

Article

Micro-Displacement Measurement Based on Dual Optical Feedback Self-Mixing Interference

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Abstract

Laser self-mixing interference (SMI) with dual external-cavity optical feedback exhibits a distinct characteristic: a change in the length of one external cavity periodically modulates the amplitude of the SMI signal produced by the other external cavity. Based on this characteristic, a micro-displacement measurement method is proposed, in which one feedback channel serves as the measurement channel and the external cavity length change is deduced from the amplitude of its SMI signal modulated by the other channel. Because the displacement information is encoded in the signal amplitude rather than only in the fringe phase, the method does not require phase unwrapping and therefore avoids the fringe-order ambiguity inherent in phase-based SMI displacement retrieval, while the amplitude readout is also less sensitive to intensity noise. A dual optical feedback SMI micro-displacement measurement system is constructed with a He-Ne laser (working wavelength 632.8 nm), a piezoelectric ceramic transducer (PZT), and a rotatable optical flat crystal. The displacement curve of the PZT moving platform is reconstructed from the measured SMI signals, and the change in the external cavity length induced by the rotation of the flat crystal is measured as well. The experimental results show that the measurement errors are 13.4–17.8 nm for the PZT feedback channel and 19.2–24.1 nm for the flat crystal feedback channel, both below 25 nm, demonstrating that the proposed method is a promising candidate for high-precision micro-displacement measurement.

Keywords: laser self-mixing interference; dual optical feedback; micro-displacement measurement; amplitude encoding; signal-to-noise ratio

1. Introduction

Self-mixing interference (SMI) refers to the phenomenon in which a small fraction of the light emitted by a laser is backscattered or reflected by an external target and re-enters the laser active cavity, where it mixes coherently with the intracavity field and modulates the output power of the laser [1–3]. In contrast to conventional interferometry, which requires a separate reference arm and an external photodetector, SMI integrates the source, the interferometric path, and the detection into a single device, because the laser itself serves as both the emitter and the detector of the interference signal. This endows SMI with a compact and self-aligned configuration, low cost, and high phase sensitivity, and has made it one of the most practical laser-based coherent sensing techniques [4,5]. In the weak-feedback regime, where only a negligible fraction of the emitted power is fed back into the cavity, the output power of the laser varies sinusoidally with the phase of the



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feedback light, i.e., with the external cavity length, which forms the basis of SMI-based displacement measurement.

Owing to these advantages, SMI has been successfully applied to the measurement of a wide variety of physical quantities, such as displacement [6,7], absolute distance [8], velocity [9,10], rotational speed [11], synthetic-wavelength displacement [12], and high-accuracy phase-modulating displacement [13], as well as to the detection of micro-nano particles [14] and the measurement of human eye parameters [15]. In recent years, remarkable progress has been made in improving the accuracy and robustness of SMI-based displacement measurement. Amin implemented a Hilbert-transform-based high-resolution phase-unwrapping method on a field-programmable gate array for real-time displacement retrieval [16]. Huang et al. analyzed SMI signals with a Lissajous-figure convergence algorithm and measured vibration amplitudes from 1 mm to 4 mm with errors below 10 nm [17]. Li et al. proposed an end-to-end deep-learning network that reconstructs displacement directly from raw SMI signals with a relative error below 1% [18]. Albert et al. extended the theoretical analysis of SMI to stand-off distances of tens of meters and validated the theory experimentally on a diffusing target at a wavelength of 1550 nm [19], while Matha et al. demonstrated high-availability displacement sensing by processing three independent SMI signals with a small neural network [20]. These approaches have substantially improved the resolution and the robustness of SMI displacement retrieval, but they share the same working principle: the displacement is extracted from the phase of the interference fringes, either by counting fringes or by unwrapping the phase. This has two intrinsic consequences. First, the measurement becomes ambiguous whenever the fringe order or the direction of motion cannot be determined unambiguously, so that additional hardware or processing effort is needed to remove the ambiguity. Second, the achievable resolution is bounded by the phase noise of the fringes, so that a high signal-to-noise ratio (SNR) has to be maintained throughout the measurement.

Despite these advances, the performance of a conventional single-cavity SMI system is fundamentally limited by its signal-to-noise ratio (SNR). Because the interference fringes are generated by the weak fraction of light that leaks back into the cavity, the fringe visibility depends critically on the feedback level and deteriorates when the target reflectivity fluctuates or the external cavity is misaligned; once the fringes are degraded, the phase-based retrieval becomes unreliable. To alleviate this limitation, balanced detection [21], balanced SMI configurations [22], and native-signal detection schemes with sub-nanometer noise-equivalent displacement [23] have been investigated, and a generalized theoretical framework for SMI with multiple external cavities has recently been established [24]. These techniques, however, improve the quality of the fringes rather than change the physical quantity that carries the displacement information, which remains the fringe phase. Among these efforts, the use of dual optical feedback has proven particularly effective. Yáñez and Royo reported that the interference signal of one external cavity can be enhanced by changing the length of another external cavity coupled to the same laser [25]. Qi et al. experimentally observed differential SMI signals in a randomly polarized laser [26], and Song et al. reduced the noise of SMI measurements by combining dual optical feedback with polarization difference [27]. In such dual optical feedback SMI systems, the two external cavities are coupled through the laser cavity, so that a length change in one cavity periodically modulates the amplitude of the SMI signal of the other, which provides a new degree of freedom for signal enhancement and noise suppression. Nevertheless, in all of these dual-feedback schemes, the amplitude modulation induced by the coupled cavity was exploited only to enhance the SNR, and the displacement was still recovered from the fringe phase.

However, to the best of our knowledge, the amplitude modulation of a dual optical feedback SMI signal has not yet been exploited as the carrier of the displacement information itself, although it offers a distinct advantage for this task: the amplitude of the SMI signal of the measurement channel can be deliberately regulated by the reference channel, so that the displacement information is encoded in the signal amplitude rather than only in the fringe phase, and the periodic amplitude variation is converted into a unique cavity-length value by means of a known reference cavity length, so that phase unwrapping is no longer needed. In this paper, a micro-displacement measurement method based on dual optical feedback SMI is proposed and experimentally demonstrated. The main contributions of this work are threefold. First, the mechanism by which the length of one external cavity periodically modulates the amplitude of the SMI signal of the other is analyzed, and an amplitude-based displacement reconstruction algorithm, which includes a continuity-constrained fringe-order determination that removes the ambiguity caused by noise, is derived (Section 2.1). Second, a dual optical feedback SMI micro-displacement measurement system is constructed with a He-Ne laser, a piezoelectric ceramic transducer (PZT), and a rotatable optical flat crystal, and the measurement procedure is described (Sections 2.2 and 2.3). Third, the displacement of the PZT moving platform and the external cavity length change induced by rotating the flat crystal are measured with errors below 25 nm in both channels, and the dynamic range and the robustness of the method are discussed (Section 3).

