

Absolute Distance Measurement With Improved Accuracy Using Laser Diode Self-Mixing Interferometry in a Closed Loop

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Abstract—We present a new method for the measurement of the absolute distance of a remote target based on the laser diode self-mixing interferometry technique, which is assisted by an electronic feedback loop that is capable of improving the measurement accuracy. The feedback loop supplies a periodic change of the emitted wavelength that exactly corresponds to a single interferometric fringe. This allows the measurement of the target distance with higher accuracy, which, in principle, is limited only by the detection shot noise and not by the fringe quantization error that is typical for the conventional fringe-counting approaches. We developed a prototype that is capable of measuring the target distance with 0.3-mm accuracy in the 0.2- to 3-m range.

Index Terms—Distance measurement, interferometry, measurement, remote sensing, semiconductor laser.

I. INTRODUCTION

LASER RANGING techniques are widely used to perform contactless measurement of the distance of a remote target for both industrial and scientific applications. These techniques are useful when contact with the target is not possible, the target is surrounded by a hostile environment, and/or no perturbation on the target is to be made.

Commercially available instruments are based either on time-of-flight methods (telemeters), which are best suited for long-range applications, or on triangulation techniques, which better apply to short-range measurements [1], [2]. Optical coherent techniques based on interferometric methods have also been proposed and demonstrated, and these are generally based on the so-called synthetic-wavelength approach that is achieved through modulation of the emission wavelength of a laser. The laser source with a continuously tunable emission wavelength is used to read out an interferometer (typically in Michelson configuration), and the obtained interferometric signal carries information about the difference in length of the reference and the measuring arms of the interferometer. These methods can have a high accuracy, but at the expense of a complicated experimental setup, which often requires a double interferometer for calibration [3], [4].

A very interesting coherent technique is the so-called self-mixing or optical feedback interferometry [1], [5] that relies on the coherent optical echo signal backscattered by the remote target that reenters the cavity of a laser diode (LD), thus generating a useful interferometric signal. The advantages of the self-mixing approach are its low cost and compactness and the very simple self-aligning optical setup that does not require a reference path. Several distance measurement approaches have been proposed based on fringe counting in the self-mixing configuration [6]–[9], achieving a resolution of a few millimeters.

In this paper, we present a new approach to absolute distance measurement based on the self-mixing effect, which makes use of an electronic feedback loop to achieve a resolution that is limited by the detection shot noise and not by the discretization error that is associated with the conventional fringe-counting technique. The feedback loop generates a square-wave modulation of the LD wavelength that exactly corresponds to a 2π variation in the interferometric phase; that is, the number of wavelengths that is contained in the path from the LD to the target and back again is varied by unity. Then, the target distance can be easily derived from the knowledge of the applied wavelength modulation. The performance of the prototype instrument that has been developed features a 0.2- to 3-m measuring range, with a resolution of 0.3 mm. Potential applications of this method are in the fields of metrology and industrial measurements, including contactless distance measurement, liquid-and powder-level measurement, profilometry, quality control, and reverse engineering.

II. ABSOLUTE DISTANCE MEASUREMENT BY THE SELF-MIXING INTERFEROMETRY: CONVENTIONAL APPROACH

In the self-mixing interferometric configuration, a fraction of the light emitted by the LD is backreflected or backscattered by a remote target, and it is allowed to reenter the laser cavity, where it mixes with the lasing electromagnetic field that is consequently modulated by a small amount, both in amplitude and frequency [1], [5]. The amplitude modulation term generates a variation of the power emitted by the LD, which is an interferometric signal that depends on the phase of the backreflected optical field and, hence, on the remote target distance. The power emitted by the LD subjected to optical feedback can thus be written as

$$P(\phi) = P_0 [1 + m \cdot F(\phi)] \quad (1)$$

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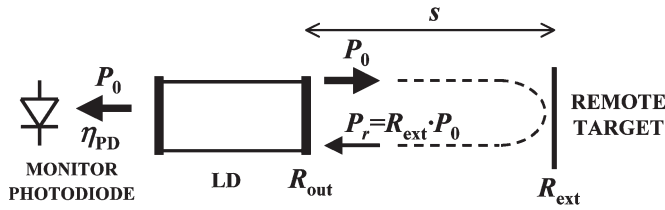


Fig. 1. Basic configuration for self-mixing interferometry.

