Proximity Sensor using Self-mixing Effect

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***Abstract*— This paper is about the utilization of the well-known self-mixing effect as base for the development of a novel proximity detector. The common used setup for this kind of a sensor is based on two elements: a laser as an emitter and a position-sensitive sensor as a detector. The sensor developed detects the optical power reflected by the object within the laser cavity itself, with no need of any additional detectors. One of the main feature is the ability to measure diffusive target accessible only from one side. A continuous range of measurement starting from 10 mm up to 80 mm is obtained by means of two different physical phenomena: from 0 up to 5mm the detection is only dependent by the level of the optical power returned into the laser cavity, whereas from 5 mm up to 80 mm reading the frequency of the modulation of the interferometric signal. The main advantage of the novel sensor is the elimination of the external detector. In addition, multiple devices configurations can be utilized and there is no need of any optical filters, cause the lase cavity itself works as an optical filter. Background rejection is intrinsically obtained because self-mixing effect shows a sharp cut-off after the focus.**

Keywords—Optical interferometry; Optical mixing; Optical sensor; Optoelectronic devices.

I. Introduction

There are different proximity sensors present in the market. Different sensors are based on different methods of detecting the proximity, some are based on magnetic field variation detection [1], some detect ultrasonic echo [2] and other optical reflections [3-4]. Typically, optoelectronic detectors are a better choice because they don't require metal target such us inductive sensor and they are faster than capacitive ones that that need to stay very near to the target in order to work. In addition, they have higher spatial resolution than ultrasound devices. Among them, optical beam proximity sensors have a receiver separated from emitter and range up to 60 m; retro-reflected sensors reach up 10 m with both receiver and emitter in the same housing and specific designed reflector placed on the target. Nevertheless, in the range from 0 to 10 mm, diffusive sensor carries out measurement simply by the means of diffused light. However, they are affected by noise due to the background. In order to overcome this problem different solutions have been proposed; in particular triangulation technique is often used to eliminate spurious signal due to objects presence out of range of interest. Drawbacks of this kind of configuration are the complexity of the signal elaboration and setup. Other than that, multiple sensors configuration requires a custom design to prevent possible interference among optical sources. The proximity sensor suggested in this paper takes advantage of so called: "self-mixing configuration" in order to overcome these problems.

The optical self-mixing technique has been lately applied for different measurements: absolute distance [5-6], vibration [7-8], and flux [9] are some of field in which it has been successfully applied. This optical configuration [3] of a self-mixing based sensor has several advantages: setup simplicity, compactness, low-cost, good resolution versus range of measurement trade-off and a very low sensitivity to environment noise. Thus, this technique is potentially suitable for contact-less detection in a variety of applications: in this contribution it shown a self-mixing based sensor as to detect proximity.

II. Theory of the Measurement

When a fraction of power, between 10^{-6} and 10^{-3}, of laser diode (LD) beam is back-reflected into the cavity itself is the moment in which the self-mixing effect happens, Fig. 1. When this happens inside the laser cavity the optical power is modulated and classic interferometric signal can be observed across the laser diode junction or through a simple photodiode, external to laser cavity too. Thus, the interferometric signal depends on the phase shift between the generated beam and the back-injected one. The power P is described by $F(\phi)$ which is periodic function of phase $\phi = 2ks$, where $k = 2\pi/\lambda$, s is the absolute target distance and λ is the LD wavelength.

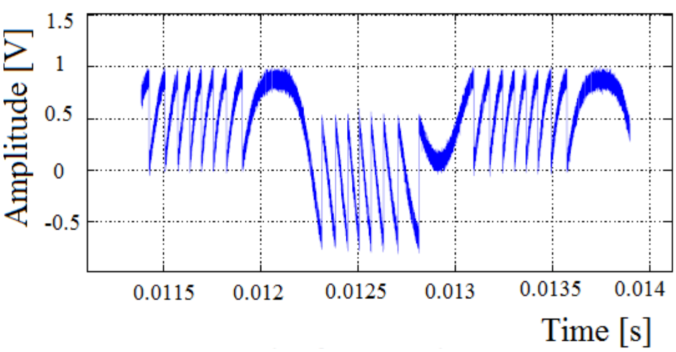

Fig. 1. Typical self-mixing signal measured on a laser diode internal photodiode.

