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Wavelength Lock-in Technique to improve Fiber Interferometer Performance for Geophysics Applications

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***Abstract*—An automatic wavelength lock-in technique is proposed to improve fiber interferometer performance for geophysics application. The proposed approach locks the laser wavelength to the absorption lines of hydrogen fluoride gas. The lock-in scheme directly benefits from the dithering signal driving the laser to obtain the required quadrature phase shift for displacement reconstruction and thus does not affect the sensor operation.**

Keywords—Lock-in, gas absorption lines, fiber interferometer

I. INTRODUCTION

Earthquakes, volcanic eruptions as well as anthropogenic activities (i.e. underground mine tunneling and storage facilities) can induce large strain states and hence provoke movements in the earth's surface [1]. The subsequent vibrations generated by these events can nevertheless be remotely detected away from their epicenters by highly sensitive sensors [2]. Fiber interferometers are particularly suitable for this task in geophysics because of their numerous advantages which are unmatched by traditional instruments. The optical glass fiber employed is dielectric and, hence, immune to electromagnetic interferences, lightning strikes and has near-zero explosion risks. In addition, its flexible geometry, low attenuation, very wide bandwidth, and multiplexing capability favor sensor systems based on the optical fiber for field deployment for remote sensing. Furthermore, when interferometric detection techniques are employed, these sensors can offer extreme sensitivity and precision and can be made suitable for applications beyond typical optical metrology. In previous work [3], we reported a sensor based on the extrinsic fiber Fabry-Perot interferometer (EFFPI) that was successfully coupled to three geomechanical instruments for long-term monitoring of the Earth’s free surface movements [4]

For applications demanding subwavelength detection or with slowly varying vibration as typically encountered in geophysics, the problems of long-term stability have to be addressed. Laser sources with highly-stabilized emission wavelength, which can be used to track and measure small-amplitude vibrations is thus of major interest for geophysics applications since they require low drift (~several 10's nm/month) and monitoring over long periods (~months to years). To date, a temperature regulator based on a Peltier module and a current driver have been used to address this issue and limit wavelength drifts. However, this approach does not consider other parameters that can affect the emission wavelength such as mechanical strain, pressure variation, ageing of the laser chip, etc. In addition, significant inconvenience arises when multiple EFFPI sensors are to be deployed in the field since this would require different settings for each laser source. Consequently, the implementation of active wavelength-locking schemes is a practical solution to overcome the environmental spectral sensitivity of the laser to ensure the stability necessary in highly-demanding applications [5-8].

Here, we propose to lock the laser wavelength to an absorption line of a reference gas with a system that seamlessly blend with our previous EFFPI sensor, thereby improving its long-term stability and providing an absolute wavelength value without any modification to the existing sensor set-up.

In Section II, we will first briefly provide an overview of the existing EFFPI sensor in order to explain how the laser lock-in scheme has been designed without affecting the sensor operation. Then, the proposed lock-in approach is discussed. Finally, preliminary experimental results are presented in Section III.

II. PROPOSED WAVELENGTH LOCK-IN APPROACH

A. Overview of *EFFPI*

The principle of the modulation-based EFFPI is illustrated with a zero-strain target in Fig. 1. The interrogating wavelength (λ) from a temperature-regulated fiber pigtailed 1310 nm DFB-type laser diode (DFB-LD) is coupled by a fiber circulator (FC) to an external target through a collimator (C). As demonstrated in [9], the use of a (highly reflective) target, such as a mirror, introduces a double reflection (DR) from the

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sensing beam. The interference between this twice-reflected wave and the direct reflection of the reference beam at the fiber tip is detected by the photodetector (PD). The PD output signal, after the transimpedance amplifier, is given by

$$V_x = V_{0x} + V_{mx}\cos(\theta + \alpha) \qquad (1)$$

with V_{0x} its dc component, V_{mx} its ac component representing the fringe visibility, θ the optical phase between the reference and sensing waves and α an arbitrary phase. However, since θ is determined modulo π, directional ambiguities arise but these are subsequently eliminated by introducing a $\pi/2$ or quadrature phase shift to V_x through α by directly modulating the DFB-LD injection current , whose wavelength-current response is A ~9 pm/mA. Hence, the amplitude of the squarewave modulation to the wavelength, f_1, has to satisfy $\Delta\lambda/\lambda^2 = 1/8nd$, where n is the refractive index of the FPI cavity (~1 in air), d the initial distance between the fiber tip and the target, and $\Delta\lambda = \lambda_2 - \lambda_1$, with λ_1 and λ_2 the wavelength limits scanned by f_1.