where P_0 is the power emitted by the unperturbed slave laser, m is the modulation index, and $F(\phi)$ is the periodic function of the interferometric phase $\phi = 2ks$ of period 2π , where $k = 2\pi/\lambda$, with λ as the emission wavelength, and s is the distance between the LD and the remote target. The modulation index m and the shape of the function $F(\phi)$ depend on the so-called feedback parameter C , i.e.,

$$C = s \cdot \sqrt{R_{\text{ext}}} \cdot \frac{\varepsilon \sqrt{1 + \alpha^2}}{L_{\text{las}} n_{\text{las}}} \cdot \frac{1 - R_{\text{out}}}{\sqrt{R_{\text{out}}}} \quad (2)$$

where R_{ext} is the remote target optical power reflectivity, α is the LD linewidth enhancement factor, ε is the mode-mismatch coefficient ($\varepsilon \sim 0.2$ in practical situations), L_{las} is the LD cavity length, n_{las} is the LD cavity refractive index, and R_{out} is the power reflectivity of the LD output facet. The amplitude modulation signal can be detected by the monitor photodiode that is placed in the laser package through a transimpedance amplifier. For practical cases, the modulation index m is around $10^{-2} - 10^{-3}$. Fig. 1 reports a schematic diagram of the experimental setup for self-mixing interferometry. Usually, the light emitted from the LD is projected onto the target through an objective lens.

For a very weak optical feedback level ($C \ll 1$), the function $F(\phi)$ is nearly a sine, and the modulation index m increases for an increasing level of optical feedback. At a higher injection level ($C \approx 1$), the interferometric waveform exhibits a slight distortion. For moderate optical feedback ($C > 1$), the interferometric signal waveform $F(\phi)$ becomes sawtoothlike, and it exhibits hysteresis. Theoretical and experimental self-mixing interferometric waveforms are reported in Figs. 2 and 3. Fig. 2(a) reports the calculated dependence of the function $F(\phi)$ on the interferometric phase ϕ for weak feedback ($C = 0.7$). Fig. 2(b) reports the corresponding experimental signal that is obtained by aiming the laser beam at a vibrating loudspeaker. Fig. 3(a) reports the calculated shape of $F(\phi)$ for the case of moderate optical feedback ($C = 3$), where the signal is sawtoothlike. This can be explained by noting that $F(\phi)$ becomes a multivalued function, and the theoretical analysis [10] reveals that the bistability shows up, and the branch between points X and Y is unstable. Suppose the system is in point W : As the interferometric phase is increased, the point moves along the curve up to point X , where it jumps down to point X' , which is located on the adjacent stable branch. Conversely, if the system is in X' and the phase is decreased, point Y is reached, and subsequently, an upper jump to point Y' occurs. Thus, when $C > 1$, the interferometric signal is discontinuous, exhibiting steplike transitions each time a 2π phase variation occurs (corresponding to a $\lambda/2$ target displacement [11]).

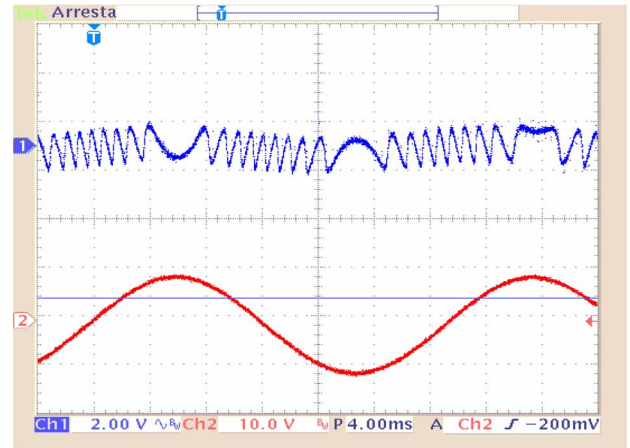
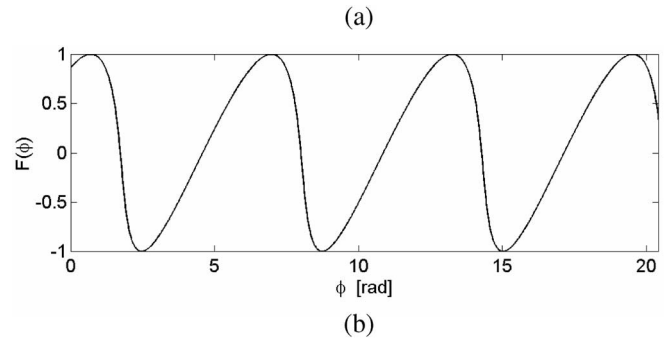


Fig. 2. Interferometric self-mixing waveforms for weak feedback. (a) Theoretical calculation of the function $F(\phi)$ for $C = 0.7$. (b) Experimental self-mixing signal (upper trace) that is obtained by aiming the laser onto a vibrating loudspeaker (lower trace: loudspeaker drive signal). Timescale: 4 ms/div.