However, a second effect has been recently discussed in literature [10]: a power amplification is produced when a large amount of light is couple back into the laser cavity. This effect can be explained considering that external cavity changes the loss per transit time. The photon lifetime τ_p can be expressed as function of target power reflectivity R_3 and mirrors power reflectivities R_1, R_2:

$$\tau_p \approx \tau_{in}\{-\ln R_1[R_2+(1-R_2)^2R_3/(1-R_2R_3)]\}^{-1} \quad (1)$$

For an unperturbed cavity ($R_3 = 0$):

$$\tau_{p0} \approx \tau_{in}\{-\ln R_1R_2\}^{-1} \quad (2)$$

From (1) and (2) τ_p rises up when R_3 rises too. Moreover the Lang-Kobayashi (L-K) equations [11] show that slope efficiency S and current threshold I_{th} are both influenced by variations of photon lifetime τ_p:

$$\frac{\Delta S}{S}=\frac{\Delta\tau_p}{\tau_{p0}}; \quad \frac{\Delta T}{ST}=\frac{\Delta\tau_p}{\tau_{p0}}\left(1+GN_0\tau_{p0}\right) \quad (3)$$

From equation (3) it can be understood that threshold changes are just lifetime changes scaled by a factor $1+GN_0\tau_{p0}$ and the slope changes follow exactly the lifetime changes percentage.

It can be said that the emitted power P increases with power injection and threshold current I_{th} decreases as well. There were made some experimental tests to validate this theory. As shown in Fig. 2 the power gain assumes a Gaussian-like shape when a chopper with cylindrical blades is placed in front of the laser beam. This signal depends on the incident angle α because R_3 rises when the diffusive target is perfectly aligned. As expected, it is not function of the interferometric phase ϕ. So, the experimental measurement is just a Gaussian-like shape signal. Amplitude, also, decreases increasing target distance due to reduction of collected power inside the cavity. In order to validate our assumption, it was measured the voltage signal across the LD: a direct measurement of the power feedback by the photodiode, because sometimes the optical re-injected power is collected directly by the monitor photodiode inside, and so not resulting in a real LD-power variation. This experiment confirmed that the monitor photodiode didn't influence the LD-power variation. Moreover, it is generated only when light emitted and light injected in the cavity have the same frequency. According to this, the optical Power is function of s and α as described in (1):

$$P=P_0(\alpha,s)(1+U(\alpha,s)) \quad (4)$$

Where P_0 is the quiescent power and U includes the modulation factor m and the function $F(2ks)$ [8]. These two effects can occur simultaneously and their combination depends on the optical configuration utilized.

III. Proximity Sensor Setup

The idea of this work is to build a proximity sensor with a range of measurement from 0 to 10 mm exploiting the two effects given by the self-mixing technique. In order to accomplish this task, the sensor whole range of measurement was divided in two parts: in the first, the measure is obtained by the means of power gain variation, in the second one by the modulation induced by the laser self-mixing. In both ranges the self-mixing interference performs as a coherent detection. The signal is given by the superposition integral of field distributions leaving and returning from the laser output mirror. As result, the environment light and other light sources with different wavelength are not detected and don't influence the measurement. Multiple sensor devices can be easily developed simply by replying the same setup under the condition that they differ in wavelength by few nanometers. This is verified among lasers of the same model too. Therefore, laser beams crossing is allowed and optical filters are not needed. The measurement range was chosen from 10 mm to 80 mm in order to use the use the proximity sensor for the washing machine application. The measurement range of the sensor can be extended changing the focusing optic of the sensor.

