm \cos\phi$, $\pm \sin\phi$), in order to remove, after some processing (differential amplification and ratio achieved by electronics or microprocessor) :

- the DC component of the S signal, which is a constant during a scan of the OPD provided by the sensor,
- the visibility factor, which is an indirect function of the X parameter.

The use of a birefringent interferometer as detection system aims at reaching simplicity and easy-to-aligne characteristics, while the choice of the passive homodyne scheme allows to fulfil the stability constraint.

The two complementary outputs of the polarimetric interferometer permit to obtain two first signals :

$$I_1 = I_0 \{ 1 + v \cos 2\pi\sigma_0(\Delta_d - \Delta_c) \}$$

$$I_2 = I_0 \{ 1 - v \cos 2\pi\sigma_0(\Delta_d - \Delta_c) \}$$

where v designates the visibility factor. Using a phase shifter ($\lambda/4$ waveplate), we produce two additional signals, in quadrature with the former expressions :

$$I_3 = I_0 \{ 1 + v \sin 2\pi\sigma_0(\Delta_d - \Delta_c) \}$$

$$I_4 = I_0 \{ 1 - v \sin 2\pi\sigma_0(\Delta_d - \Delta_c) \}$$

The differential amplification of each pair of values leads to the following quantities :

$$S = I_3 - I_4 = 2\,v\,I_0 \sin 2\pi\sigma_0(\Delta_s-\Delta_d)$$

$$C = I_1 - I_2 = 2\,v\,I_0 \cos 2\pi\sigma_0(\Delta_s-\Delta_d)$$

and the phase information can be extracted by forming :

$$\phi_0 = \text{Arctan}\left(\frac{S}{C}\right) = 2\pi\sigma_0\,(\Delta_s - \Delta_d) \quad [\text{mod}.2\pi]$$

the 2π determination of the Arctangent function obviously involving the knowledge of the sign of the corresponding Cosine function (C quantity). The effect of the intensity or visibility factor variations has been actually totally removed.

Figure 2 gives a schematic description of the optical detection head which provides these four phase signals (here the value of the fixed OPD Δ_d is determined by the value of the birefringence $e\Delta n$ of the tuning plate).

Using besides two LED, with slightly different central wavenumbers, we can synthetize a beat wavelength Λ, much larger than each single wavelength :

$$\Lambda = \frac{\lambda_1\,\lambda_2}{\lambda_2 - \lambda_1}$$

and which allows to remove the 2π ambiguity in the phase determination on a $\pm\,\Lambda/2$ range. As a first step, we must obtain the value of the phase for each LED :

$$\Phi_1 = \frac{2\pi}{\lambda_1}\,\{\,\Delta_s - \Delta_d\,\} = \phi_1 + 2k_1\pi$$

$$\Phi_2 = \frac{2\pi}{\lambda_2}\,\{\,\Delta_s - \Delta_d\,\} = \phi_2 + 2k_2\pi$$

then, if the variation range of Δ_s is not too large ($\pm\,\Lambda/2$ around $\Delta_s(0)$), we can : first, compute the differential phase $\Delta\phi$ ($\Delta\phi = \phi_1 - \phi_2$) by combining the two previous informations and second, readjust the result in the $[-\pi,+\pi]$ interval, to obtain a first evaluation of Δ_s-Δ_d :

$$\Delta_s - \Delta_d = \frac{\Lambda}{2\pi}\,\Delta\phi$$

This first approximation is used to determine the interference order k_1 for the first wavelength and to recover an extremely precise value of the parameter in a large range of variations :

$$\Delta_s(X) = \Delta_d + \phi_1 + 2k_1\pi$$

As an example, for 2 LED respectively centered at 850 nm and 880 nm, the usefull range can be extended with the same resolution ($\lambda/40000$) from .8 μm (one fringe) to 25 μm (30 fringes).