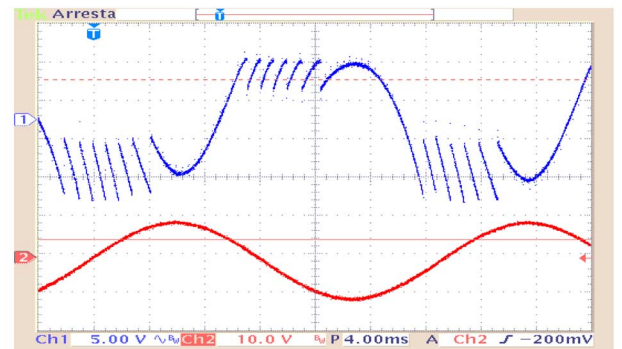
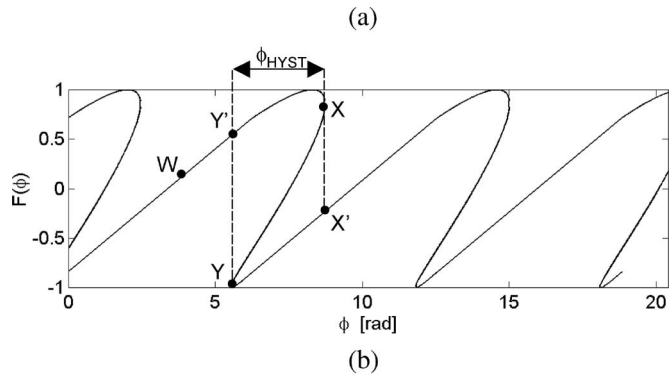


Fig. 3. Interferometric self-mixing waveforms for moderate feedback. (a) Theoretical calculation of the function $F(\phi)$ for $C = 3$. (b) Experimental self-mixing signal (upper trace). In this experimental condition, we have $C \approx 10$. Timescale: 4 ms/div.

Fig. 3(b) reports an experimental signal for the case of moderate optical feedback, where the value of C is around 10, and a strong hysteresis effect can be observed. The proposed method operates in the moderate feedback regime, which is easily obtained also on rough target surfaces, because when $s = 1$ m, a target power reflectivity of 10^{-5} is sufficient.

The self-mixing configuration in the moderate feedback regime has been previously demonstrated to be capable of effectively performing the measurement of the absolute target distance, offering the advantage of a simpler optical setup with respect to other synthetic-wavelength methods. The LD emission wavelength is modulated by an amount $\Delta\lambda$, and an interferometric signal is generated because the optical phase is varied by the amount $\Delta\phi = -4 \cdot \pi \cdot s \cdot \Delta\lambda / \lambda^2$. Practical implementations of this principle have been demonstrated by applying a triangular modulation to the LD injection current, generating a known wavelength variation of amplitude $\Delta\lambda$. By counting the number N of fringes occurring in the self-mixing interferometric signal within one semiperiod, the target distance s can be retrieved as

$$s = \lambda^2 \cdot N / (2 \cdot \Delta\lambda). \quad (3)$$

The resolution of the fringe-counting method is limited by the fringe quantization error $\Delta s_{\text{err}} = \pm \lambda^2 / (2 \cdot \Delta\lambda)$. Hence, the accuracy can be improved by increasing the extent of the wavelength modulation. Unfortunately, continuous thermal wavelength tuning by injection current in Fabry–Pérot LDs is typically limited to about 0.1 nm by longitudinal mode hopping, and the attainable resolution cannot be better than a few millimeters for a single-shot measurement [6]–[9]. In principle, the quantization error can be reduced if the fractional part of the fringe number is also taken into account. This can be done by accurately measuring the fractions of the first and last interferometric fringes that are generated just after the triangular modulating signal changes slope (first fractional fringe) or just before it changes slope again (last fractional fringe). This method can be implemented by acquiring the self-mixing signal and by performing the analysis using a personal computer. Another viable approach is that of measuring the average fringe duration by counting an integer number of fringes and simultaneously measuring their whole duration [8]. The two aforementioned methods for resolution improvement need computing resources (i.e., signal acquisition and subsequent digital signal processing), and their accuracy is limited to about 1 mm by nonlinearities in the wavelength–current characteristics, which are caused by LD thermal effects [8].

