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Nanometric sensing with laser feedback interferometry

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We demonstrate a nanometric sensor based on feedback interferometry in a DFB laser by using a measurement of either the optical frequency or laser voltage. We find that in an optimal range of optical feedback, the sensor operates reliably down to an extrapolated 12 nm; for the sensor demonstrated here at ~ 1550 nm, this provides a minimum detectible displacement of $\lambda/130$. © 2020 Optical Society of America

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Nanodisplacement sensors have been demonstrated based on a variety of physical effects and for a range of applications [1, 2]. The laser feedback interferometry (LFI) or self-mixing interferometry sensor [3, 4] we demonstrate is a noncontact sensor, and therefore we set aside discussion of most MEMS-based approaches. As for noncontact nanodisplacement sensors, there are a number of approaches, including those based on capacitance, eddy currents, and atomic-force microscopy [5, 6]. These approaches, while in some cases sensitive to atomic-scale displacements can be complex, costly, and sensitive to quite small displacement ranges (small dynamic range).

LFI is based on light, reflected back into the active region, which in turn affects the laser diode (LD) operation in a fashion dependent on the phase of the reflected light [7, 8]. LFI itself provides sensitivity at least on the scale of the emission wavelength λ , though below we show that the minimum detectible displacement (MDD) can be $\ll \lambda$.

A LD with optical feedback is generally known as an external-cavity semiconductor laser (ECL). Heuristically, when the target distance L is varied by ΔL , the properties of an ECL (frequency ν , linewidth, and threshold gain) undergo periodic variation, which is broadly understood on the basis of the Lang and Kobayashi (LK) equations [9]. The feedback-phase sensitivity of the LFI sensor depends on the change of frequency ν with L , which in turn is also manifested in the optical output power P_{PD} measured by a photodiode (PD) and change of carrier concentration measured by the LD terminal voltage V_{LD} (under constant injection current I).

We demonstrate LFI sensors enabling unprecedentedly high sensitivity providing a linear sawtooth dependence on L of the sensing parameter, here focusing on V_{LD} .

LFI has been exploited for imaging [10, 11], biomedical sensing [12] and measuring absolute distance [13, 14], displacement [15–17], reflective index [18], velocity [19, 20], and flow [21]. Recently, Keeley *et al.* [22] investigated the emission spectrum of a THz QCL by measuring ν and V_{LD} as functions of the displacement ΔL and showed that LFI can achieve a similar spectral resolution as Fourier-transform infrared spectroscopy.

LFI displacement sensors have been demonstrated usually using a moving target, *e.g.* a harmonic piezo-actuator or loudspeaker that sweeps several μm , combined with high sampling rates to measure fringes of the LFI signals. Their MDDs are from a few to hundreds of nm but require post-processing of the LFI signals and/or substantial modifications of the basic LFI setup [23–28], laser feedback grating (< 10 nm) [26], Fourier transform ($\lambda/50$) [27], phase shifting ($\lambda/12$) [28–30]. In contrast, our approach requires neither modification of the basic LFI setup nor any signal processing, but relies on the direct physical measurement of the LFI signals in parameter ranges leading to high linearity and signal-to-noise ratio (SNR). Specifically, we demonstrate a LFI sensor with a MDD of $\lambda/130$, assuming the feedback level can be adjusted in an optimal range. Since the LFI sensing mechanism is based on the feedback phase, such a sensor can also be used as a gas or liquid sensor using refractive index change. For the MDD and geometry we focus upon, this translates into the ability to sense refractive-index changes in the optical feedback loop of $\Delta n_{\min} \sim 10^{-8}$.