Naturally all these results suppose that the OPD mismatch between the sensor and the detector is not dispersive (that is not spectral dependent). In a general way, and especially if birefringent materials are used, this is not true and the simplified approach that we have used here must be given up. However, a complete analysis of the dispersion effects[8] shows that the proposed method remains valid and usefull (phase extraction using passive homodyne scheme and range extension by dual-wavelength arrangement).

4. PROTOTYPE DESCRIPTION

A functional description of the prototype Emission/Detection Unit (the **ACCORD®** Module) is presented in Figure 3.

The light provided by two standard LED is launched into multimode step index fibers of 100 microns core diameter (butt coupling). The main features of these sources are as follows :

- LED number 1 : λ_1 = 841 nm; $\Delta\lambda_1$ = 50 nm
- LED number 2 : λ_2 = 855 nm; $\Delta\lambda_2$ = 47 nm

The coherence lengths of each source is about 15 µm, while the beat wavelength related to the differential phase reaches 50 microns.

Since the use of a dichroic duplexer is naturally impossible (the central wavenumbers of these sources are too close from each other regard to their spectral bandwiths), the multiplexing of both emitters is achieved through a standard 3dB coupler (C1) and an interleaved ON/OFF modulation of the driving currents. One arm of this coupler is connected to the sensor by means of another 3dB coupler (C2). The light reflected by the sensor is launched into the optical detection head through a 10 dB coupler (C3) and an optical switch (S1), which allows to suppress the light part encoded by the sensor. In the same manner, the second arm of the C1 coupler is connected to the 10 dB arm of the C3 coupler through a second optical switch (S2) and an attenuator. During the calibration step, the switch S1 is off while the switch S2 is on : the spectrum of the light detected by the module is not encoded and the signal levels are used to achieve a periodic recalibration of the gain and of the sensitivity of the four detectors included in the electronic assembly. During the measuring step, the configuration of the switches is inverted and the detected light contains the spectrally encoded sensor information.

The electronic assembly performs time demultiplexing and digitizing (16 bits A/D converter) of the four phase signals related to each wavelength. A personal computer drives the bistable elements (S1, S2) through a PIA interface and processes the data, in order to provide either the OPD mismatch or the value of the X parameter, after a calibration phase.

The shape of a phase signal associated to both LED and recorded by the ACCORD® prototype is shown in Figure 4, while the OPD in the sensor is scanned over a 20 microns range around the matching value. In this experiment, the used sensor is a Michelson interferometer driven by a piezoelectric stage (0-2000V). On these curves, we can observe the damped sine oscillations with phase dependent visibility predicted by the theory, as well as the gaussian behaviour of the envelopes. Figures 5A and 5B give the corresponding data for the differential phase and the OPD mismatch provided by the prototype after processing. We can remark that the Differential Phase and the OPD mismatch are not zero for the same voltage value : this effect is due to the spectral dependence of the OPD mismatch, and involves the interference orders are high at the center of the tuning range[8].

5. PERFORMANCES

The main performances of a Detection Unit as ACCORD® are : the tuning range, the sensitivity and the long-term stability.

The tuning range of the prototype is directly determined by the spectral bandwith of the LED used in the Emission part : with 50 nm, we have obtained a ±10 microns tunability around the matching OPD. If necessary, larger values can be reached with different emitters (Super Luminescent Diodes) or different wavelengths (1300 nm).

The sensitivity can be estimated by recording the HF noise on the data over a large timescale (several hours). The experimental results obtained with a FABRY-PEROT gauge as sensor are shown in Figure 6. The rms phase noise performance is better than 150 μrads.$(Hz)^{-1/2}$. **The ACCORD® Module is then a 10^6 points detection system.**

The long term behaviour has been studied for a 4 months period and the recorded amplitude of the overall drift is less than 1 nm.

The principle of the method allows to multiplex different sensors on the same module[5], by using dedicated modulation frequencies (or OPD) for each sensor and suitable tuning plates in the optical detection head. Preliminary experimentations performed on a dual parameter sensor (Temperature and Pressure in the same probe)[9] have been allow to establish, besides the same kind of sensitivity and tuning range as previously described, the lack of any crosstalk between both parameters and the possibility to remote the sensing part to a large distance (up to 2 kilometers without problem or down-lead sensitivity).