In addition to this modulation, when the target is immobile or displaces very slowly, where either no fringes are generated or the resulting signals might be misconstrued as intrinsic drifts of the sensor system, a second modulation f_2, which can be of triangular waveform, is necessary to generate a set of reference fringes to provide a bidirectional trajectory of $\geq 2\pi$ on the phase diagram to satisfy $\Delta\lambda/\lambda^2 = 1/2nd$. Further, quadrature phase errors and power variations due to the dual modulation of the sensor system are also corrected to achieve nanometric resolution and accuracy [4,9].

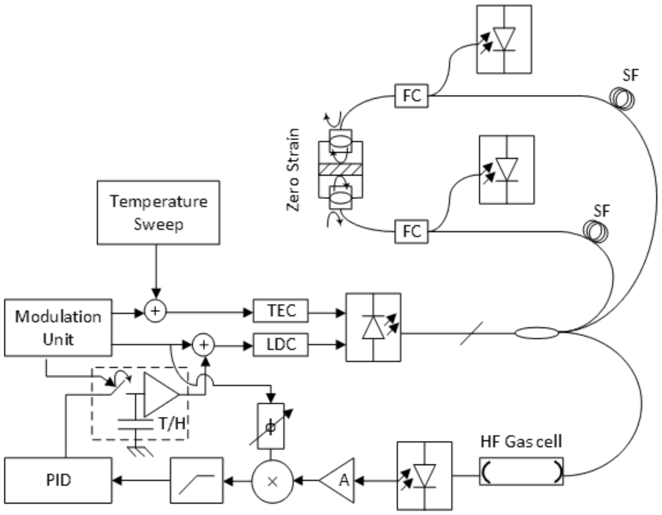

Fig. 1. Schematic of a differential modulation-based EFFPI for displacement measurements with the proposed automatic laser frequency locking system. with a zero-strain target (TEC: thermo-electric cooler; LDC: laser diode controller; FC: Fiber Circulator; SF, Sensing Fiber; T/H: Track and Hold; PID: Proportional Integral Derivative controller)

B. *Laser Lock-In system*

The principle behind the wavelength lock-in technique is to generate a signal approximating the derivative of the absorption line shape of a reference gas cell with respect to wavelength. This can be achieved by modulating the laser wavelength via its driving current from which the interaction of the modulation sidebands with the absorption line creates the derivative-like signal. This has the useful property of going through a zero-crossing when the laser is about the center of the absorption line (Fig. 2) [8]. Lock-in can then be accomplished by implementing a feedback loop to actively tune the laser to maintain the spectroscopic signal which serves as an error signal at the zero-crossing point(s).

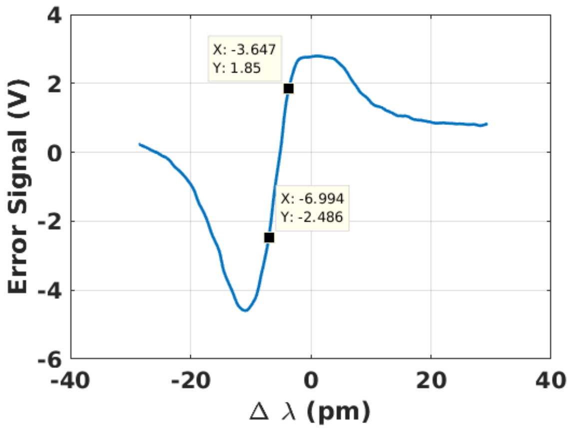

Fig. 2.Derivative-like error signal produced from scan of DFB-LD across HF absorption line around 1310.92 nm

As mentioned in the previous sub-section, the modulation signal f_1 can be used directly to perform the lock-in function. Fig. 1 illustrates the dual-modulation EFFPI incorporating the wavelength lock-in system. A fiber coupler is used to couple 33% of the laser beam into a hydrogen fluoride (HF) reference gas cell where the absorption line of interest is at 1310.92 nm with a 5 pm spectral width. The output optical power from the gas cell is monitored by a photodiode. This signal is then demodulated and filtered to generate the spectroscopic signal. which is subsequently fed to a proportional integral derivative (PID) system controlling the laser current.