2. Materials and Methods

2.1. Principle

The schematic diagram of the proposed dual optical feedback-based SMI system is shown in Figure 1. As the figure shows, M_1 and M_2 are the two inner cavity surfaces of a laser resonator whose cavity length is L_0 . The light emitted from the laser resonator is split into two beams, which are reflected by the external cavity surfaces M_3 and M_4 , respectively. The two beams are then fed back into the laser resonator and interfere with the light inside it, so that the output power of the laser is modulated. This phenomenon is referred to as dual optical feedback SMI.

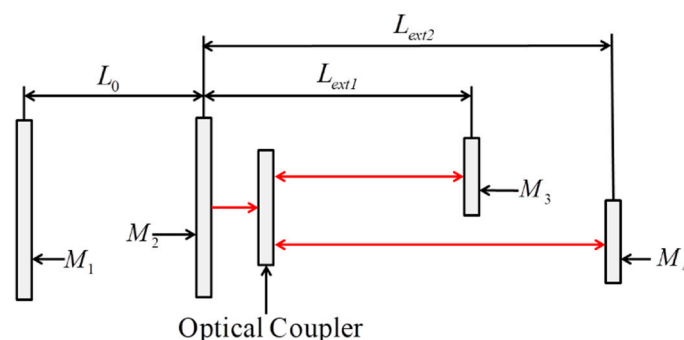


Figure 1. Schematic diagram of the dual optical feedback SMI system [27].

In the context of SMI, the intensity of the reflected light is also known as the strength of feedback. When SMI occurs, the resulting output power of the laser is dependent on the strength of the feedback, which is commonly classified by the feedback parameter C into the weak, moderate and strong feedback regimes [28,29]. In the weak-feedback regime ($C \ll 1$), the laser remains single-mode and stable, and the output power varies sinusoidally in time, whereas moderate or strong feedback produces sawtooth-like fringes, hysteresis and multi-stability that invalidate the sinusoidal description. Throughout this work the

system is operated in the weak-feedback regime, so that the output power of the laser can be expressed as [25,27]:

$$p_1 \approx p_0 [1 + \eta_1 \zeta_1 \cos(\frac{4\pi L_{ext1}}{\lambda})] \times [1 + \eta_2 \zeta_2 \cos(\frac{4\pi L_{ext2}}{\lambda})] \quad (1)$$

where p_0 is the original power of the laser, L_0 is the inner cavity length of the laser (length of the resonator), L_{ext1} and L_{ext2} represent the lengths of the first and the second external cavities, respectively, λ is the working wavelength of the laser, η_1 and η_2 are the split ratios, and ζ_1 and ζ_2 are the power modulation coefficients of the laser. Specifically, $\zeta_1 = 2r_3(1 - |r_2|^2)/r_2 \ln(r_1 r_2)$ and $\zeta_2 = 2r_4(1 - |r_2|^2)/r_2 \ln(r_1 r_2)$, where r_1 and r_2 are the reflection coefficients of the two inner cavity surfaces, M_1 and M_2 , of the laser resonator, respectively, and r_3 and r_4 are the reflection coefficients of the two feedback external cavity surfaces, M_3 and M_4 , outside the laser, respectively.

According to Equation (1), the SMI signal of one external cavity depends on the lengths of both external cavities; in other words, a length change of one external cavity also affects the SMI signal of the other cavity. In the following, the length change of the first cavity is used to regulate the amplitude of the SMI signal generated by the second feedback external cavity. Denoting the length of the first external cavity by L'_{ext1} , Equation (1) can be rewritten as:

$$p_2 \approx p_0 [1 + \eta_1 \zeta_1 \cos(\frac{4\pi L'_{ext1}}{\lambda})] \times [1 + \eta_2 \zeta_2 \cos(\frac{4\pi L_{ext2}}{\lambda})]. \quad (2)$$

Dividing Equation (1) by Equation (2), we obtain

$$p_1/p_2 \approx [1 + \eta_1 \zeta_1 \cos(\frac{4\pi L_{ext1}}{\lambda})] / [1 + \eta_1 \zeta_1 \cos(\frac{4\pi L'_{ext1}}{\lambda})]. \quad (3)$$

According to Equation (3), η_1 , η_2 , ζ_1 , ζ_2 , and λ are intrinsic constants that are determined by the laser and by the optical system, and they do not depend on the length of either external cavity. The first external cavity length (the reference external cavity length) L_{ext1} is adopted as a known condition in the calculation. The signal intensities p_1 and p_2 of the dual optical feedback self-mixing interference signal are acquired experimentally, so that the relative value L''_{ext1} of the first cavity length L'_{ext1} can be derived from their ratio p_1/p_2 . Two approximations are made in the derivation of Equation (3). First, only the fundamental component of the interference signal is retained, and higher-order harmonic terms are neglected. Second, the cross-coupling terms, i.e., the field components that leave one external cavity, are reflected by the surface associated with the other external cavity and then return to the laser, are treated as small perturbations. Under the weak-feedback regime, the amplitudes of these terms are much smaller than that of the fundamental component, so they act as small perturbations and have negligible effects on p_1 and p_2 ; these terms are therefore neglected in the derivation [28,29]. As the cosine function in Equation (3) is periodic, the value of L''_{ext1} is not unique. Here, the reference value L_{ext1} is used to determine the number of cycles k , with which the value of L'_{ext1} can be obtained. Assuming that $\frac{4\pi L_{ext1}}{\lambda} = \frac{4\pi L''_{ext1}}{\lambda} + 2k\pi$, we have

$$L_{ext1} = \frac{k\lambda}{2} + L''_{ext1}. \quad (4)$$

By substituting the reference value L_{ext1} and L''_{ext1} into Equation (4) and rounding the result, we obtain k . Because the cosine function in Equation (3) is many-valued, k is not uniquely determined by a single measurement: when noise drives the fractional part of Equation (4) close to 0.5, straightforward rounding may produce a spurious jump of the

fringe order. To overcome this problem, a continuity-constrained anti-jump algorithm is adopted. Displacement is a slowly varying and continuous physical quantity; therefore, the fringe order k cannot abruptly change between adjacent sampling instants. This is the same continuity assumption on which classical phase-unwrapping algorithms rely [30,31]. The algorithm compares the candidate k of the current sample with the historical k sequence obtained from the preceding sampling points: a jump of the candidate value with respect to the historical sequence is identified as a noise-induced misjudgment, and k is forced to preserve continuity. This constraint suppresses fringe-order jumps caused by phase jitter and amplitude fluctuation and thereby improves the robustness of the integer k estimation. Moreover, the actual length of the first cavity can be derived through $L'_{ext1} = L''_{ext1} + \frac{k\lambda}{2}$, where the difference between L'_{ext1} and L_{ext1} gives the change in the external cavity length.

