Adaptive self-mixing vibrometer based on a liquid lens

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A self-mixing laser diode vibrometer including an adaptive optical element in the form of a liquid lens (LL) has been implemented and its benefits demonstrated. The LL arrangement is able to control the feedback level of the self-mixing phenomenon, keeping it in the moderate feedback regime, particularly suitable for displacement measurements. This control capability has enabled a remarkable increase in the sensor-to-target distance range where measurements are feasible. Target vibration signal reconstructions present a maximum error of $\lambda/16$ as compared with a commercial sensor, thus providing an improved working range of 6.5 cm to 265 cm. © 2010 Optical Society of America

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The self-mixing (SM) phenomenon in laser diodes (LDs) has been extensively researched during the past decades, notably for displacement sensing [1,2]. The behavior of a laser operating as a SM vibrometer can be depicted through a phase equation presenting different regimes for increasing optical feedback levels [3] described by C, a feedback coupling factor varying in particular with the linewidth enhancement factor α, the feedback level, and D_0 the sensor-to-target distance [2].

Displacement measurements are generally performed in the moderate feedback regime (corresponding to $C>1$) [2]. The signal is then characterized by hysteresis and even fringe loss—caused by variations of C with D_0 and/or the feedback level [4]—that may result in a decrease in accuracy. However, the marked slope of the fringes indicates the direction of motion of the external reflector. An efficient method has previously been proposed that keeps the operating point of the SM interferometer fixed at the half-fringe value [2]. As a consequence, there is no influence of fringe loss, thus avoiding sophisticated signal processing. However, this approach requires an objective lens that collimates the LD beam onto a second focusing lens placed at a distance of 40 cm in order to project the LD beam spot on the target. In addition, an optical attenuator has to be inserted in the optical path to prevent the optical feedback from becoming excessive. Furthermore, the absolute distance to the target D_0 has to be measured at the beginning of each measuring session.

The approach we are proposing consists in replacing the second focusing lens and the optical attenuator by the use of adaptive optics (AO) in the shape of a liquid lens (LL) (Fig. 1). AO was originally used in large telescopes for compensation of atmospheric turbulence effects, but applications for the enhancement of optical sensors [5] have been developed in the past few years using a number of active optical elements, from deformable mirrors to LLs or LCDs. In our setup, an ARCTIC 416SL V3 liquid lens from Varioptic has been used. In this lens the curvature of the interface between two immiscible liquids of different refractive indices is controlled using an external voltage [6]. The LL has an optical power ($1/f_{LL}$) variation of −12 dioptre to 18.75 D, corresponding to a voltage variation of 30 V to 60 V, where f_{LL} is the focal length of the liquid lens. The LL holding assembly, containing the collimation lens (CL) and the LL, is placed in front of the LD (a Hitachi HL7851G LD with a maximum output power of 50 mW, emitting at $\lambda=785$ nm, where λ is the LD emission wavelength). The LL focuses the laser beam onto an oscillating target, which is at a distance D_0 from the LD. The target is the P-753.2 CD piezoelectric transducer (PZT) from Physik Instrumente, equipped with an integrated capacitive sensor for direct-motion metrology having an accuracy of 2 nm. The CL having a focal length $f_1=5$ mm, placed at the distance of $d_1=6$ mm from the LD, concentrates the strongly divergent laser beam onto the LL, placed at a distance $d_{CL}=18$ mm. Such an optical arrangement combines near-distance focusing capabilities with an extended range of focused distances. The f_{LL} can be changed through the LL

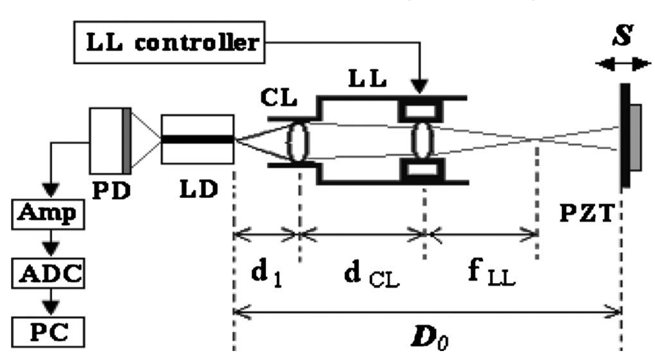

Fig. 1. Schematic diagram of the experimental setup for the adaptive self-mixing vibrometer.

controller. The built-in monitor photodiode (PD) is used to retrieve the variations in the optical output power (OOP) of the LD (i.e., the SM signal). The OOP signal is then amplified, digitalized and, at present, processed on a computer (PC). The whole optical setup stands on an optical table such that D_0 can have a maximum value of 265 cm (limited by the optical table) and a minimum value of 5 cm (taking into account the LL assembly plus a minimum focusing distance of 2.5 cm).

