Improved method of phase detection scheme for displacement optic sensors

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Based on a novel method for overcoming DC drift in RF subcarrier phase detection scheme for fibre optic sensors we propose an improved method for the measurement of small displacements and vibrations. The method works in open loop and is characterized by low distortions in the modulation process, good signal-to-noise ratio and low cost. Considering the receiver ideal, we obtained for the measurements of small distances a minimum of 0.74 μm with a 6.6×10^{-7} dB dynamic range. The system can be exploited in the measurement of small distances, vibrations and seismic detection.

(Received January 5, 2006; accepted January 26, 2006)

Keywords: Optic sensor, Small displacement measurements, Phase detection scheme

1. Introduction

In the last decade, several papers presented optical sensors for displacements and vibrations measurement using different techniques [1-5]. The optical sensors used to measure positions and distances are attractive because they are non-contact. The principle of operation of the most sensitive optical sensors is based on optical interferometry. This offers displacement sensitivity much smaller than the wavelength of the radiation source.

The method based on sub-carrier phase measurements of RF intensity modulated light is well known and was applied in the measurement of optical fibre length changes. In this case, a RF amplitude modulated light is launched into an optical fiber and detected using a photodiode receiver placed at the output of the optical fibre. After that, the obtained electrical signal is introduced into an electrical mixer together with a reference generator signal which produces the RF modulation. The signal obtained from the mixer after being low pass filtered produces a dc signal whose magnitude is determined by the phase difference between the signal from the receiver and the reference signal. In case the phase of the reference signal is constant, the changes in the phase of the optically derived signal generates a change in the output which may be produced for instance by straining the fibre to change its physical length or modifying its refractive index. It is possible to measure the changes in optical path length by measuring the changes in the modulation frequency required to maintain a null output from the mixer. For long term static measurements there is the possibility that the dc drift from the mixer generates spurious signals [4]. In this case it is possible to obtain a noise limited quasi-static resolution of about 20 μm and ac sensitivity of tens of nanometers [4].

Over the last 30 years, optical fiber technology proved to be useful in sensors offering numerous operational benefits. Fiber sensors proved to be cost competitive when compared to other established measurement approaches [5].

Based on a novel method for overcoming DC drift in RF sub-carrier phase detection scheme for fibre optic sensors outlined in paper [5], we proposed an improved method displacements and vibrations measurement. The presented method is characterized by rather low distortions in the modulation process and small distances measurement, good signal-to-noise ratio and low cost electronic systems.

The paper is organized as follows: Section 2 presents the experimental set-up and performances of the devices used in measurement, Sections 3 is dedicated to discussion of the experimental results and to the evaluation of sensor characteristics (magnitude of the displacement, signal-to-noise ratio) while Section 4 presents the conclusions.

2. Experimental set-up

Based on a phase detection scheme for overcoming DC drift in RF subcarrier optic sensors [4], we proposed an improved method to measure small displacements and vibrations. The experimental set-up is presented in Fig. 1, where VCO represents a voltage controlled oscilator. The detection was performed using a low noise photoreceiver (diode).

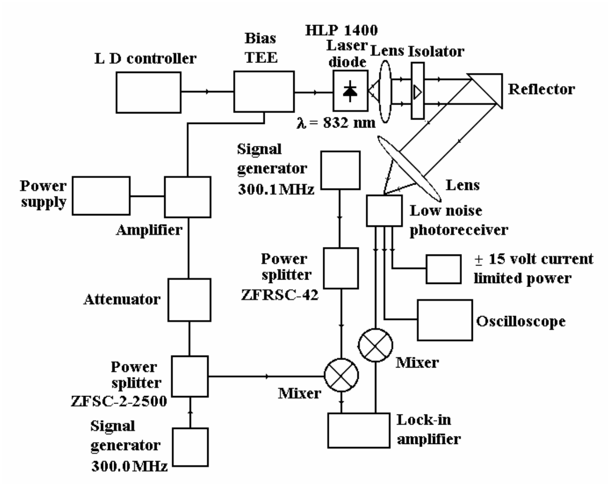


Fig. 1. Experimental set-up for phase detection (open loop).