2.2. Experimental Setup

We validate the proposed method in micro-displacement measurement, and the schematic diagram of the measurement system is shown in Figure 2. A bidirectional 0.3 mW He-Ne laser (inner cavity length 15 cm, working wavelength 632.8 nm) manufactured by Nanjing Laichuang is used as the light source. The distances between the He-Ne laser and the two feedback mirrors are 50 cm and 20 cm, respectively. The He-Ne laser outputs a well-collimated beam. Within the selected range of cavity lengths, the beam divergence effect can be neglected. Slight beam expansion reduces the optical feedback strength, but it will not affect the measurement accuracy as long as the system operates under the weak-feedback regime. We use a PZT (PI P-621.1CD) to induce the change in the length of one external cavity. The PZT was fully calibrated at the PI factory using a laser interferometer under standard constant-temperature conditions. Equipped with an integrated capacitive position sensor, the stage forms a closed-loop system with its digital controller, and the Digital Dynamic Linearization (DDL) algorithm is implemented to compensate for the nonlinearity of the piezoelectric actuator. The stage has a full travel range of 100 μm with typical closed-loop linearity error of 0.02% FS and repeatability of ± 1 nm. The expanded uncertainty of displacement measurement is 20 nm ($k = 2$). Calibration parameters are pre-stored in the digital controller. We also use an optical parallel flat crystal (Daheng GCL-13, refractive index 1.5163, thickness 20 mm, diameter 50 mm, parallelism 30'') to induce the change in the length of the other external cavity. The optical parallel flat crystal is fixed on the rotating platform (Zolix TBRK100) and driven by a stepping motor with a minimum resolution of 0.0003125 degrees. The attenuation coefficients of the two attenuation plates are 0.3 and 0.7, respectively. The reflectivity of the two mirrors is greater than 92%. To measure the laser intensity, we use a photodiode (Hamamatsu S7686). The reflectivity-to-transmittance ratio of the non-polarizing beam splitter (NPBS) is 1:1, and the NPBS provides nearly identical transmittance and reflectance for different polarization states, so that the splitting ratios of the two feedback channels are almost independent of the state of polarization. The optical paths of the two channels are separated by the NPBS. The residual reflected light from channel 2 is greatly attenuated before entering channel 1. With the present experimental setup, the secondary modulation effect introduced by channel 2 is weak and negligible. The self-customized signal processing circuit converts the photocurrent detected by the photodiode into voltage, and the measured SNR of the detection circuit is 50 dB. The resulting electrical signal is fed to the data acquisition board (National Instruments, PCI 6220, maximum sampling rate 250 k samples/s, the time interval between adjacent sampling points is 4 μs).

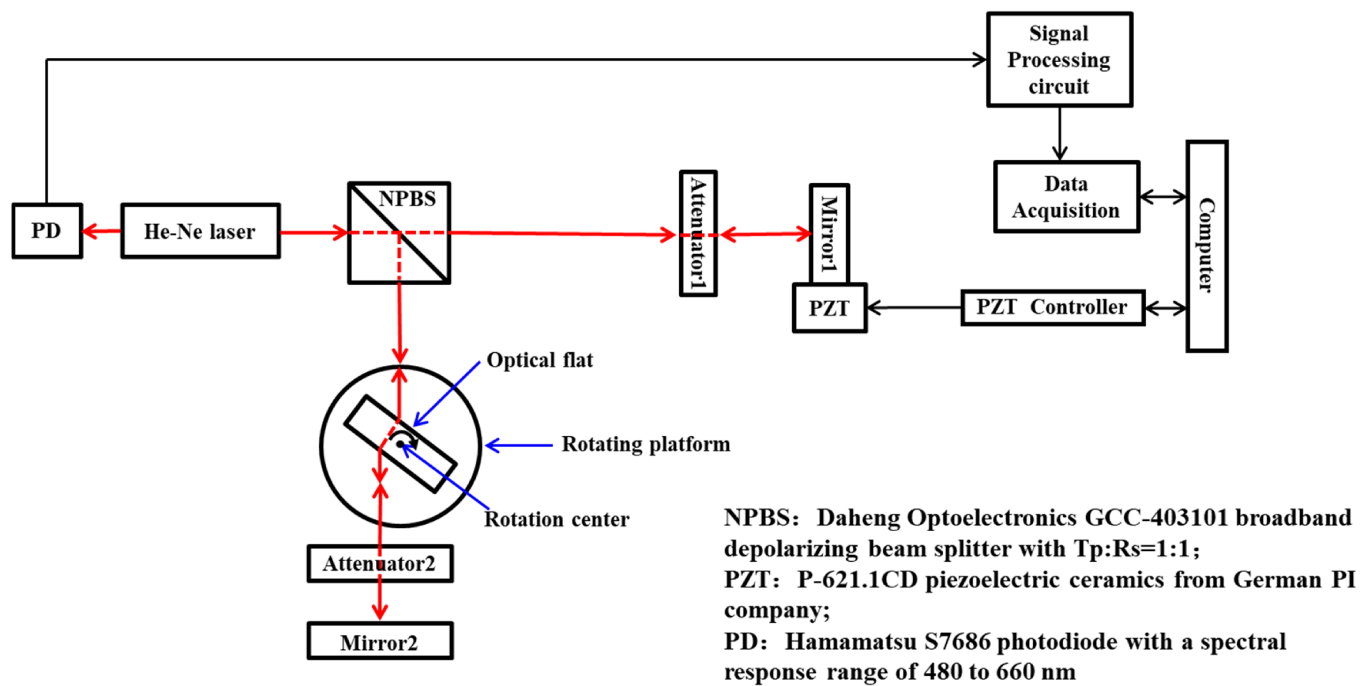


Figure 2. Dual optical feedback SMI micro-displacement measurement system.

To guarantee the stability that nanometer-scale measurements require, the whole optical system was mounted on a vibration-isolated optical table, and the experiment was carried out in a temperature-stabilized and quiet laboratory. The He-Ne laser was warmed up for 60 min before each measurement, so that its thermal drift was negligible over the duration of a scan, and the external-cavity optical paths were enclosed with an acrylic cover to suppress air turbulence. With these measures, the residual drift of the whole system during one measurement remained well below the measurement errors reported in Section 3. The rotation of the optical flat crystal may also slightly modify the polarization state of the feedback beam and hence the amplitude of the SMI signal. In the present configuration this contribution is weak, because the NPBS provides nearly identical transmittance and reflectance for different polarization states and because the total angular range employed here is well below 1 mrad; its effect on the reconstructed displacement is therefore small compared with the errors reported in Section 3.