In this Letter, because of the key rôle played by ν in LFI, we start with its dependence on L before proceeding to focus on V_{LD} . We first review important theoretical points that describe the variation in ν and consequently in V_{LD} with L . The theory of LFI is discussed in Refs. [7, 31]. Briefly, the excess-phase equation derived from the LK model relates ΔL to $\Delta\nu = \nu - \nu_0$ as a periodic function where ν is the output frequency of the ECL and ν_0 is the frequency of the free-running LD (*i.e.*, in the absence of optical feedback). When ΔL changes, $\Delta\nu$ obeys $\Delta\nu(\Delta L) = mF(\Delta L)$ with m the optical-feedback modulation index that defines the signal slope with respect to ΔL , $F(\Delta L)$ a periodic function with period λ_0 where $\lambda_0 = c/\nu_0$ with c the speed of light *in vacuo*. Qualitatively, the dependence of ν on ΔL tends to be sinusoidal for weak feedback. The shape can become close to a piecewise linear function,

Fig. 1. Experimental setup. LD: laser diode, L: external-cavity length, TC: temperature controller, CS: current supply, CL: collimation lens, BS: beam splitter, LP: linear polarizer, QWP: quarter-wave plate, RM: reflecting mirror, LMS: linear motor stage, OI: optical isolator, MM: multimeter, FL: focusing lens and OSA: optical spectrum analyzer.

Fig. 2. $\Delta\nu$ (top) and V_{LD} (bottom) versus ΔL (in units of λ_0) from experiment. ΔL is characterized by movement away from the LD (40 nm/step). $L = 30$ cm, $J = 69$ mA, and $\nu_0 = 193281.8$ GHz. The signal gradually becomes a piecewise linear function known as a regular sawtooth for $0.003 < \eta < 0.01$, corresponding conventionally to moderate feedback level ($1 < C < 4.6$). In the curve for $\eta = 0.015$, it is visible that some fringes are skipped, which occurs in the strong feedback regime ($C > 4.6$).

also known as a sawtooth wave, at moderate feedback level with discontinuities due to mode hopping to a neighboring external-cavity mode (ECM) [3, 4] with period $\lambda/2$. Also, increasing feedback level results in greater amplitudes of $\Delta\nu$ over ΔL . To conclude the review of the excess-phase equation, we mention that the C parameter, defined e.g. in [4], is conventionally used to qualitatively classify the regimes from various self-mixing interferometry systems [4].

A schematic diagram is shown in Fig. 1. We use a single-longitudinal-mode multi-quantum well InGaAsP DFB laser [32]. The LD emits at $\lambda_0 \sim 1550$ nm with a free-running threshold current $J_{th} = 29.8$ mA. The LD is unpackaged providing direct access to the LD injection terminals. J and temperature are stabilized to an accuracy of 0.01 mA and 0.01 K. The light is split via a 50/50 beam splitter. The distance between the reflecting mirror (RM) and the LD determines L . RM is not diffusive, and the quarter-wave plate (QWP) is used to control the feedback with high precision. A reflection cancellation technique [33] can be applied for the measurements from diffuse surfaces. One optical path is adjusted for experimental feedback strength η and L . The other is used to observe the optical spectrum (10 MHz resolution, Aragon Photonics BOSA 200C). The RM is placed on a linear motor stage (LMS, Newport XMS50) whose position is adjusted by a driver (Newport XPS-RL2) with 40 nm/step, error $< \pm 10$ nm; this error limits our ability to determine the MDD. A motorized piezo-actuation stage adjusts the angle of QWP with 0.01° precision relative to the polarizer such that we can change η ; conventionally, the maximum $\eta = 1$ occurs when $\sim 18\%$ of the optical power is fed back onto the emitting facet of the LD. V_{LD} is directly measured by a multimeter (Agilent 34410A) with 5 1/2 digit-resolution and 0.003% accuracy.