In our experiments we used a laser diode (LD) Hitachi HLP 1400 which emits at a wavelength of λ = 827 nm.

The power and spectral characteristics in the range 822 nm-830 nm of the laser diode Hitachi HLP 1400 are presented in Figs 2 and respectively 3 a), b) for 60 mA (λ =826.85 nm) and 90 mA (λ =828.75 nm) injection currents.

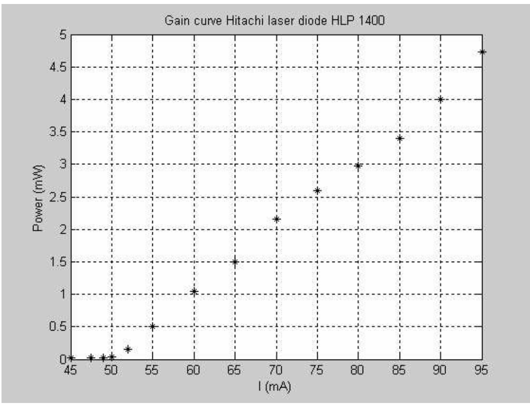
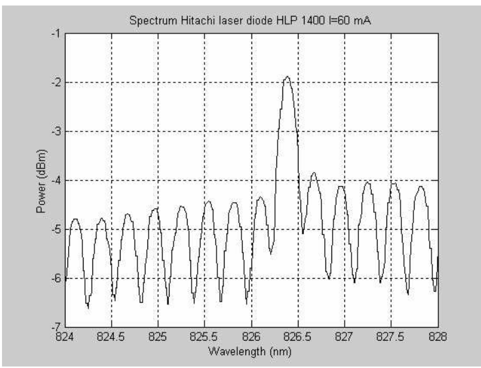
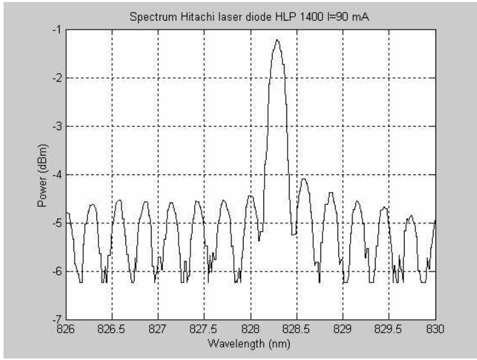


Fig. 2. Power characteristic of laser diode Hitachi HLP 1400.



a)



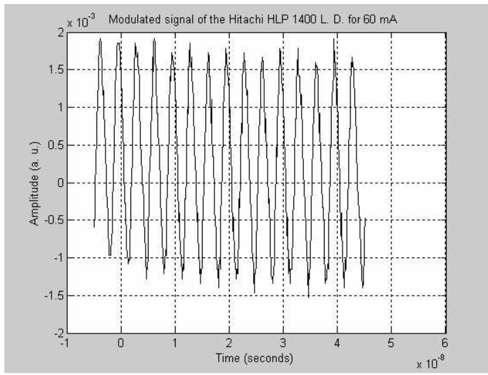
b)

Fig. 3. a), b). Spectral characteristic of the laser diode Hitachi HLP 1400 for: a) 60 mA and respectively b) 90 mA injection currents.

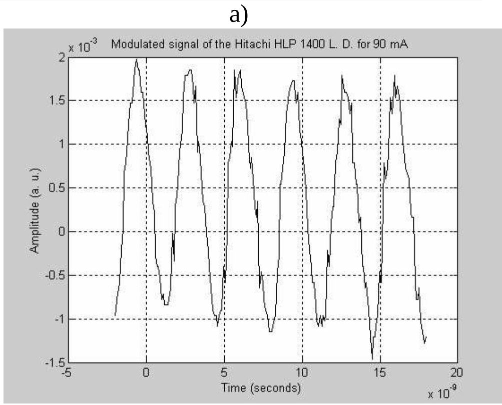
For high frequencies (~10 MHz) the mode hoping effect is small in the case of the laser diode Hitachi HLP 1400.

The modulated signals of the laser diode Hitachi HLP 1400 for 60 mA and respectively 90 mA injection currents are presented in Figs. 4 a), b).