The approach that is proposed here seeks to achieve a better resolution (limited by the photodetection shot noise) and to realize a prototype that solely makes use of analog electronics for the real-time processing of the interferometric signal.

III. PRINCIPLE OF DISTANCE MEASUREMENT BY THE SELF-MIXING INTERFEROMETRY IN A CLOSED LOOP

The resolution of the conventional self-mixing method for distance measurement based on fringe counting is limited by the quantization error, and it is far above the intrinsic theoretical

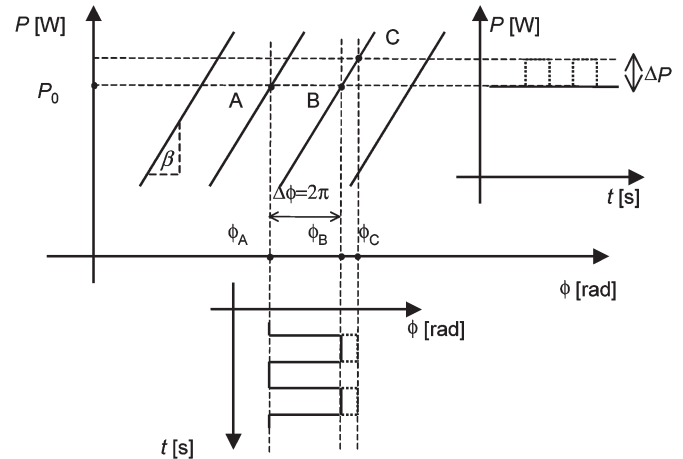


Fig. 4. Principle of operation of the absolute distance measuring system based on self-mixing interferometry in a closed loop. The sawtooth shape schematically represents the self-mixing signal in the moderate feedback regime. The phase modulation is achieved through the LD wavelength.

limit of interferometric measurements, i.e., the photodetection shot noise [1]. To overcome this limitation, we propose and demonstrate a new approach that conveniently makes use of an electronic feedback loop to improve accuracy. The basic principle is illustrated in Fig. 4, where the self-mixing signal in the moderate feedback regime is schematically represented by a sawtooth. The goal is to apply a square-wave modulation to the LD emission wavelength of proper amplitude $\Delta\lambda^*$ so that the corresponding interferometric phase variation $\Delta\phi$ exactly corresponds to 2π . This condition can be verified in practice by looking at the self-mixing signal in the time domain. When the desired 2π wavelength modulation is applied to the LD, the self-mixing signal is identically zero because the system jumps from a specific point of one interferometric fringe to the same point of the adjacent fringe (solid time-domain signals in Fig. 4). When the wavelength modulation amplitude is not properly set to 2π , the resulting self-mixing signal will be a square wave because, as the system jumps on the adjacent interferometric fringe, it will settle on a different point within the fringe, which corresponds to a different value of the emitted power (dashed time-domain signals in Fig. 4). The exact 2π phase modulation can be practically obtained with the help of a proper electronic feedback loop that acts on the amplitude of the wavelength modulation $\Delta\lambda$. In fact, when the system is out of the desired set point, the amplitude and the sign of the resulting square-wave self-mixing signal carry the information about the variation that will be applied to the amplitude of wavelength modulation to reach the 2π set point. The feedback loop uses the amplitude of the resulting square-wave self-mixing waveform as an error signal (see Fig. 4), together with its sign relative to a reference square wave. The loop amplifies this voltage error signal ΔV and consequently sets the amplitude ΔI of the injection current modulation of the LD through a voltage-controlled current source of admittance Y . The injection current variation ΔI causes the emitted LD wavelength to change by an amount $\Delta\lambda = \xi \cdot \Delta I$, where $\xi \equiv d\lambda/dI$ (in meters per ampere) is the coefficient of wavelength drift versus injected current (typical

value of $\xi = 10$ pm/mA). If we denote by $\Delta\lambda^*$ the amplitude of the wavelength modulation that will be imposed to the LD to match the 2π condition, we can derive the target distance s by setting $N = 1$ in (3), i.e.,

$$s = \lambda^2/2 \cdot \Delta\lambda^* \quad (4)$$

where the quantity $\Delta\lambda^*$ can be calculated from the knowledge of ΔI .