This method can be adapted to a great number of physical parameters, as temperature, pressure, linear and angular positions, electric current and magnetic field[10], electric field, ... (see for example Figure 7).

6. CONCLUSION

This work demonstrates the efficiency of a dual-wavelength passive homodyne detection scheme for the accurate demodulation of fiber optic sensors using spectral modulation encoding techniques.

The attractive performances of this Module can be turned to account to demodulate either a few high resolution sensors (resolution better than 10^{-4} FS) or a large number of usual sensors (resolution about 10^{-2} FS) organized in an extended network applied to the simultaneous monitoring of several different parameters.

7. REFERENCES

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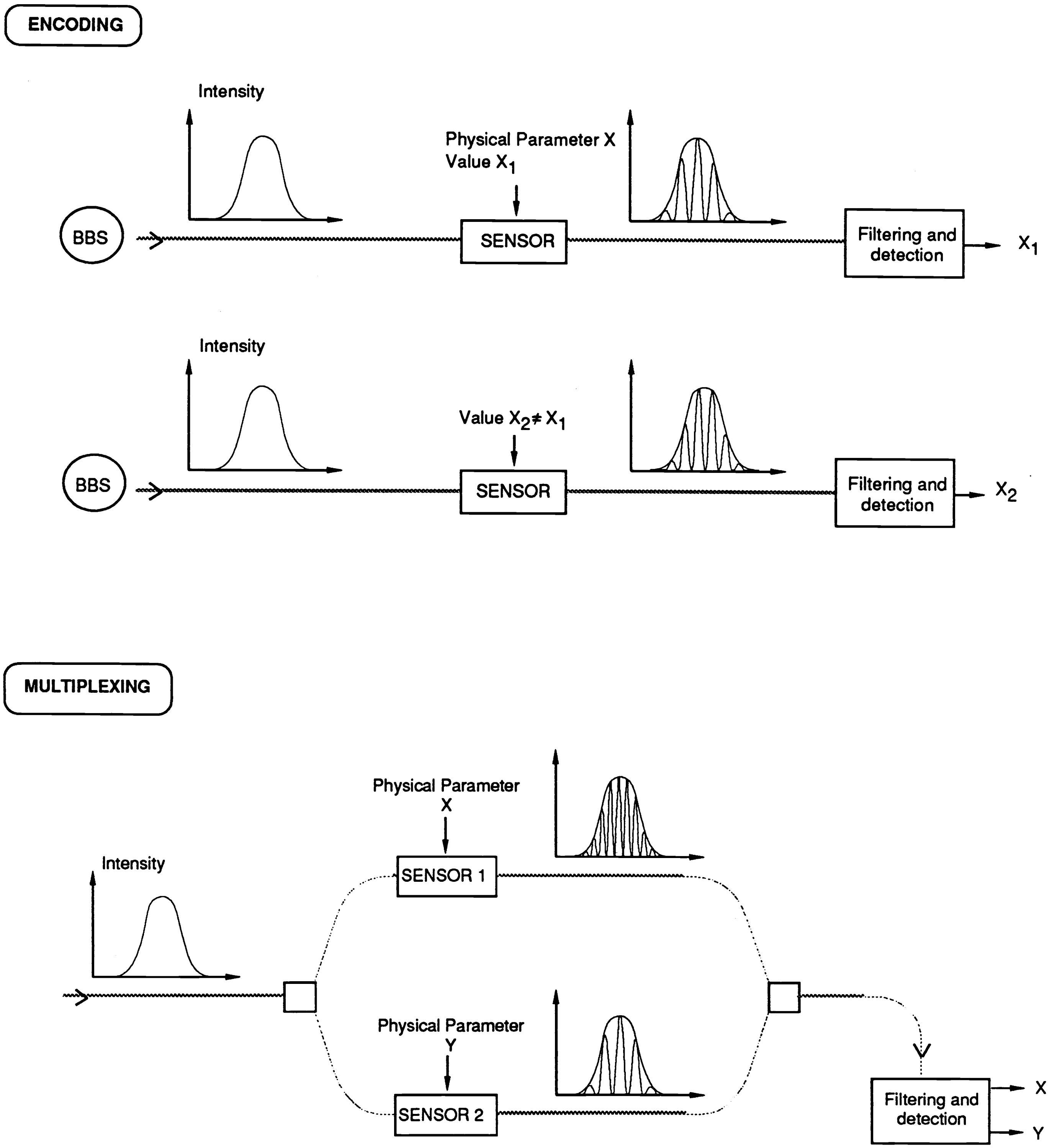