For the system to be fully compatible with the EFFPI sensor, it should not affect the second modulation signal f_2 that is used to calibrate the sensor. However, while the first modulation signal f_1 directly contributes to the wavelength lock-in system, f_2 has a larger current modulation amplitude which would be perceived as a disturbance signal. Consequently, the system will try to eliminate or mitigate the influence of f_2. It is thus mandatory to “freeze” the locking scheme during the calibration period using the PID controller to maintain the last correct output value during this period.

In addition, to ensure that λ is within the absorption line of interest before closing the lock-in loop, it is swept by applying a temperature ramp on the laser instead of a current ramp as the former provides a wider operating range. Once the optical power minimum of interest is found, the temperature of the laser is maintained.

Finally, a diagnostic mode is performed in the background to check if the laser is locked. Once locked, λ should be at the center of the absorption line. This absorption line thus behaves as an absolute operator and the optical output power's modulation frequency is then twice that of f_1. Therefore, it is

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possible to verify the system status by performing an FFT on output signal from the gas cell.

Fig. 3 shows a flow chart of the automatic laser frequency locking system.

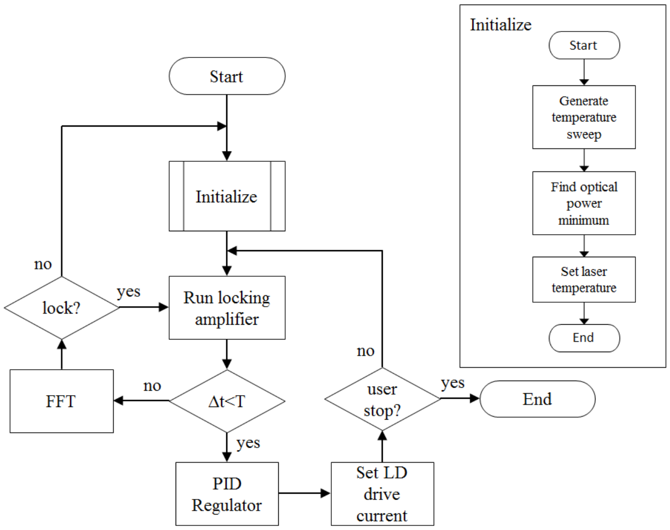

Fig. 3. Flow chart of the proposed automatic lock-in scheme. Δt is defined as the time since the last FFT calculation. Inset: flow chart of Initialize procedure.

III. EXPERIMENTAL RESULTS

A. *Experimental Set-up*

The interrogating wavelength from a temperature-regulated fiber pigtailed 1310 nm DFB-LD is coupled by a fiber coupler and FCs to an external HF gas cell, with an absorption line at 1310.92 nm, as well as to an external zero strain cavity through Cs. The lock-in algorithm including the PID regulator and FFT routine check is embedded within a STM32 microcontroller allowing the laser current to be updated at 600 Hz.

B. *Wavelegnth Lock-in Performance*

The accuracy of the frequency lock-in can be analyzed from the error signal originating from the lock-in amplifier. The FFT of this signal is shown in Fig. 4 with and without the activation of the lock-in control loop over a 1-hr period of frequency locking. The corresponding RMS values are 6.4 mV and 210 mV with and without the lock-in activated respectively. The maximum frequency deviation is observed to be less than 9.5 MHz from the target absorption line, as illustrated in Fig. 5. Without lock-in applied to the system, the linewidth was initially 98 MHz over the same sampling period of 1 hr. This corresponds to a 10-fold improvement in spectral width.