A. Sensitivity

The sensitivity of the method, i.e., the relationship between the output electrical quantity ΔV and the target distance s , will now be derived by supposing that the measuring system is working at the 2π set point. From (4), ΔV is obtained, i.e.,

$$\Delta V = [\lambda^2/(2 \cdot \xi \cdot Y)] \cdot (1/s). \quad (5)$$

The error signal ΔV represents the electrical output of the measuring system, and it is shown to be in inverse proportionality with the distance s to be measured. Hence, the sensitivity or scale factor can be defined as follows:

$$\text{SENS} \equiv \Delta V/s^{-1} = \lambda^2/(2 \cdot \xi \cdot Y). \quad (6)$$

B. Resolution

The attractive feature of the proposed method is that, in principle, its resolution is limited by the photodetection shot noise, that is, it can reach the ultimate measurement accuracy limit as imposed by the signal-to-noise ratio [1]. We describe the noise in the domain of the interferometric phase in the form of a fluctuation $\delta\phi$ so that, around the set point, we have $\Delta\phi = 2\pi + \delta\phi$. Correspondingly, the measured distance is affected by an uncertainty δs . From (3) and (4), we have $2\pi + \delta\phi = (4 \cdot \pi \cdot \Delta\lambda^*/\lambda^2) \cdot (s + \delta s)$, and we obtain

$$\delta s = (\delta\phi/2\pi) \cdot s. \quad (7)$$

There are three possible sources for the phase noise $\delta\phi$: 1) interferometric phase noise arising from the nonzero LD linewidth [12]; 2) mechanical vibrations of the experimental setup; and 3) equivalent conversion of the optical power shot noise into the phase noise through the characteristic slope $\beta = dP/d\phi$ (in watts per radian) of the self-mixing signal (see Fig. 4). For a target distance well below the LD coherence length (i.e., $s < 2\text{--}3$ m for typical Fabry–Pérot LDs), the third phase noise term is by far the largest [13]. Hence, $\delta\phi = \delta P/\beta$, where $\delta P = (2 \cdot \eta_{\text{PD}} \cdot h\nu \cdot P_0 \cdot B)^{1/2}$ is the optical power shot noise, and P_0 is the average power emitted by the LD, B is the measurement bandwidth, and η_{PD} is the collection efficiency of the monitor photodiode (a typical value is $\eta_{\text{PD}} = 0.02$). A theoretical and experimental analysis [13] reveals that in the moderate feedback regime ($C > 1$), the slope β (as shown in Fig. 4) depends on the emitted power and is also inversely proportional to the target distance, yielding $\beta = (\gamma(P_0))/s$, where the coefficient γ depends on the particular LD, and a typical

value is $\gamma = 1.45 \cdot 10^{-4}$ m/rad. Summarizing, the uncertainty in the measured distance is given by

$$\delta s = \frac{\sqrt{h\nu \cdot B}}{\sqrt{2} \cdot \pi \cdot \gamma \cdot \sqrt{\eta_{\text{PD}} \cdot P_0}} \cdot s^2. \quad (8)$$

We note the usual dependence on the emitted power and the proportionality to the square of the distance s to be measured. For typical values $\lambda = 630$ nm, $P_0 = 10$ mW, $\eta_{\text{PD}} = 0.02$, and $\gamma = 1.45 \cdot 10^{-4}$ m/rad, the noise-limited resolution is calculated as $\delta s = 0.61, 61.6,$ and $554 \mu\text{m}/\sqrt{\text{Hz}}$ for target distances $s = 0.1, 1,$ and 3 m, respectively.

IV. PRACTICAL IMPLEMENTATION OF THE NEW METHOD

The new method for distance measurement by the self-mixing technique in a closed loop has been implemented using an infrared Fabry–Pérot LD, emitting at $\lambda = 800$ nm, and an LD objective lens to focus the light on the target, which can be any kind of rough surface. The main blocks of the electronic control feedback loop are depicted in Fig. 5 (shown in black). Additional blocks, which are not strictly related with the measuring principle but are required to obtain a working practical system, are reported in gray.