As Figure 2 shows, the light emitted from the forward output end of the laser is vertically incident on the NPBS and divided into the reflected beam and the transmitted beam. After passing through the attenuation plate 1, the transmitted beam is vertically incident on the mirror on the PZT, and then reflected into the laser cavity to produce the first optical feedback channel. Meanwhile, the reflected beam is incident on the optical flat crystal, then passes through attenuation plate 2, and is finally incident on the fixed mirror vertically. The resulting beam is reflected into the laser cavity and produces the second optical feedback channel. The length of external cavity 1 can be changed by the PZT, whereas the length of the external cavity 2 can be changed by the rotation of the optical flat [32]. As such, phase modulation of the SMI signal is achieved. At the backward leakage end of the laser resonator, the modulated SMI signal is collected by the PD. Zero-phase low-pass filtering is first applied to suppress high-frequency noise. Then, a Hilbert-transform-based envelope detection algorithm is used to acquire the slowly varying amplitude, and p_1 and p_2 are extracted from the envelope curve. Denoising techniques developed specifically for SMI signals, such as the improved wavelet threshold method and the Savitzky–Golay filter, can further improve the reliability of the amplitude extraction [33,34]. The collected SMI signal carries the position information of the PZT.

According to the relationship between the amplitude of the interference signal and the position of the PZT, the micro-displacement of the PZT can be measured.

2.3. Measurement Procedure

We set the position of PZT to 50.20 μm , 50.15 μm , 50.35 μm , 50.55 μm , 50.75 μm , 50.95 μm , and 51.15 μm , respectively, where 50.20 μm serves as the reference. It should be emphasized that 50.20 μm is not a theoretical zero-offset point of the system; it is an operating point selected empirically in the range where the setup operates in the weak-feedback regime with a high fringe contrast, so that the amplitude of the SMI signal varies smoothly and reproducibly with the external cavity length. The resulting SMI signals detected by the PD are shown in Figure 3a–g. To ensure the linear change in the cavity length by the rotation of the flat crystal, the rotation range of the rotating platform is set within the linear region, that is 26 degrees in the experiment. The step size of rotation (single rotation angle) is 0.0003125 degrees. It takes 210 steps to accomplish the whole rotation process.

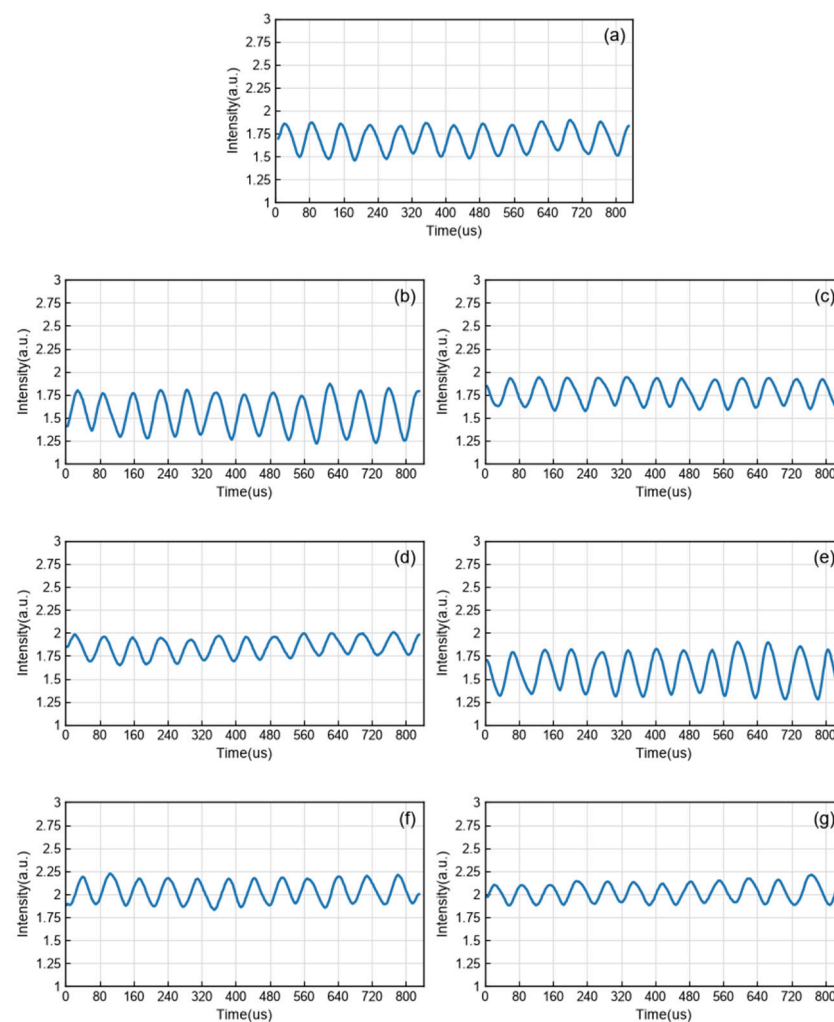


Figure 3. Dual optical feedback SMI signal: (a) $L_{ext1} = 50.20 \mu\text{m}$, (b) $L_{ext1} = 50.15 \mu\text{m}$, (c) $L_{ext1} = 50.35 \mu\text{m}$, (d) $L_{ext1} = 50.55 \mu\text{m}$, (e) $L_{ext1} = 50.75 \mu\text{m}$, (f) $L_{ext1} = 50.95 \mu\text{m}$, and (g) $L_{ext1} = 51.15 \mu\text{m}$.

3. Results and Discussion

In this section, the SMI signals measured at different external cavity lengths are first analyzed, and then the displacement reconstruction results of the two feedback channels are presented and discussed.

The resulting feedback SMI signals for different L_{ext1} are shown in Figure 3. It can be seen that when the external cavity length is 50.15 μm or 50.75 μm , the signal amplitude is slightly larger than that of the reference signal (Figure 3a). On the contrary, when the external cavity length is 50.55 μm or 51.15 μm , the signal amplitude is slightly smaller than that of the reference signal. Interestingly, when the external cavity length is 50.35 μm or 50.95 μm , the signal amplitude is almost the same as that of the reference signal.

The flowchart of the micro-displacement measurement performed by the system is shown in Figure 4.