The effects of such a setup on feedback level control as well as on the extension of the range of D_0 values have then been analyzed.

For varying focus and at a fixed D_0 of 78 cm, moderate feedback regime SM signals obtained with this setup are presented in Fig. 2. The PZT has been excited with a simple harmonic motion of peak to peak amplitude S of 4.25 μm at a frequency of 100 Hz. For this amplitude S, the number of fringes N of the SM signal in every half period of target oscillation should then be 11 [$N=\text{round}(2S/\lambda)$], as each fringe represents a displacement of $\lambda/2$. Now, when the laser beam is focused, the signal exhibits a large hysteresis as well as three lost fringes [Fig. 2(a)]. Then, when the LL is used to defocus the beam, the SM signal regains one lost fringe and has comparatively less hysteresis [Fig. 2(b)]. The same happens for Fig. 2(c), showing ten fringes. Further defocusing results in a moderate SM signal without fringe-loss [Fig. 2(d)]. So, N has been varied here from eight to the correct value of 11 by the use of the LL arrangement.

Thus, the varying defocusing modifies the feedback level that causes the fringe loss. Table 1 presents the direct influence of this fringe loss on the accuracy of the displacement or vibration measurement for each of the SM signals shown in Fig. 2. For the fringe counting method (FCM), each lost fringe causes an error of $\lambda/2$. Likewise, even sophisticated approaches, such as the phase-unwrapping method (PUM) [7], cannot completely recover the lost information. The PUM provides a better accuracy, as it unrolls the laser phase around each detected fringe to obtain a rough approximation of laser phase. The final phase, corresponding to the target movement, is then achieved by a joint estimation of C and α, based on an optimization process. The error results of the vibration maxima have been found by comparison with the integrated capacitive sensor results.

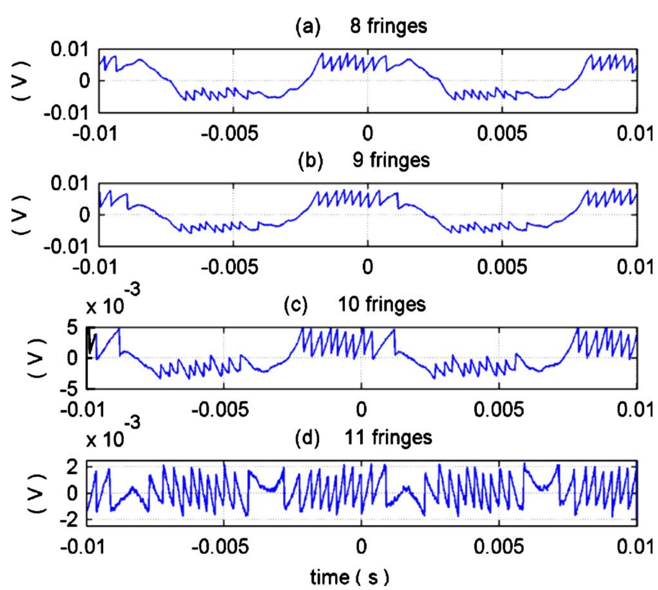

Fig. 2. (Color online) Experimental OOP signals in the moderate-feedback regime for a 785 nm FP LD with $D_0=78$ cm for varying focus.

Table 1. Influence of Fringe Loss on the Error at the Vibration Maxima in Reconstructed Vibration Signals as Compared with a Reference Sensor for SM Signals Obtained at $D_0=78$ cm with $S=4.25$ μm

No. of Fringes (N)	8	9	10	11
Error FCM (nm)	1110	718	325	68
Error PUM (nm)	180	116	48	32

The impact of fringe loss on the measurement error is easily seen. The use of the LL arrangement has thus successfully allowed us the control of the feedback level, leaving a reliable moderate regime SM signal at a given fixed distance [Fig. 2(d)].

The influence of a variation in D_0 on the SM signal has also been observed. A decrease in D_0 may reduce C [2]. This means that an SM LD sensor setup measuring a target vibration in the moderate-feedback regime may change to the weak-feedback regime (with quasi-sinusoidal fringes implying possible directional ambiguity) if D_0 is reduced [Fig. 3(a)]. Conversely, a large increase in D_0 while keeping all other operating conditions constant will cause a large increase in C, thereby resulting in fringe loss, and reduced accuracy as already described.

Thus, further usefulness of the LL-based setup is demonstrated by maintaining the SM phenomenon in the moderate regime with no fringe loss, even for a large variation in the value of D_0. Figures 3(b)–3(g) present such OOP signals acquired for a D_0 variation from 6.5 cm to 265 cm. The number of SM fringes has been kept constant ($N=9$) for $S=3.6$ μm. To distinguish the moderate regime from the weak regime, an algorithm was used [8]. Although this algorithm can successfully treat the weak regime signals, it requires additional signal processing due to quasi-sinusoidal shape of the fringes, which was avoided by using the LL.