A. Main Blocks

The clock generates a 1-kHz square wave that is the input to a variable gain block. The gain of this block is controlled by the amplified error signal (which is a dc voltage) that sets the amplitude of the square wave that is supplied to the voltage-controlled current source of admittance Y , which, in turn, generates the LD wavelength modulation. Obviously, the current source is also fed with a dc bias V_0 that sets the laser operating current. The self-mixing signal that is obtained from the monitor photodiode is amplified by a transimpedance amplifier, and this is the square-wave signal that must be zeroed. This square wave is multiplied by the reference clock. The output signal is low-pass filtered (at 1 Hz), and it represents the (dc) error signal, which is then amplified by a high-gain amplifier (block A, gain = 60 dBdB). The amplified dc signal represents the instrument output, and it is inversely proportional to the distance to be measured [see (5)].

An essential block is represented by the connection between the output of sum node 1 and the input of sum node 2. This connection is required to subtract the unwanted photocurrent signal term that is caused by the power modulation that takes place when the LD current is modulated. This term is subtracted (after a careful trimming) because we would like to virtually deal with an LD that responds to a current modulation only with a wavelength change.

The system that is realized with the main blocks that are described here is capable of demonstrating the proposed measurement method. The open-loop gain of the electronic feedback circuit is around 60 dB, and it is compensated with a single dominant pole, obtaining a phase margin larger than 55° and a settling time in closed loop of 10 ms. However, in this simple form, the measuring system does not perform satisfactorily

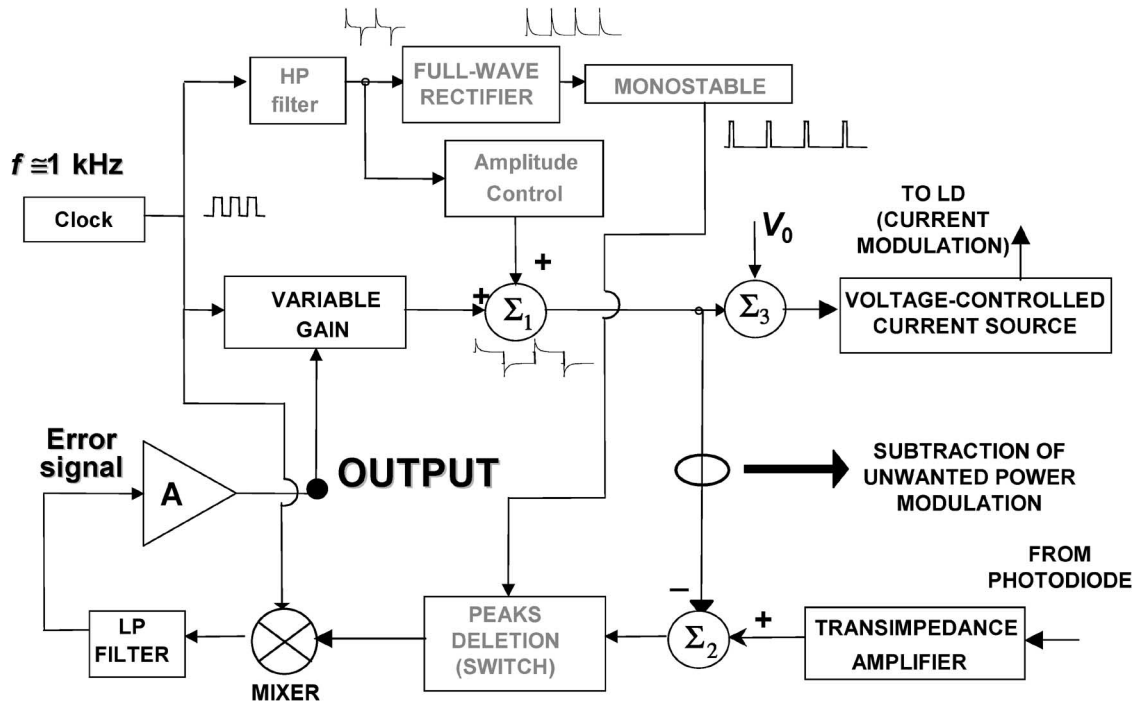


Fig. 5. Block scheme of the electronic feedback loop of the self-mixing distance measuring prototype. Main blocks are reported in black, and auxiliary blocks are reported in gray.

because some secondary effects make the measurement meaningful only for a limited number of time slots. Solutions to this inconvenience are provided by the use of secondary blocks.