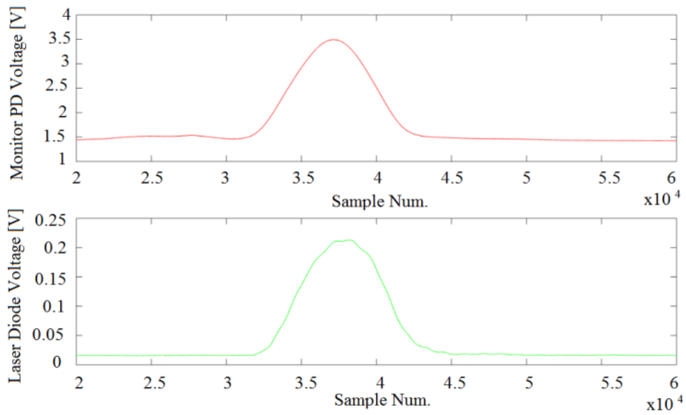

Fig. 2. Monitor photodiode voltage signal (upper) and laser diode voltage signal (lower) show the same Gaussian-like shape.

As explained, one of the main advantages of a self-mixing sensor is the setup simplicity. Detector is described in Fig. 3 where a single optical channel configuration is composed just by the LD source and the output lens.

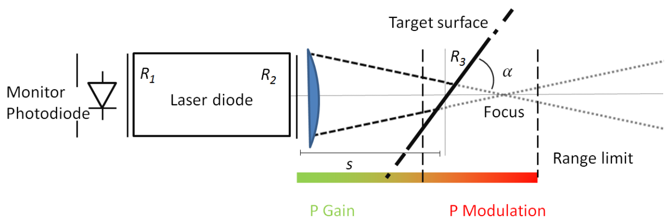

Fig. 3. Schematic of sensor: target surface reflects laser diode beam focused by the lens. The amount of light rejected back into the cavity depends on α and s. The equivalent reflectivity R_3 obtained determines the range in which the two effects occur. Rear photodiode measure the power on the laser.

The experiments are carried out on a single frequency Fabry-Perot laser operating at 650 nm with 5 mW power output. The sensor sensitivity and range of measurement is determined by the focus position. Since the modulation effect is strongly related to the focus position it is very import to choose it correctly in order to have the desiderated range of measurement. The self-mixing signal increases when the target is placed near the focus. In that case, great part of the laser beam power is reflected coherently and destructive interference is at its minimum. On the contrary, if it is considered the spatial range before the focus *s*, laser beam spot size increases and coherence drops proportionally with *s* decreasing. When the target is very close to the LD, the modulation phenomenon disappeared. Instead, the cut-off due to light beam divergence affects the self-mixing signal intensity as well. Experimental results show that modulation effect occurs from about 20 mm before, up to 20 mm after the focus that was placed at about 5 cm from the laser diode output lens. As consequence, the sensor is blind 3 cm after the focus in this setup. This gives the great advantage of having a natural background rejection after this distance. When the target is very near the LD the gain power modulation is used to measure the proximity: the effect guarantees object detection from 0 mm up to 45 mm. The reflected light collected by the lens after that distance is too low to produce the phenomenon.

From these results, it was decided to place the laser focus at about 50 mm in order to measure from 0 mm to 80 mm without lack of continuity. From 40 mm to 45mm the signal is caused by the combination of the two effects, while from 0 to 45 mm gain effect prevails and from 45 to 80 mm the self-mixing effect prevails. These results are shown in Fig. 4-5.

Furthermore, self-mixing technique is often used to retrieve information about target displacement with $\lambda/2$ resolution [12]. In this case the only information carried out is the target detection. The detection consists in the signal amplitude comparison with a threshold. As consequence, classical interferometric signal variation is not only meaningless; but also, it can represent a problem in terms of threshold value choice. If we consider the scenario illustrated in Fig. 3a), where the chopper rotating-disc is detected, it can be observed that several spikes are generated due to the self-mixing modulation. Although the object is still in the sensor proximity, the signal amplitude decreases steeply, due to the interferometric fringes shape, causing multiple false detections in the same measurement. Despite this behavior, the sensor it is able to work properly even if speckle pattern causes *C* variation or laser instability [13]. Indeed, under the assumption that signal amplitude is sufficient to exceed the threshold, the signal shape is irrelevant.