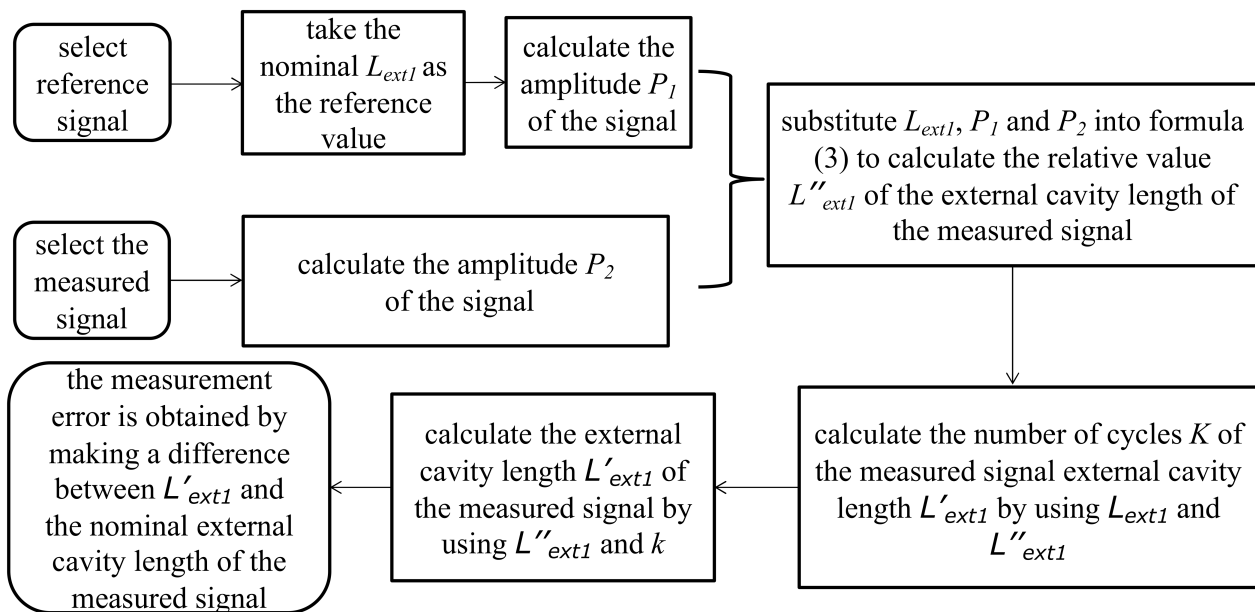


Figure 4. Flowchart of the dual optical feedback SMI micro-displacement measurement.

The measured external cavity lengths of the PZT feedback channel are listed in Table 1.

Table 1. Measurement results of the external cavity length of the PZT feedback channel.

Nominal Position of PZT/ μm	50.15	50.35	50.55	50.75	50.95	51.15
Measured position of PZT/ μm	50.1678	50.3634	50.5341	50.7338	50.9356	51.1355
Measurement error/nm	17.8	13.4	15.9	16.2	14.4	14.5

The displacement curve of the PZT moving platform of the first feedback channel, obtained from the data in Table 1, is shown in Figure 5. In Figure 5, curve 2 is the nominal displacement line of the PZT moving platform, and curve 1 is the displacement line of the PZT moving platform measured by dual optical feedback self-mixing interferometry. It can be seen from Table 1 and Figure 5 that the displacement line of the PZT moving platform measured by dual optical feedback self-mixing interferometry coincides with the nominal displacement line of the PZT moving platform, and that the measurement error ranges from 13.4 to 17.8 nm, indicating that this method can be used for the measurement of micro-displacement. It is worth noting that this error is comparable to the 20 nm expanded uncertainty ($k = 2$) of the capacitive position sensor integrated in the PZT stage that provides the reference, so that the residual error of this channel is dominated by the metrological limit

of the reference rather than by the SMI reconstruction itself. The lower measurement limit of the system is determined by the noise floor. Corresponding to the signal-to-noise ratio of 50 dB in this experiment, the noise-limited lower limit of displacement measurement is approximately 8 nm. The upper measurement limit is constrained by the valid interference fringe range under the weak-feedback regime. An excessively large displacement will cause severe distortion of the SMI signal and destroy the sinusoidal approximation as well as the linear relationship of amplitude coding. With the linear fringes well preserved, the measurable upper displacement limit of the system is $\pm 8 \mu\text{m}$. Thus, the effective dynamic range of this method ranges from 8 nm to $\pm 8 \mu\text{m}$.

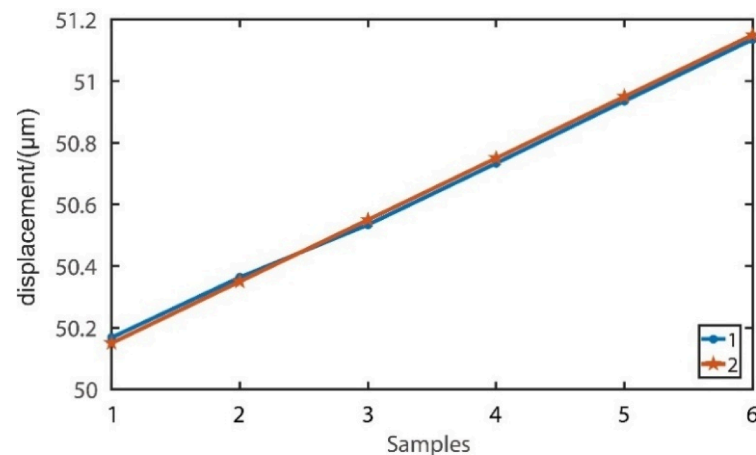


Figure 5. Displacement curve of the PZT moving platform.

The resolution limit imposed by the detection noise deserves a more explicit discussion. For the SMI signal obtained at the reference operating point, the SNR of the detection circuit was measured to be 50 dB. Since the displacement is retrieved from the ratio of the two signal amplitudes, the relevant quantity is the noise of the amplitude estimate rather than the noise of the raw trace, and the combination of zero-phase low-pass filtering and Hilbert-transform envelope detection reduces the amplitude noise by more than an order of magnitude with respect to the raw signal. This is the reason why the measured errors (13.4–24.1 nm) are close to, but not limited by, the noise-limited resolution of about 8 nm estimated from the 50 dB SNR: the accuracy of the present experiments is set by the reference cavity length and by the positioning accuracy of the rotation stage, whereas a further reduction in the detector noise, for example by balanced detection or by a lower-noise transimpedance stage, would translate directly into a lower displacement resolution.

To further demonstrate the proposed method, the PZT driver is used to control the PZT moving platform to perform nanometer translation. The rotating platform is controlled to drive the rotation of the optical flat crystal, which changes the external cavity length of the second optical feedback channel and thereby regulates the amplitude of the SMI signal of the first optical feedback channel through the second (flat crystal) feedback channel. When the laser is perpendicular to the first outer surface of the optical flat crystal, the rotation angle θ of the rotating platform is marked as 0 rad. When θ is 0.45411285 rad, 0.45405831 rad, 0.45416740 rad, 0.45427648 rad, 0.45438556 rad, 0.45449465 rad, and 0.45460373 rad, respectively, PZT performs translational scanning to obtain the modulated self-mixing interference signal, as shown in Figure 6a–g. The scanning starting point and end point of the PZT are 0 μm and 10.5 μm , respectively. The modulation scanning translation is accomplished through 210 single movements of 50 nm each. The PZT-modulated interference signal in the second optical feedback (flat crystal feedback) channel $\theta = 0.45411285$ rad is taken as the reference signal, as shown in Figure 6a.