Fig.1. Schematic description of the spectral modulation encoding techniques

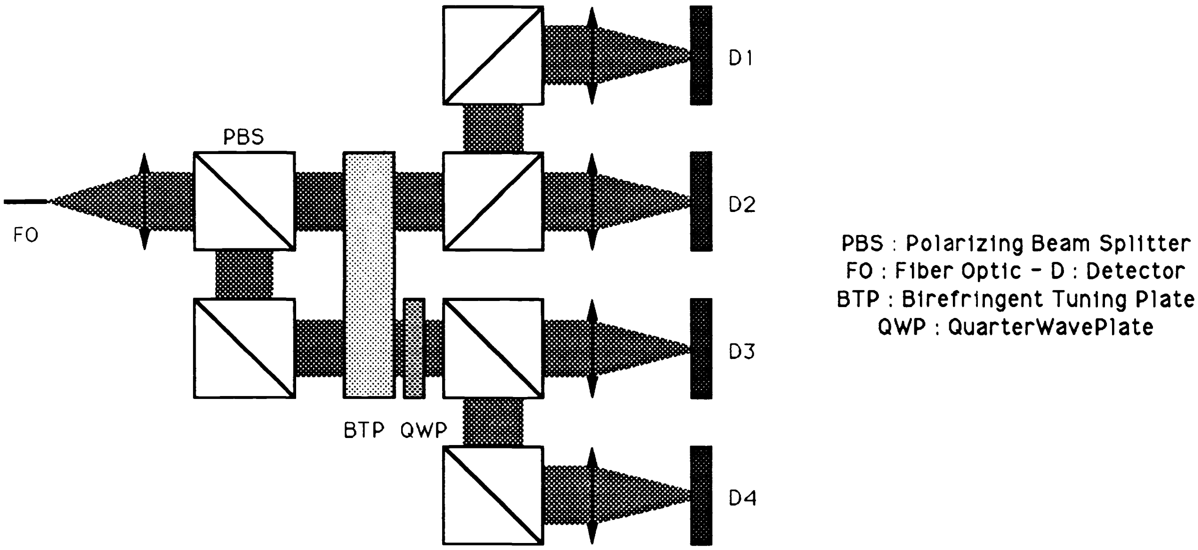

Fig. 2. Functional description of the optical detection head