The phase signal registered from the Lock-in amplifier incremented by 100 μm steps is presented in Fig. 5 a) and respectively for the long time drift in Fig. 5 b). The drift, compare angles, is well below a step width of 100 μm.

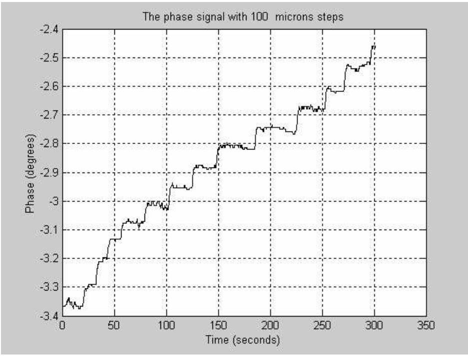


a)

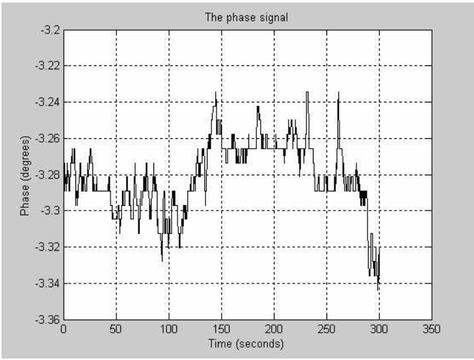


b)

Fig. 4. a), b). The modulated signals of the laser diode Hitachi HLP 1400 in the case of: a) 60 mA and respectively b) 90 mA injection currents.



a)



b)

Fig. 5. a), b). The phase signal with 100 μm steps (a) and with long time drift (b).

The oscilloscope traces show the modulation signal (and reference) in the time domain at two different positions, i.e. 0 mm (Fig. 6 a)) and 20 mm (Fig. 6 b)) apart. As can be seen the phase shift is visible.

3. Discussion of the experimental results

The operation of the experimental set-up presented in Fig. 1 can be analysed using the theoretical model outlined in paper [6].

Ideally the coherent optical signals have constant frequency and phase and for the coherent detection these parameters must be known at the receiver. The optical frequency may usually be considered as fixed, but in practice a phase estimator is needed in the receiver. The more realistic is the situation where phase noise is added to the signal.

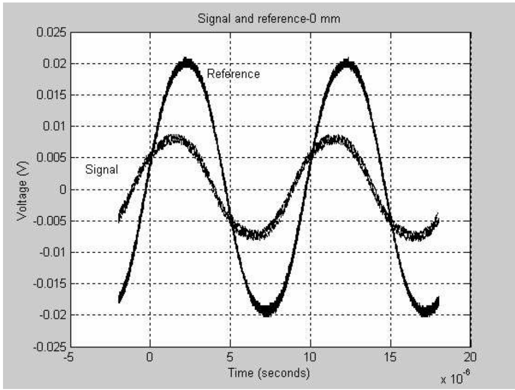
Using an optical heterodyne system for detection, the received optical signal is converted to an electrical signal by a photodetector [6].

Based on the theoretical model presented in ref [6] the signal-to-noise ratio, ρ at the decision point is given by:

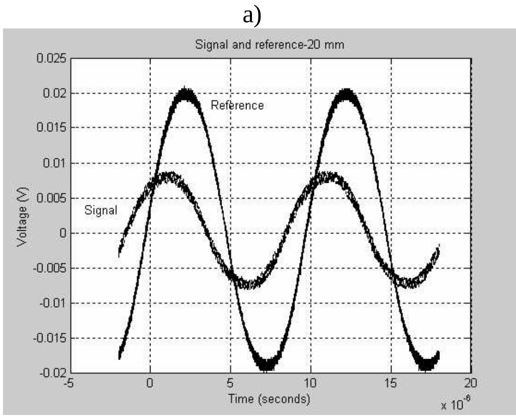
$$\rho = \frac{E_1 - E_0}{\sigma_1 + \sigma_0} = \left(\int_0^T A^2(t)\,\mathrm{d}t \right)^{1/2} \tag{1}$$

where $E_{0,1}$ are the means of the decision variable, $\sigma_{0,1}$ are the standard deviations when the symbols "one" and "zero", respectively are transmitted and A is the amplitude of the signal.