When $\theta = 0.45405831$ rad and $\theta = 0.45438556$ rad, the signal amplitude is slightly larger than that of the reference signal. On the contrary, when $\theta = 0.45416740$ rad and $\theta = 0.45460373$ rad, the signal amplitude is slightly smaller than that of the reference signal. When $\theta = 0.45427648$ rad and $\theta = 0.45449465$ rad, the signal amplitude is almost the same as that of the reference signal.

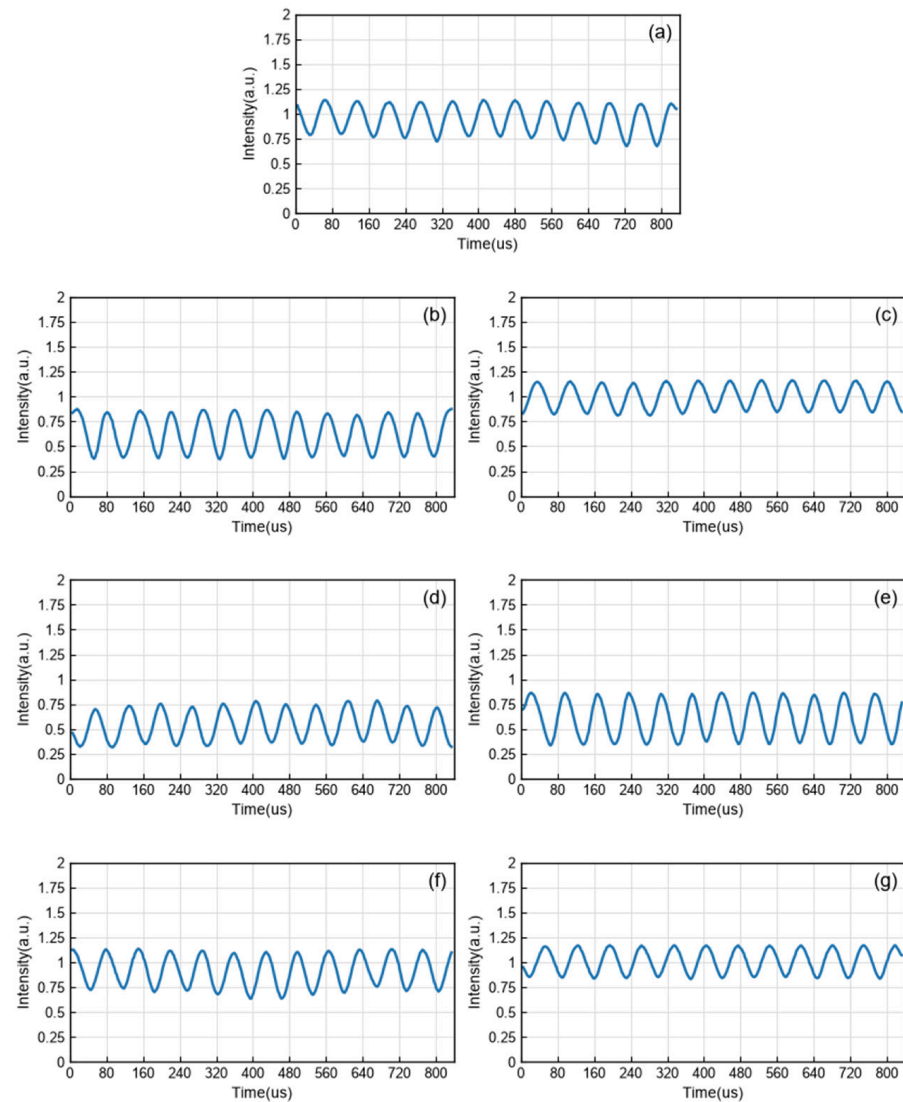


Figure 6. Dual optical feedback SMI signal: (a) $\theta = 0.45411285$ rad, (b) $\theta = 0.45405831$ rad, (c) $\theta = 0.45416740$ rad, (d) $\theta = 0.45427648$ rad, (e) $\theta = 0.45438556$ rad, (f) $\theta = 0.45449465$ rad, and (g) $\theta = 0.45460373$ rad.

The relationship between the rotation angle θ of the rotating platform (flat crystal) and the optical path change (external cavity length) of the second optical feedback channel is as follows [32]:

$$\Delta L = \frac{n_2 d}{\sqrt{1 - \left(\frac{n_1}{n_2} \sin \theta\right)^2}} - n_2 d + d - \frac{d}{\sqrt{1 - \left(\frac{n_1}{n_2} \sin \theta\right)^2}} \cos \left(\theta - \arcsin \left(\frac{n_1}{n_2} \sin \theta \right) \right). \quad (5)$$

where $d = 20$ mm is the thickness of the optical flat crystal, $n_1 = 1.0003$ is the refractive index of air, and $n_2 = 1.5163$ is the refractive index of the optical flat crystal. Both refractive indices are treated as constants. Since the light source is a single-frequency He-Ne laser, wavelength dispersion does not introduce any additional uncertainty: the value

of n_2 is the refractive index of the plate material at 632.8 nm and remains fixed during the measurement. The ambient temperature was stabilized within ± 0.2 °C, so that the thermo-optic coefficient of the plate, which is of the order of 10^{-6} K $^{-1}$ [35], changes n_2 by less than 1×10^{-6} . Moreover, the quantity compared below is always a difference of external cavity lengths between two rotation positions, and the sensitivity of such a difference to n_2 is much weaker than that of the absolute optical path: an uncertainty of 0.001 in n_2 changes the difference by only a few nanometers. The temperature and dispersion contributions are therefore well below the level of the errors reported in Table 2 and can be neglected. According to Equation (5), the external cavity length of the second optical feedback (flat crystal feedback) channel was calculated when θ is 0.45405831 rad, 0.45416740 rad, 0.45427648 rad, 0.45438556 rad, 0.45449465 rad, and 0.45460373 rad, respectively. Then, the interference signal when $\theta = 0.45411285$ rad was used as the reference. The above dual optical feedback micro-displacement calculation method was adopted to calculate the corresponding external cavity length of the flat crystal feedback channel when θ was set (nominal value) at 0.45405831 rad, 0.45416740 rad, 0.45427648 rad, 0.45438556 rad, 0.45449465 rad, and 0.45460373 rad, respectively. The results are compared in Table 2.

Table 2. Measurement results of the external cavity length of the flat crystal feedback channel.