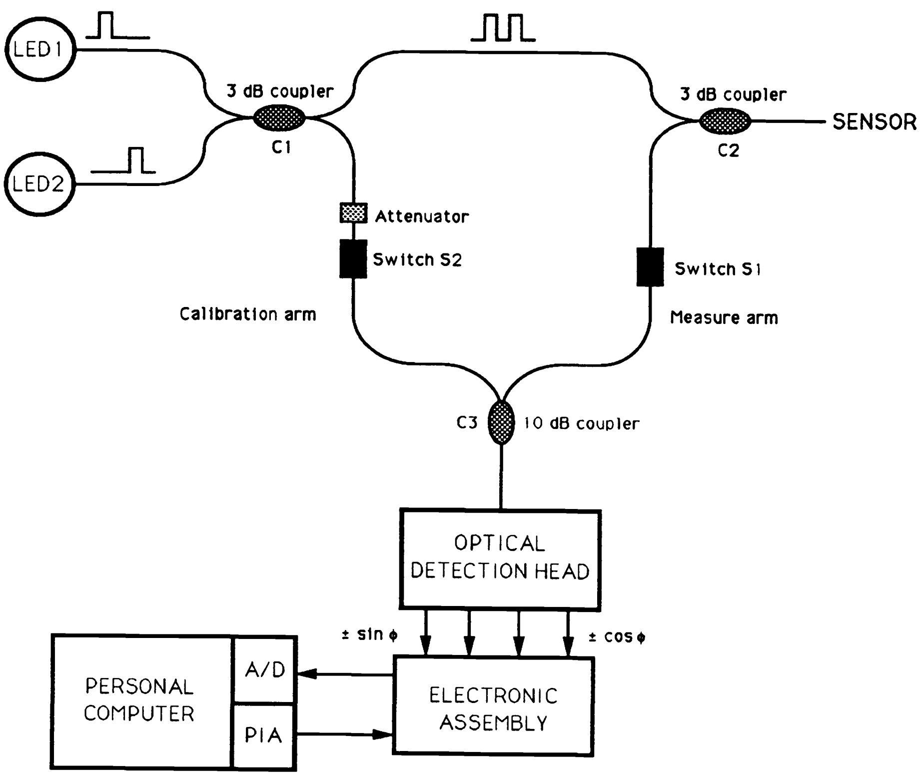

Fig. 3. The ACCORD® Module : schematic description

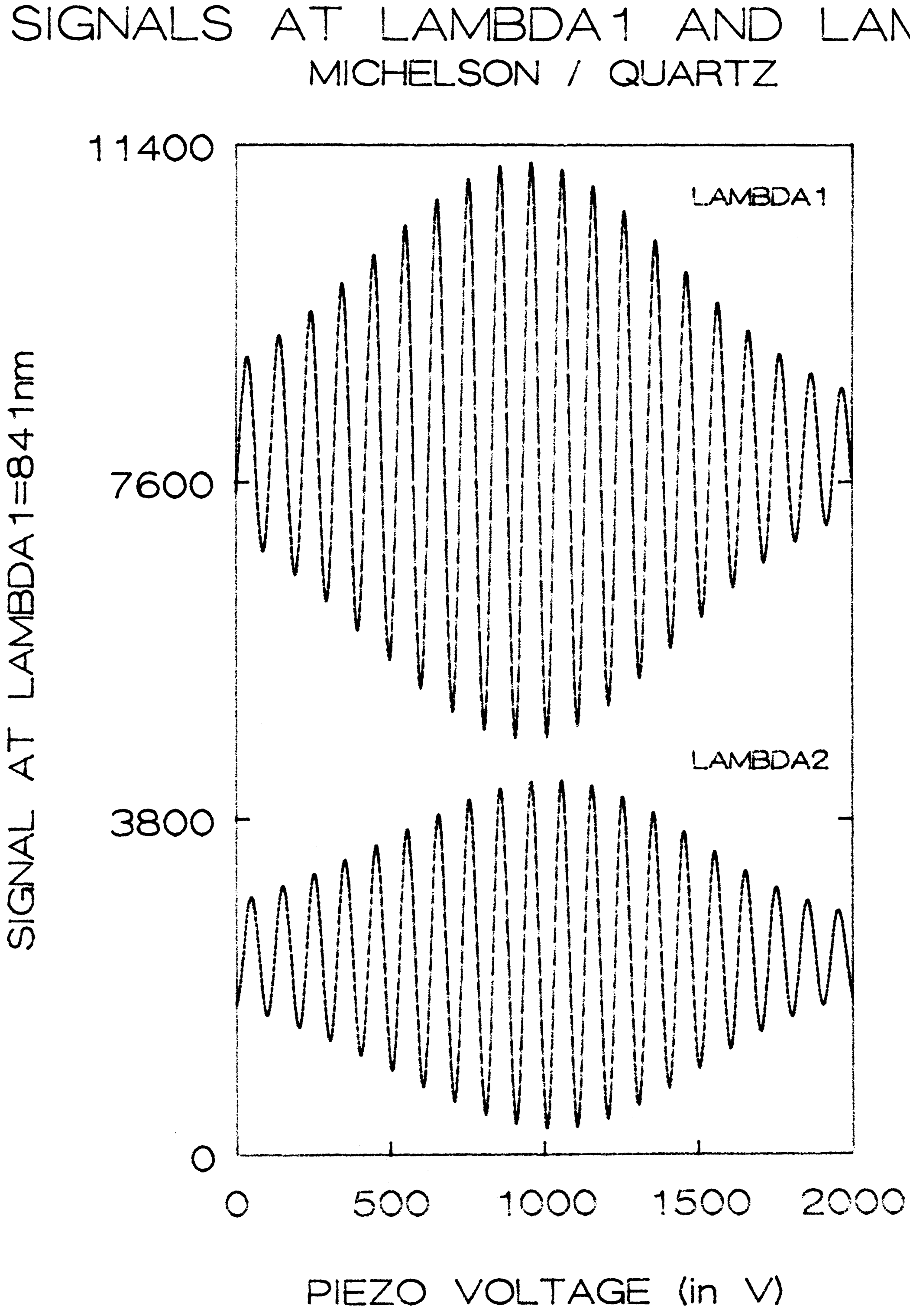