Based on these moderate SM signals, vibration reconstructions for all of indicated distances have been performed. Figure 4 shows the reconstructed vibration signal as compared with the reference capacitive sensor signal for the SM signal at $D_0=265$ cm of Fig. 3(g).

The error at the vibration signal maxima for the moderate SM signals in Figs. 3(b)–3(g) has been calculated and is presented in Table 2. The worst error value over the whole distance range ($D_0=6.5$ cm to $D_0=265$ cm) corresponds to about $\lambda/16$ for a 785 nm LD. Furthermore, the presented setup has also been used to measure triangular and square as well as arbitrary displacement signals (not presented here for brevity).

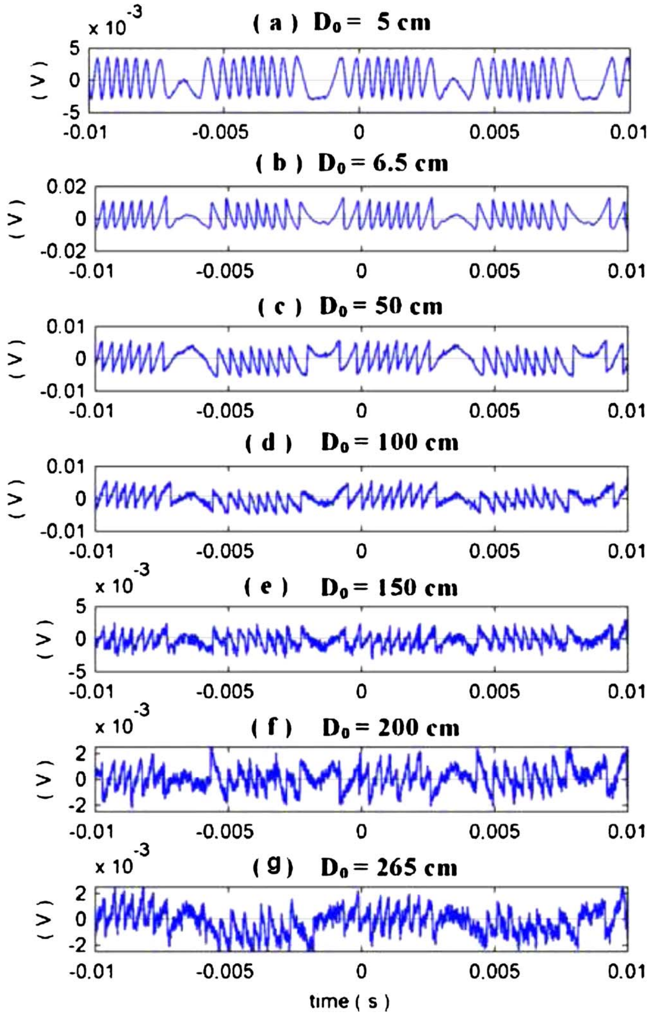

Fig. 3. (Color online) Experimental OOP signals for a variation in D_0 from 5 cm to 265 cm for a constant target vibration of 3.6 μm.

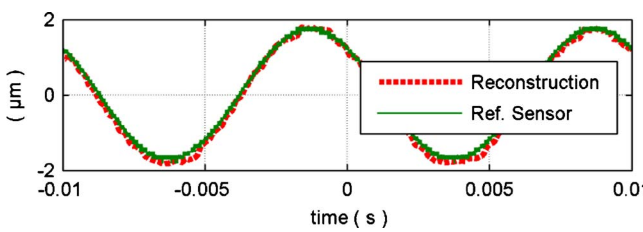

Fig. 4. (Color online) Vibration reconstruction for OOP signal at D_0=265 cm as compared with the reference sensor signal.

Table 2. Error at the Maxima of the Reconstructed Vibration Signals as Compared with a Reference Sensor, for a Given Distance D_0

Distance [cm]	6.5	50	100	150	200	265
Error PUM [nm]	44	23	20	45	32	36

Thus, we have demonstrated the interest of an adaptive optical element in the form of a voltage controlled LL for maintaining the self-mixing phenomenon in the moderate-feedback regime over a large range of sensor-to-target distance. We have also shown the capability of the presented vibrometer for changing the feedback level at fixed distances. The vibration measurements based on these signals as compared with a commercial sensor validate the usefulness of our AO for self-mixing applications. The future implementation of an automated LL-based setup shall result in a more accurate and autonomous self-mixing metrological sensor that will be able to measure with precision over a large sensor-to-target distance range.

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