The variation of optical power delivered by the laser diode Hitachi HLP 1400 in the case of 60 mA and respectively 90 mA injection currents can be approximated by a quasi-sinusoidal signal of periods: 3.4×10^{-9} s (Fig. 7 a)) and 3.25×10^{-9} s (Fig. 7 b)).



a)



b)

Fig. 6. a), b). The modulation signal in the time domain for 0 mm distance (a) and 20 mm distance (b).

Taking into account the phase shifts, $\Delta\varphi$ obtained experimentally (Figs. 5 and 6) we obtained for the measurements of the small distances ($\Delta x = \Delta\varphi \frac{\lambda}{2\pi}$, λ being the wavelength of the laser diode) the values 4.51 μm and respectively 0.74 μm. Using a MATLAB programme we evaluated the errors (Fig. 5 a)) corresponding to the above mentioned small distances measurement. As can be seen from Fig. 7 they are in the range $1.45\times 10^{-4} \div 0{,}19$ μm.

Also, using the Eq. (1) and the processed (fitted) graph of the experimental results (Fig. 8 a), b)) we evaluated the amplitude and the period of the modulated signals of the laser diode Hitachi HLP 1400 and finally the signal-to-noise ratios and we obtained the following values: 6.9×10^{-7} dB and respectively 6.6×10^{-7} dB.

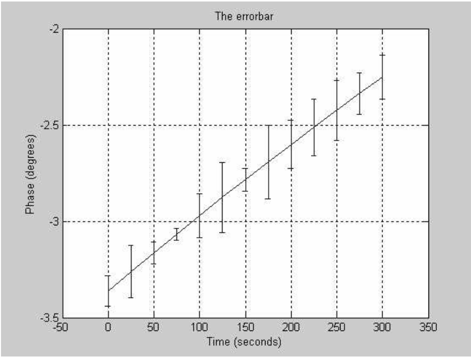
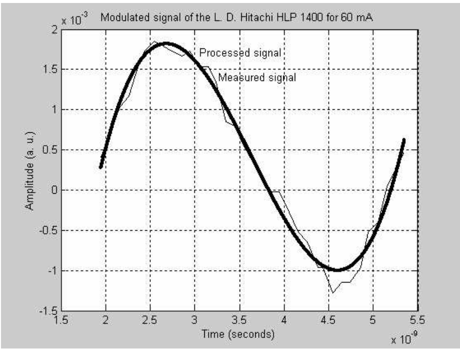
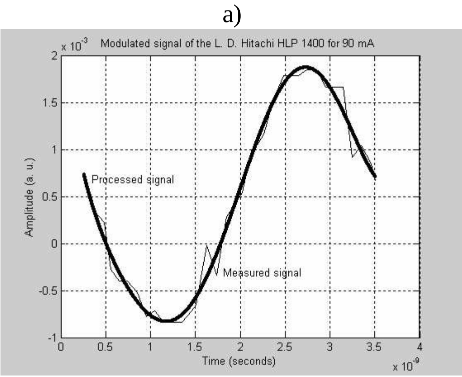


Fig. 7. The error bar graph corresponding to the data presented in Fig. 5 a).



a)



b)

Fig. 8. a), b). The modulated signals of the laser diode Hitachi HLP 1400 in the case of: a) 60 mA and respectively b) 90 mA injection currents.

4. Conclusions

Based on the method presented in reference [5] to overcome the DC drift in RF subcarrier phase detection schemes used in fibre optic sensors we proposed an improved method (*open loop*) for the measurement of small displacements and vibrations.

For two values of the injection currents of the laser diode Hitachi HLP 1400 used in the experimental work and based on the theoretical model of the ideal receiver we obtained for the measurements of small distances values of 4.51 μm and respectively 0.74 μm and for the signal-to-noise ratios: 6.9×10^{-7} dB and respectively 6.6×10^{-7} dB.

Acknowledgements

This research was partially performed under the project: *Novel optical device and techniques for seismic activity detection and measurement*, Programme "Energy, Environment and Suistainable Development, Contract nr. EESD-ESD-3 (JO 2000/C 324/09), European Commission, Research Directorate General, Preserving the Ecosystem: environmental research, 2002-2005.

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