Fig. 4. Experimental Phase Signals for both LED

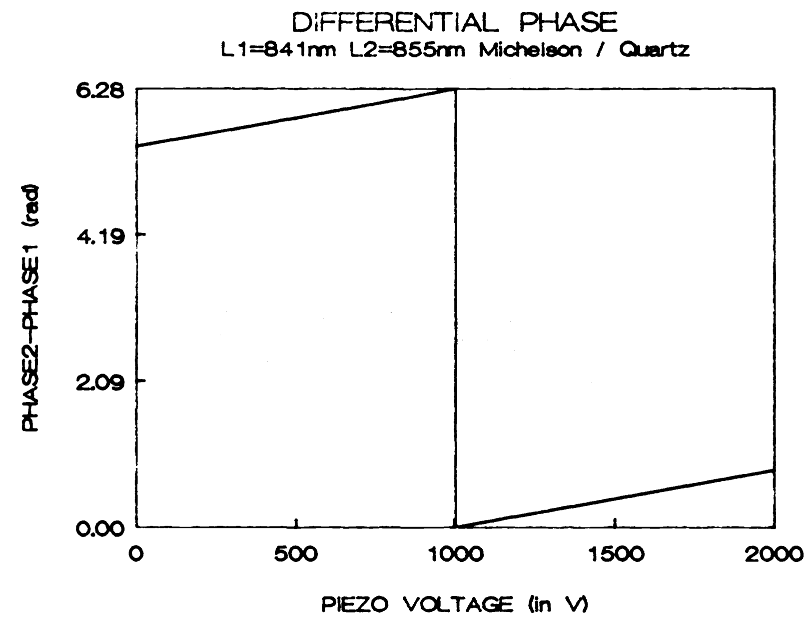

Fig. 5A. Differential Phase

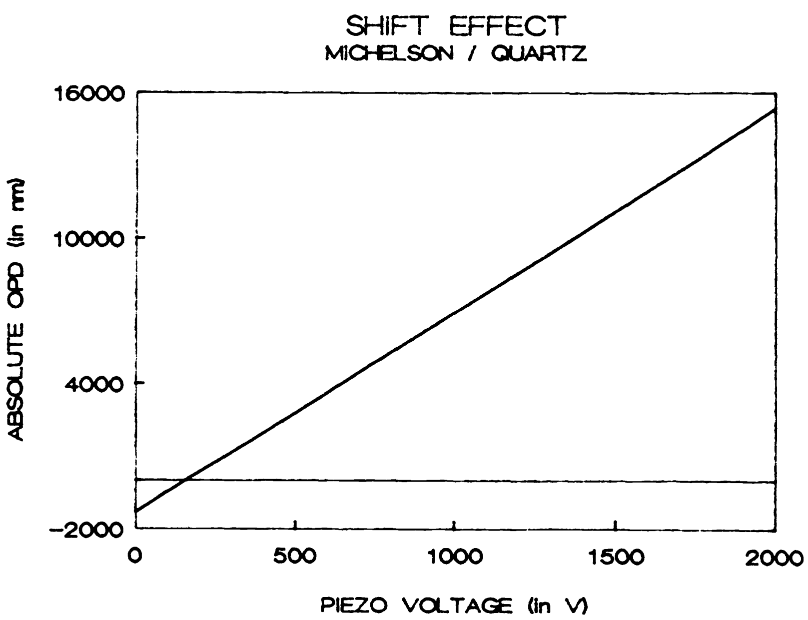