B. Secondary Blocks

A number of secondary blocks shall be used to make the system fully working in all practical experimental conditions. The main problem is caused by the hysteresis that is typical of the self-mixing signal in the moderate feedback regime (sawtoothlike signal, see Fig. 3). The hysteresis can be quantified through the extension (in terms of the optical phase) of the region where the function $F(\phi)$ is multivalued, which is represented by the amount ϕ_{HYST} in Figs. 3(a) and 6. Referring to Fig. 6, it is clear that, in the presence of hysteresis in the phase, the so-called “ 2π ” square-wave modulation that is imposed on the LD wavelength cannot always be sufficient to make the system jump onto the next interferometric fringe. To solve this problem, we arranged to modify the temporal waveform of the modulating signal by adding positive and negative overshoots, as shown in Fig. 6. The amount of the overshoots depends on the hysteresis width, which, in turn, depends on the optical feedback strength (the hysteresis increases for increasing optical feedback) [10]. For practical operating conditions, an optimum choice of the overshoot amplitudes can be made so that the system behaves well in the presence of hysteresis, and it is tolerant to variations in the strength of optical feedback that can always occur in a real experiment. The required positive and negative pulses are generated, starting from the clock signal, by the gray blocks that are depicted in the upper part of Fig. 5. A high-pass filter generates the peaks that are trimmed in amplitude before being added to the square-

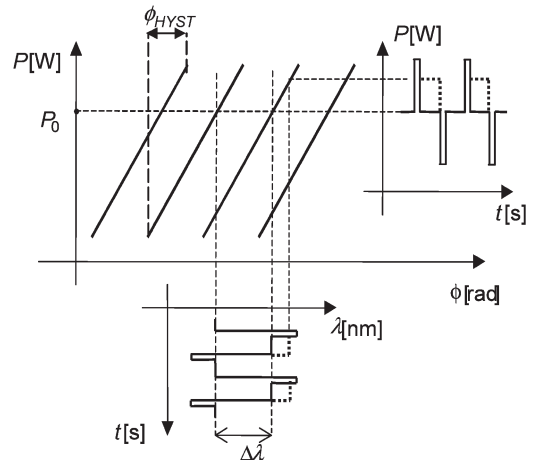


Fig. 6. Hysteresis in the phase domain of the self-mixing waveform and of the adopted method to avoid malfunctions by adding overshoots to the square wave that is used for the LD wavelength modulation.

wave modulating signal. As these overshoots actually change the operating point on the interferometric fringe, they generate unwanted transients in the self-mixing signal, which should be cancelled before the mixing with the clock signal (see Fig. 6). The deletion of the unwanted part of the self-mixing signal is achieved through properly generated monostable pulses that set the signal to the zero level for a certain time interval.

A still better performance can be obtained if the starting point on the interferometric fringe is set exactly at the middle of the fringe itself. If the system is not locked to half-fringe, malfunctions can occur, as caused by the combined effects of the hysteresis and the drift of the operating point along the fringe due to slow environmental perturbations (i.e., thermal

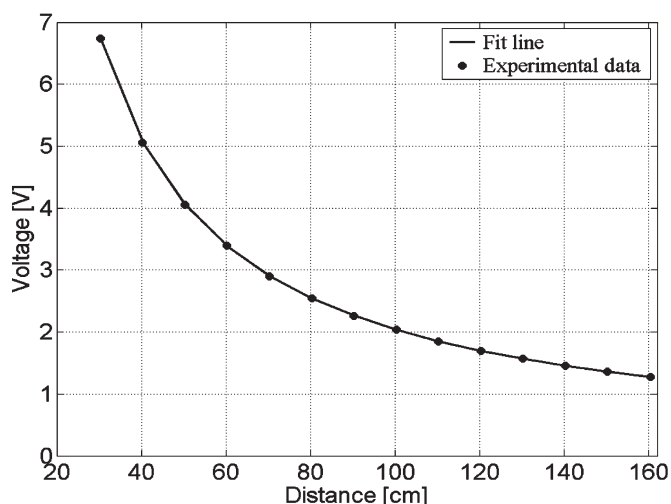


Fig. 7. Experimental results. Output voltage signal versus target distance; the expected inverse proportionality is observed. The accuracy of the measurement is 0.3 mm.

variations). To eliminate this inconvenience, the operating point of the system can be stabilized right at half-fringe by using another electronic loop circuit (not shown in Fig. 5). This stabilization loop (basically a closed-loop self-mixing vibrometer, as explained in [13]) operates in parallel with the measurement loop but in a different frequency range. In fact, the measurement loop operates around the clock frequency (greater than 1 kHz), and the stabilization loop operates at much lower frequencies (less than 10 Hz), as this must only compensate for slow environmental phase variations.