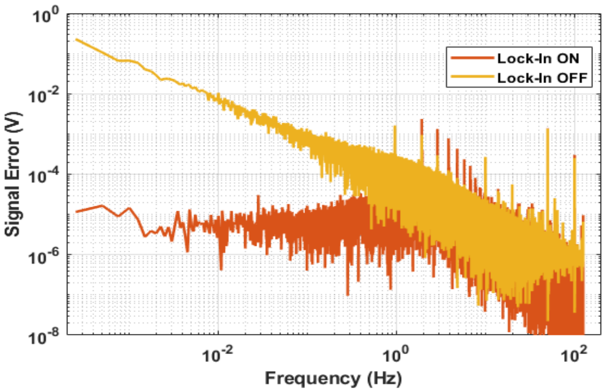

Fig. 4. FFT of the measured Error Signal with and without Lock-In to HF gas absorption line at 1310.92nm

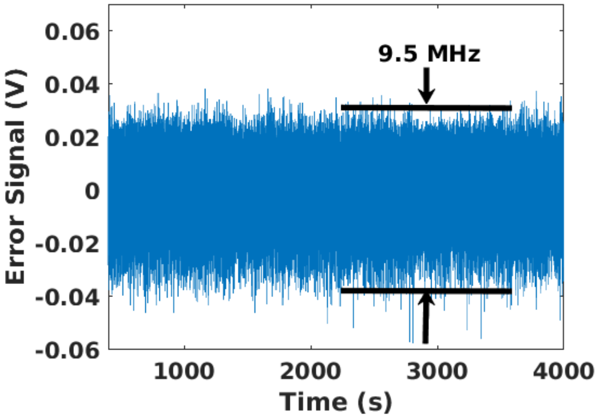

Fig. 5. Error signal for DFB-LD locked to HF 1310.92 nm absorption line over a period of 1h period

IV. CONCLUSION

We have proposed and designed an innovative laser wavelength lock-in technique which directly exploits one of the modulation signals applied to the interrogating laser in an EFFPI sensor. This technique works by wavelength modulation spectroscopy using a reference HF gas cell to result in an fiber interferometric sensor which has 10-fold improved performance in terms of linewidth and, in particular, long-term stability. This wavelength lock-in technique can be implemented directly into the current EFFPI sensor without affecting set-up or operating characteristics and will be exploited for dedicated geophysics applications requiring very high sensitivity and long-term stability to detect slow ground movements with minute amplitudes.

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REFERENCES

[1] S. W. Smith and W. V. de Lindt, "Strain adjustments associated with earthquakes in Southern California," Bull. Seismol. Soc. Am., vol. 59, no.4, pp. 1569-1589, 1969

[2] A. A. Tronin, "Remote sensing and earthquakes: A review," Phys. Chem. Earth, vol. 31, no. 4-9, pp. 138-142, 2006

[3] H. C. Seat et al., "A fiber Fabry-Perot interferometer for geophysics applications," Proc. IEEE Sensors 2015, pp. 1-4, Busan (S. Korea), 1-4 Nov 2015.

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[4] H. C. Seat, P. Chawah, M. Cattoen, A. Sourice, G. Plantier, F. Boudin, J. Chéry, C. Brunet, P. Bernard and M. Suleiman, "Dual-modulation fiber Fabry-Perot interferometer with double reflection for slowly-varying displacements," Opt. Lett., vol. 37, no. 14, pp. 2886-2888, 2012

[5] T. W. Hansch, B. Couillaud, "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity," Opt. Communications, vol. 35, no. 3, pp. 441-444, 1980

[6] R. Romero, F. Araújo, and L. Ferreira, "Absorption-line-locked fiber laser for gas-sensing applications," Appl. Opt., vol. 46, pp. 7900-7905, 2007

[7] W. Yin, W. Ma, S. Jia, "A novel control system for automatically locking a diode laser frequency to a selected gas absorption line," Meas. Sci. Technol., vol. 18, no. 5, pp 1447-1452, 2007

[8] G. J. Koch, “Automatic laser frequency locking to gas absorption lines,” Opt. Eng., vol. 42, no. 6, pp. 1690-1693, 2003

DOI : 10.1109/SENSORS43011.2019.8956756