Fig. 5B. OPD Mismatch

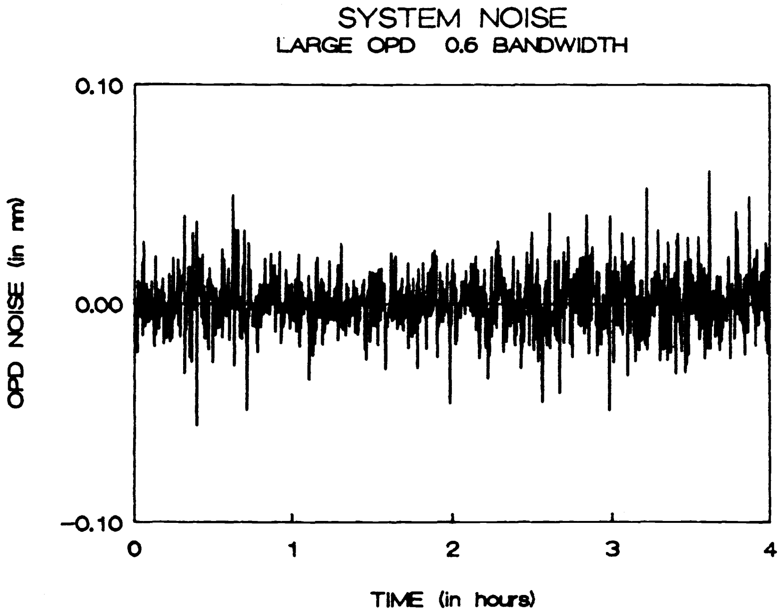

Fig. 6. HF Noise

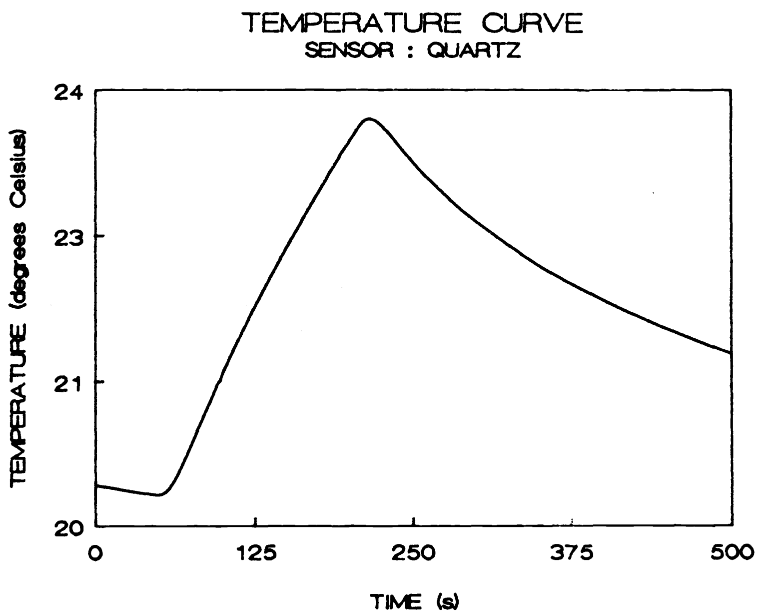

Fig. 7. Response of a Prototype Temperature Sensor