Nominal Angle of Optical Flat Crystal/Rad	0.45405831	0.45416740	0.45427648	0.45438556	0.45449465	0.45460373
Theoretical external cavity length of the flat crystal feedback channel/ μm	730.0232	730.3877	730.7522	731.1169	731.4817	731.8466
Measured external cavity length of the flat crystal feedback channel/ μm	730.0473	730.4098	730.7326	731.0930	731.4592	731.8658
Measurement error/nm	24.1	22.1	19.6	23.9	22.5	19.2

It can be seen from the data in Table 2 that, for the flat crystal feedback channel, the measurement error of the external cavity length obtained by dual optical feedback self-mixing interference lies in the range 19.2–24.1 nm. This error is of the same order as, but systematically larger than, the error range of the PZT feedback channel (13.4–17.8 nm). The origin of this difference is discussed in the following paragraph, and both sets of results confirm that the proposed method can be used for the measurement of micro-displacement.

The difference between the two channels originates from the different ways in which the external cavity length is changed. In the PZT channel the cavity length is varied by a closed-loop piezo stage whose position is servo-controlled by an integrated capacitive sensor, and the residual error of 13.4–17.8 nm is already at the level of the 20 nm expanded uncertainty ($k = 2$) of that sensor. In the flat crystal channel, in contrast, the cavity length is varied by rotating the plate with the Zolix TBRK100 stage. The external cavity length changes by only about 0.018 μm per minimum rotation step of 0.0003125 degrees, as can be computed from the two first entries of Table 2 (0.3645 μm over 20 steps). Consequently, an angular positioning error of a single minimum step of the rotation stage is sufficient to produce a deviation of the same order as the residual error of 19.2–24.1 nm observed for this channel, whereas no such error appears in the PZT channel. A second, smaller contribution arises from the residual change of the polarization state and of the feedback strength caused by the rotation of the plate. Both effects act on the reference (flat crystal) channel, which explains why the error of the flat crystal channel is consistently larger.

These contributions could be reduced in future work by using a rotation stage with a higher angular resolution and repeatability, or by measuring the actual rotation angle with an auxiliary angular encoder.

Finally, the robustness of the method with respect to the properties of the reflecting target deserves comment. The present experiments use mirrors as the feedback surfaces, for which the reflection coefficient is high and stable. In the dual optical feedback scheme, the displacement is retrieved from the ratio of the two SMI amplitudes; a change of the target reflectivity modifies the power modulation coefficients of Equation (1) and hence the feedback level, but, as long as the system still operates in the weak-feedback regime, it does not invalidate Equation (3). A strong reduction in the target reflectivity, as would be the case for a rough or strongly absorbing surface, can nevertheless drive the system out of the weak-feedback regime and degrade the fringe contrast; for such targets an additional attenuator in the coupling path or a laser with a higher output power would be required. The quantitative dependence of the reconstructed displacement on the color, the pigment and additive content, the thickness and the surface condition of a target will therefore be the subject of a dedicated study in future work.

4. Conclusions

In this paper, a micro-displacement measurement method based on dual optical feedback SMI has been proposed and experimentally demonstrated. The main contributions and conclusions are summarized as follows.

(1) The mechanism of dual optical feedback SMI is clarified: a length change in one external cavity periodically modulates the amplitude of the SMI signal of the other channel. Based on this mechanism, an amplitude-based displacement reconstruction algorithm is derived, in which the cycle number of the periodic signal is resolved by a known reference cavity length together with a continuity-constrained fringe-order determination. This constitutes the core innovation of the present work: the amplitude modulation that the coupled cavity imposes on the SMI signal, which has so far been used only to enhance the signal-to-noise ratio, is here exploited as the carrier of the displacement information itself, so that the displacement can be retrieved without unwrapping the fringe phase.

(2) A dual optical feedback SMI micro-displacement measurement system is constructed with a He-Ne laser, a PZT-driven mirror, and a rotatable optical flat crystal. The displacement of the PZT moving platform measured by the proposed method coincides with its nominal displacement line, with measurement errors of 13.4–17.8 nm, and the external cavity length change induced by rotating the flat crystal is recovered with measurement errors of 19.2–24.1 nm. Both are below 25 nm and are comparable to the 20 nm expanded uncertainty of the reference capacitive sensor, which verifies the feasibility and the accuracy of the proposed method.

(3) Compared with conventional single-cavity SMI, the proposed method is more robust against noise, because the displacement information is carried by the signal amplitude, which is regulated by the reference feedback channel. In contrast to phase-based retrieval schemes, the proposed amplitude-encoding scheme requires neither phase unwrapping nor the resolution of the fringe-order ambiguity, and it relaxes the requirements on the sampling rate and on the bandwidth of the detection electronics. At present, the accuracy of the method relies on the weak-feedback condition and on a known reference cavity length, and the resolution is limited by the amplitude noise of the detection circuit. Future work will focus on extending the method to two-dimensional displacement measurement and on implementing the system with compact semiconductor lasers for practical sensing applications.