V. EXPERIMENTAL RESULTS

A prototype instrument was assembled using a Fabry–Pérot LD emitting at 800 nm and an objective lens (Thorlabs C230220P-B) as the optical setup. The electronics were designed and realized using general-purpose operational amplifiers, keeping the realization cost very low.

The prototype was tested on a variety of target surfaces, obtaining good results. The system was used to repeatedly measure the distance of a solid metal target with unfinished surface. The target was placed at different distances from the laser; these distances were measured by a calibrated scale with an uncertainty of ± 0.2 mm. Measurement results are reported in Fig. 7 (dots) together with a regression fit, which reveals that the predicted inverse proportionality sensitivity is followed to a very good extent [see (5) and (6)]. The curve of Fig. 7 can be obtained with a very good repeatability, and in particular, it does not depend on the strength of the optical feedback into the LD as long as the LD operates in the moderate feedback regime (i.e., sawtoothlike signal, $C > 1$), which is easily obtained when working on unfinished metal surfaces. When the optical feedback drops to a level for which the interferometric signal is no longer sawtoothlike ($C < 1$), measurement is not possible, and the output signal is zero.

To assess the system accuracy, repeated single-shot measurements were performed, and their statistical distribution was analyzed. The average standard error is independent from

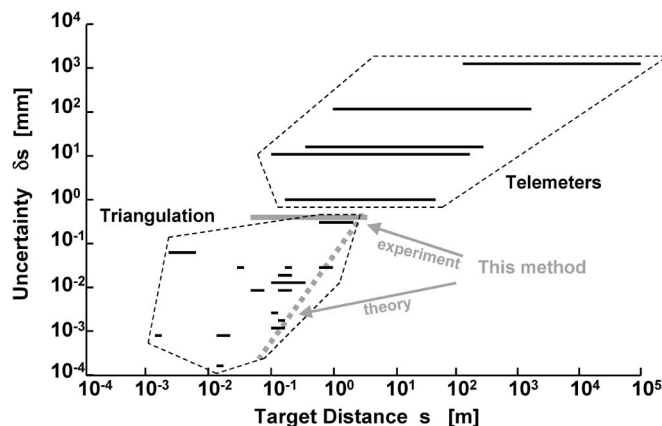


Fig. 8. Performance of several commercial measuring systems based on time-of-flight measurements and on triangulation. The theoretical and actual performances of the proposed method are reported in gray, showing the performance in between the two aforementioned techniques.

the target distance and is equal to 0.3 mm. The experiments did not show the expected increase of the measurement error with increasing distance (see Section III-B). This means that, probably, the actual error is not due to the intrinsic detection shot noise, and another uncertainty source is present.

The prototype performed well for a wide range of diffusive target surfaces. When the laser was aimed at reflective or superdiffusive targets (such as ScotchLite adhesive paper), an optical attenuator had to be inserted along the light path to avoid excessive optical feedback.

It is interesting to compare the performance offered by this new measurement technique with those achieved by two techniques that have found good commercial success, namely telemeters (based on time-of-flight measurement) and triangulation measuring systems. Fig. 8 shows the performance of several commercially available products with respect to accuracy and measuring range. Triangulation systems offer the best accuracy but with a very limited measuring range. On the other side, telemeters have a very wide measuring range (although limited toward short distance), but accuracy cannot be better than approximately 1 mm. The closed-loop self-mixing technique that is proposed here has a performance that falls in between those of the two categories of the previously cited instruments, thus offering a convenient and interesting tradeoff between accuracy and dynamic measuring range.

VI. CONCLUSION

We have proposed and experimentally demonstrated a new approach for the measurement of the absolute distance of a remote target without contact. The method is based on the self-mixing interferometric configuration that makes use of a low-cost LD and has a very simple optical setup, which is solely made up of a laser, a focusing lens, and the target. A prototype of the instrument was designed and built, yielding an operating range of 3 m and an accuracy of about 0.3 mm.

The proposed approach brings about a relevant accuracy improvement with respect to the conventional self-mixing distance measuring method based on fringe counting.

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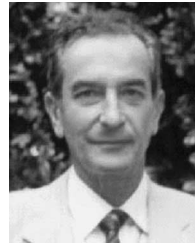
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