We present our experimental results pertaining to nano-displacement sensing. $\Delta\nu$ is related to small variations ΔL based on the excess phase equation as discussed above. Working in the vicinity of $L = 30$ cm, we adjust $\Delta\nu$ by changing L in 40 nm steps using the LMS. Figure 2 shows $\Delta\nu$ and V_{LD} versus ΔL beginning at very weak η . For $\eta = 0.0005$, $\Delta\nu$ exhibits a noisy skewed sine-like behavior, corresponding conventionally to the weak feedback regime ($C < 1$). As η is increased, the dominant optical peak at ν is shifted down in frequency with respect to ν_0 and displays increasingly pronounced sawtooth behavior with discontinuity periods $\lambda/2$. When the linewidth of a single longitudinal mode extends over the external-cavity free-spectral range $f_{ECM} \simeq 460$ MHz, at very weak η (i.e., 0.0005 in Fig. 2), this leads to a smooth transition to a neighboring ECM. As η is increased, the linewidth of ECL is narrowed ($\ll 40$

Fig. 3. MDD determined by $\Delta\nu$ and V_{LD} and average discontinuity in $\Delta\nu$ as a function of η . The average RMSE (inset) displays the deviation of the differences between the best linear fit and measured values. Lower RMSE for $\eta > 0.01$ leads to MDD=12 nm.

MHz), thereby inducing abrupt discontinuities. When $\eta \geq 0.01$ (Fig. 2), the initial sawtooth periods for small ΔL are lost. This is because the single-mode laser dwells on one of several ECMs prior to jumping to another ECM [34]. Since the results in Fig. 2 are obtained by moving the target away from the LD, the slopes of the linear variations in $\Delta\nu$ are negative. The slopes are positive when the target moves closer to the LD and hysteresis is observed (not shown). Sine-like LFI signals correspond to weak feedback, sawtooth to moderate, and loss of sawtooth periods to strong feedback [4, 35].

As expected from the theory, we observe sawtooth behavior in $\Delta\nu$ as well as V_{LD} with periodic discontinuities separated by $\lambda/2$ in ΔL . Of note, the sawtooth behavior in $\Delta\nu$ is *not* around 0 (*i.e.*, the value in the absence of feedback) because ν is shifted as soon as η is applied. Larger η leads ν to be shifted further away from ν_0 [36]. Sawtooth behavior appears as long as the ECL shows continuous-wave (CW) operation. The ECL can be destabilized by complicated dynamics with undamped relaxation oscillations [37] at which point sawtooth behavior is suppressed.

It is useful to trace the impact of the experimental feedback strength η on ECM spectra. We make this analysis via the side-mode suppression ratio (SMSR), the ratio between the dominant mode and the largest neighboring ECM, which is typically f_{ECM} away in the optical spectrum [38]. We can thus track the transition from single-mode behavior to one where several ECMs are active around ν by considering the SMSR. The participation of more than one ECM will lead to more complicated dynamics, and consequently degrade LFI signals. We increase η from the weakest possible value and monitor the crossover from weak to moderate feedback. For weak feedback, the ECL emits on only one ECM, corresponding to CW operation, and SMSR $\gtrsim 35$ dB. For moderate feedback, the ECL still operates on one ECM for a given L , but the SMSR is slightly degraded ($25 \text{ dB} < \text{SMSR} < 35 \text{ dB}$), revealing the participation of several ECMs. As η is further increased, the number of ECMs increases and some periods of the sawtooth are lost [4]. SMSR appears to be a useful tool to determine the feedback range where sawtooth periods are observed.

We have concentrated attention on the behavior of $\Delta\nu$ as L is varied. ν and the carrier density are related since the effective refractive index and the threshold gain vary with optical feedback [16]. In turn, the variation of carrier density is manifested in V_{LD} [39], providing a more practical LMI signal than $\Delta\nu$.

We now optimize MDD. Our focus is on $\Delta\nu$; since $\Delta\nu$ is highly correlated with V_{LD} , optimal feedback conditions will also apply well to V_{LD} as the LFI signal. We measure the magnitude of the discontinuities in $\Delta\nu$ for various η . As shown in Fig. 3, increasing η , the average discontinuity is increased, and then stays around at $f_{ECM} \simeq 460$ MHz for which we observe clear sawtooth periods in $\Delta\nu$. It is also well-known that as an ECM is born through a feedback increase [3, 4], the distance from its closest neighbor increases with feedback strength until it reaches a value close to f_{ECM} .