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References

1. Wang, W.M.; Boyle, W.J.O.; Grattan, K.T.V.; Palmer, A.W. Self-mixing interference in a diode laser: Experimental observations and theoretical analysis. *Appl. Opt.* **1993**, *32*, 1551–1558. [[CrossRef](#)] [[PubMed](#)]
2. Zhang, S. Laser feedback technology and development. *Laser Optoelectron. Prog.* **2007**, *44*, 65–71.
3. Liu, G.; Zhang, S.; Xu, T.; Zhu, J.; Li, Y. Optical feedback characteristics of two orthogonally polarized light beams in a He-Ne laser during cavity tuning. *Acta Phys. Sin.* **2005**, *54*, 4701–4709. [[CrossRef](#)]
4. Taimre, T.; Nikolić, M.; Bertling, K.; Lim, Y.L.; Bosch, T.; Rakić, A.D. Laser feedback interferometry: A tutorial on the self-mixing effect for coherent sensing. *Adv. Opt. Photon.* **2015**, *7*, 570–631. [[CrossRef](#)]
5. Donati, S. Vibration measurements by self-mixing interferometry: An overview of configurations and benchmark performances. *Vibration* **2023**, *6*, 625–644. [[CrossRef](#)]
6. Guo, D.; Wang, M.; Tan, S. Self-mixing interferometer based on sinusoidal phase modulating technique. *Opt. Express* **2005**, *13*, 1537–1543. [[CrossRef](#)] [[PubMed](#)]
7. Dong, T.; Gao, B.; Chen, S.; Zhang, Z.; Cui, X.; Jiang, C.; Zhao, C. Quadrature phase detection based on phase shift of self-mixing interferometer for real-time displacement measurement. *Opt. Commun.* **2021**, *498*, 127202. [[CrossRef](#)]
8. Shinohara, S.; Yoshida, H.; Ikeda, H.; Nishide, K.; Sumi, M. Compact and high-precision range finder with wide dynamic range and its application. *IEEE Trans. Instrum. Meas.* **1992**, *41*, 40–44. [[CrossRef](#)]
9. Giuliani, G.; Norgia, M.; Donati, S.; Bosch, T. Laser diode self-mixing technique for sensing applications. *J. Opt. A Pure Appl. Opt.* **2002**, *4*, S283–S294. [[CrossRef](#)]
10. Scalise, L.; Yu, Y.; Giuliani, G.; Plantier, G.; Bosch, T. Self-mixing laser diode velocimetry: Application to vibration and velocity measurement. *IEEE Trans. Instrum. Meas.* **2004**, *53*, 223–232. [[CrossRef](#)]
11. Sun, H.; Liu, J.G.; Zhang, Q.; Kennel, R. Self-mixing interferometry for rotational speed measurement of servo drives. *Appl. Opt.* **2016**, *55*, 236–241. [[CrossRef](#)] [[PubMed](#)]
12. Wang, X.; Ge, W.; Chen, P.; Bi, H. Synthetic wavelength displacement measurement based on self-mixing interference. *Opt. Commun.* **2019**, *453*, 124383. [[CrossRef](#)]
13. Xia, W.; Wang, M.; Yang, Z.; Guo, W.; Hao, H.; Guo, D. High-accuracy sinusoidal phase-modulating self-mixing interferometer using an electro-optic modulator: Development and evaluation. *Appl. Opt.* **2013**, *52*, B52–B59. [[CrossRef](#)] [[PubMed](#)]
14. Zhang, C.; Chen, T.; Zhao, Y. Single micro-nano particle detection based on laser self-mixing interferometry. *Laser Optoelectron. Prog.* **2020**, *57*, 192803. [[CrossRef](#)]
15. Wang, K.; Cao, M.; Liu, B. A method of human eye parameter measurement based on laser self-mixing interference. *J. Russ. Laser Res.* **2020**, *41*, 197–206. [[CrossRef](#)]
16. Amin, S. Implementation of Hilbert transform based high-resolution phase unwrapping method for displacement retrieval using laser self-mixing interferometry sensor. *Opt. Laser Technol.* **2022**, *149*, 107887. [[CrossRef](#)]
17. Huang, Z.; Xu, H.; Wang, X.; Tang, Y.; Shen, L.; Li, D. Self-mixing interference signal analysis based on Lissajous figure convergence algorithm for vibration measurement. *Measurement* **2024**, *229*, 114407. [[CrossRef](#)]

18. Li, Q.; Quan, L.; Xia, W.; Guo, D. Laser self-mixing interferometry for direct displacement reconstruction using deep learning. *Opt. Laser Technol.* **2025**, *192*, 113423. [[CrossRef](#)]
19. Albert, A.; Donati, S.; Lee, S.-L. Self-mixing interferometry on long distance: Theory and experimental validation. *IEEE Trans. Instrum. Meas.* **2024**, *73*, 1–8. [[CrossRef](#)]
20. Matha, R.; Barland, S.; Gustave, F. High-availability displacement sensing with multi-channel self-mixing interferometry. *Opt. Express* **2023**, *31*, 21911–21923. [[CrossRef](#)] [[PubMed](#)]
21. Li, K.; Cavedo, F.; Pesatori, A.; Zhao, C.; Norgia, M. Balanced detection for self-mixing interferometry. *Opt. Lett.* **2017**, *42*, 283–285. [[CrossRef](#)] [[PubMed](#)]
22. Esmaili, P.; Norgia, M.; Donati, S. Noise decrease in a balanced self-mixing interferometer: Theory and experiments. *IEEE Trans. Instrum. Meas.* **2023**, *72*, 7004808. [[CrossRef](#)]
23. Donati, S.; Norgia, M. Native signal self-mix interferometer has less than 1-nm noise-equivalent-displacement. *Opt. Lett.* **2021**, *46*, 1995–1998. [[CrossRef](#)] [[PubMed](#)]
24. Jha, A.; Cenkeramaddi, L.R.; Royo, S. Generalized multi-cavity laser self-mixing interferometry based on scattering theory. *Opt. Express* **2023**, *31*, 16508–16522. [[CrossRef](#)] [[PubMed](#)]
25. Yáñez, C.; Royo, S. Improvement of the signal-to-noise ratio in a low power self-mixing interferometer using a coupled interferometric effect. *Opt. Express* **2020**, *28*, 37708–37720. [[CrossRef](#)] [[PubMed](#)]
26. Qi, P.; Cheng, J.; Li, S.; Zhang, Z.; Song, G.; Weng, J.; Zhong, J. Experimental observation of differential self-mixing interference signals using a randomly polarized laser: A differential self-mixing interferometry. *Opt. Lett.* **2020**, *45*, 1858–1861. [[CrossRef](#)] [[PubMed](#)]
27. Song, G.; Qi, P.; Li, Y.; Zhong, J. Dual-polarization differential noise reduction technology in dual-beam feedback self-mixing interferometer. *Laser Optoelectron. Prog.* **2022**, *59*, 1126001. [[CrossRef](#)]
28. Donati, S.; Horng, R.-H. The diagram of feedback regimes revisited. *IEEE J. Sel. Top. Quantum Electron.* **2013**, *19*, 1500309. [[CrossRef](#)]
29. Tkach, R.W.; Chraplyvy, A.R. Regimes of feedback effects in 1.5- μm distributed feedback lasers. *J. Light. Technol.* **1986**, *4*, 1655–1661. [[CrossRef](#)]
30. Bes, C.; Plantier, G.; Bosch, T. Displacement measurements using a self-mixing laser diode under moderate feedback. *IEEE Trans. Instrum. Meas.* **2006**, *55*, 1101–1105. [[CrossRef](#)]
31. Ghiglia, D.C.; Pritt, M.D. *Two-Dimensional Phase Unwrapping: Theory, Algorithms, and Software*; Wiley: New York, NY, USA, 1998.
32. Zhou, B.; Qi, P.; Zhang, Z.; Li, S.; Zhong, J. Phase modulation self-mixing interferometry by using a rotated optical flat. *Optik* **2019**, *185*, 1253–1260. [[CrossRef](#)]
33. Liu, H.; You, Y.; Li, S.; He, D.; Sun, J.; Wang, J.; Hou, D. Denoising of laser self-mixing interference by improved wavelet threshold for high performance of displacement reconstruction. *Photonics* **2023**, *10*, 943. [[CrossRef](#)]
34. You, Y.; Li, X.; Liu, H.; He, D. Micro displacement reconstruction of laser self mixing interference based on wavelet threshold filtering and S-G filtering. *High Power Laser Part. Beams* **2024**, *36*, 081002. [[CrossRef](#)]
35. Ghosh, G. *Handbook of Thermo-Optic Coefficients of Optical Materials with Applications*; Academic Press: San Diego, CA, USA, 1998.

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