Let G be the LFI signal measured (*e.g.*, $\Delta\nu$, ΔP_{PD} (change in photodiode output power), or ΔV_{LD} (change in the LD terminal voltage for the given J with respect to the case of $\eta = 0$). The ideal sensitivity is $dG/dL = s$ where s is the signal slope with respect to L (neglecting discontinuities in G). It is therefore advantageous to choose parameters to maximize $|s|$. Due, however, to unavoidable sensitivity error, MDD (ΔL_{min}) also depends on the error variations $n(L)$ in G . To find ΔL_{min} , we begin with G including $n(L)$, $G = sL + n(L)$. ΔL will produce a change ΔG in F given by

$$\Delta G = \frac{dG}{dL} \Delta L \approx s \Delta L + [n(L + \Delta L) - n(L)]. \quad (1)$$

This can be detected provided $\Delta L \gg \frac{1}{s} [n(L + \Delta L) - n(L)]$. This quantity on average is independent of L though it does depend on ΔL . We can simply identify the quantity in brackets on the right-hand side of the equation as a characteristic noise amplitude n_{avg} . Namely, suppose it is adequate to identify n_{avg} with the root-mean square error (RMSE) between experimental G and its best linear fit. We therefore approximate values for the MDD as $\Delta L_{min} = \frac{1}{s} n_{avg}$. This analysis is expected to be valid so long as the correlation length of $n(L)$ is less than the MDD. We find that when the discontinuity in ν is locked at $\sim f_{ECM}$, the linewidth of the ν gets narrower and highly linear behavior of $\Delta\nu$ between the discontinuities is observed, resulting in significantly reduced RMSE of ν (inset of Fig. 3). As shown in Fig. 3 ($0.015 < \eta < 0.02$), MDD obtained by ν is as small as 12 nm, which is very close to the experimentally limited resolution (10 nm) of the LMS, strongly suggesting that the LMS is itself a major limitation. Let us note that, some sensing applications require measurements in the longer displacement range and may benefit from a recently suggested

Fig. 4. ΔV_{LD} as a function of η . A certain range of $\Delta V_{LD} < 0$ is observed before jumping back to 0 for larger values of η . The double arrowed lines indicate the optimal η range for improved MDD. Higher J leads to longer intervals of η where $\Delta V_{LD} < 0$.

feedback phase retrieval algorithm, called Consecutive Samples based Unwrapping [40]. However, our focus in this work is to directly measure a minimum detectable displacement.

We have verified that Δv and ΔV_{LD} are highly correlated by programming the LMS to change its position with random step size in the range 40–500 nm. We find the correlation coefficient reaches ~ 0.96 when the discontinuity saturates at $\sim f_{ECM}$, i.e., when $0.01 < \eta < 0.02$ in Fig. 3. When no clear sawtooth in Δv is observed at very weak η (i.e., $\eta < 0.0005$ in Fig. 3), the correlation coefficient between Δv and ΔV_{LD} is reduced to ~ 0.88 . The lower correlation at weaker η , we suspect, is due to the broad linewidth of the ECL, which leads v and V_{LD} to be susceptible to noise.

To verify MDD based on V_{LD} , as an example at $L = 30$ cm, when Δv and ΔV_{LD} vary with ΔL , the slope dG/dL (i.e., dv/dL , dV_{LD}/dL) gives values of 1.2 MHz/nm and 0.25 μV /nm, which can be converted to $dV_{LD}/dv \approx 0.2 \mu V$ /MHz. With RMSE computed at various η for ΔL_{min} , we can derive MDD by ΔV_{LD} , enhanced close to MDD based on v when the discontinuity is $\sim f_{ECM}$. This observation indicates that ΔV_{LD} can be used to detect displacement on a par with Δv at a certain range of η .

As the next step, we find the optimal range of η minimizing MDD by ΔV_{LD} . As shown in Fig. 4, when η is increased, ΔV_{LD} typically decreases, plateaus, then increases. This negatively shifted plateau corresponds to where the discontinuity sticks at $\sim f_{ECM}$, for nano-displacement sensing. In addition, we can see that the plateau tends to broaden with increasing J because stronger η is required to render an ECL unstable [41]. Beyond the plateau, SMSR is significantly degraded to less than 25 dB, indicating that more than two ECMs are involved in the ECL dynamics. Thus, it is difficult to maintain a periodic sawtooth. Of note, the procedure for determining the optimal η range does not require any movement of the target.

Optimal L is now considered. Assuming ΔL will be at most a few λ , what is critical is that f_{ECM} does not become so small that more than one ECM contributes to the emission at η required to keep the discontinuity of v at $\sim f_{ECM}$. Once more than one ECM begins to participate, the ECL becomes more susceptible to noise and begins to exhibit complex dynamics related to undamped relaxation oscillations. To understand how this affects sensor performance, we vary L by 10 cm increments and find that when $L \geq 60$ cm, the ECL tends to lose stability for LFI even with a very low η resulting in $SMSR < 25$ dB and frequent mode hopping. Thus, combined with the observation that larger J enables sawtooth behavior for a broader range of η , sawtooth behavior in Δv and ΔV_{LD} can be maintained when $J \gtrsim 1.5J_{th}$ and $L < 60$ cm; however, the details will depend on λ and other LD parameters.

To check the robustness of the results, we conducted experiments using an ECL based on a packaged DFB laser to monitor ΔP_{PD} using the internal PD. The LFI signals were found to have no significant difference between ΔP_{PD} and ΔV_{LD} . The previous observations are dependent on the characteristics of our multimeter, whose noise floor likely limits the accuracy of the measurement. Other authors have concluded that signals obtained by internal PDs have slightly better SNR than those from ΔV_{LD} [16, 42, 43]; however, we did not observe the negative shifted behavior in P_{PD} with increasing η unlike ΔV_{LD} as shown in Fig. 4. Under conditions where ΔP_{PD} and ΔV_{LD} are affected by independent noise sources, ΔV_{LD} can be used to calibrate optimal η when it is negative. Thus, it seems reasonable to use ΔV_{LD} when an internal PD is not available because ΔV_{LD} provides a direct measurement and eliminates noise due to optical-to-electrical conversion for the PD. Additionally, P_{PD} can be affected by stray light [39].

As the physical basis of LFI sensing is the sensitivity of the ECL operation to changes in optical phase, the change of refractive index within the external cavity due to a transparent gas or a liquid can be sensed with the LFI technique. To translate the results to this domain, suppose we wish to determine the minimum detectable refractive index change (MDRIC) Δn_{min} associated with the minimum relevant feedback-phase change $\Delta \phi_{min}$. We have $\Delta \phi_{min} = 4\pi L \Delta n_{min} / \lambda$ or $\Delta n_{min} = \frac{\lambda \Delta \phi_{min}}{4\pi L}$. For conventional interferometry, $\Delta \phi_{min} \sim \pi/2$, and so for our parameters ($L = 30$ cm, $\lambda = 1550$ nm), $\Delta n_{min} = 6.5 \times 10^{-7}$. For LFI, however, $\Delta \phi_{min}$ is determined by the MDD as $\Delta \phi_{min} = \frac{4\pi(MDD)}{\lambda}$, which for our parameters is $4\pi/130$. This gives $\Delta n_{min} = 4.0 \times 10^{-8}$, a 16-times improvement over the sensitivity of conventional interferometry. This is also to be compared with the performance observed in Ref. [18] where MDRIC of $\Delta n_{min} = 2.0 \times 10^{-5}$ was reported.

To conclude, we have experimentally investigated an LFI sensor based on an ECL. By selecting the operating regime with highest correlation and linearity between Δv and ΔV_{LD} , we obtain an extrapolated MDD of 12 nm or $\lambda/130$, a record for a sensor making a direct use of the native LFI signal. MDD of 12 nm is likely due to limitations of our piezo-actuator with a precision of 10 nm and the multimeter resolution used to make V_{LD} measurements.

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