The choice of the optic determines the spatial resolution. The light emitted is confined in a narrow cone. The spot size is at its minimum value at the focus (diameter $w_0 = 1$ mm) and it increases until it reaches lens dimensions. Thus, the spatial resolution with the experimental setup explained varies from 1 mm to 1 cm.

Our results can be improved by using different sources and lenses. Range and depth of field can be enhanced to meet application constrains.

IV. Experimental Results

It was built a sensor with the principles previously discussed to carry out industrial tests. The aim of this study was to monitor the frequency rotation of washing machine spinner by measuring the period between spokes, each one 1.5 cm wide (Fig. 6). The maximum frequency was equal to 80 Hz, which means a time period of around 2.5 ms between the spokes. The distance of measurement range was from 0 mm to 80 mm and the washing machine plastic structure was 30 mm away from the spinner.

The proximity sensor designed for the measurement is so structured: the optical setup is equal to the one described Fig. 3, an LD laser with photodiode integrated was utilized. After the signal amplification by the means of a transimpedance amplifier, with gain 100, an analog comparator generates a pulse when the signal exceeds a fixed threshold. Threshold value V_{th} = 25 mV avoids spurious pulses due to noise. A monostable multivibrator maintains the signal output in the high state for 2 ms when signal exceeds the V_{th}. In this way false positives due to fringes and spikes are not detected. However, the frequency measurement is limited at about 500 Hz. This means that the sensor shows a trade-off between maximum rotation frequency and maximum spokes width.

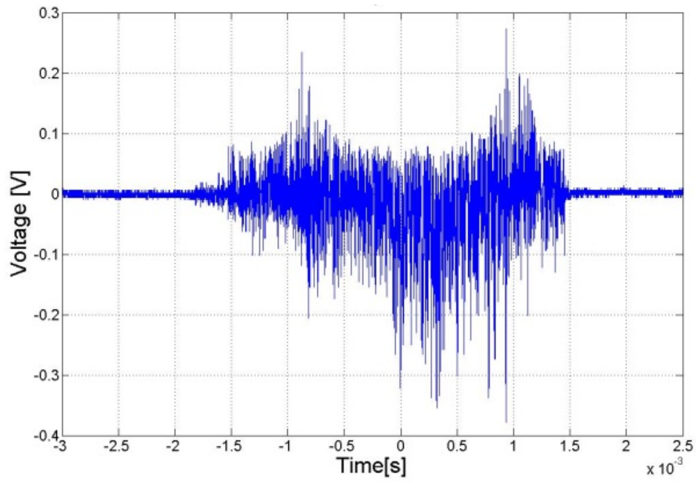

Fig. 4. Fringes due to modulation effect.

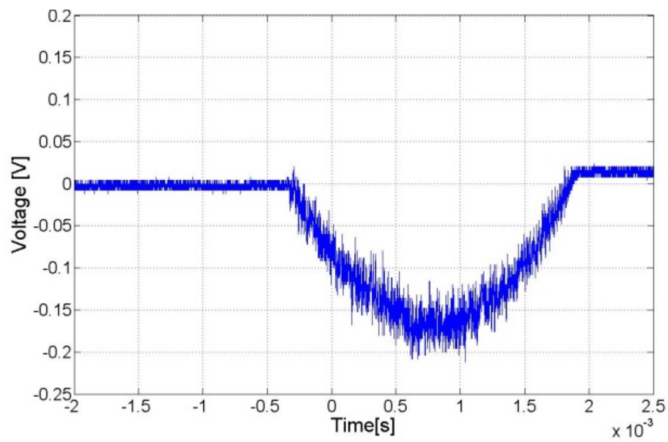

Fig. 5. Modulation fringes superimposed to signal gain variation.

In addition, it is possible to understand the rotation direction if a second laser source is utilized. The same acquisition system

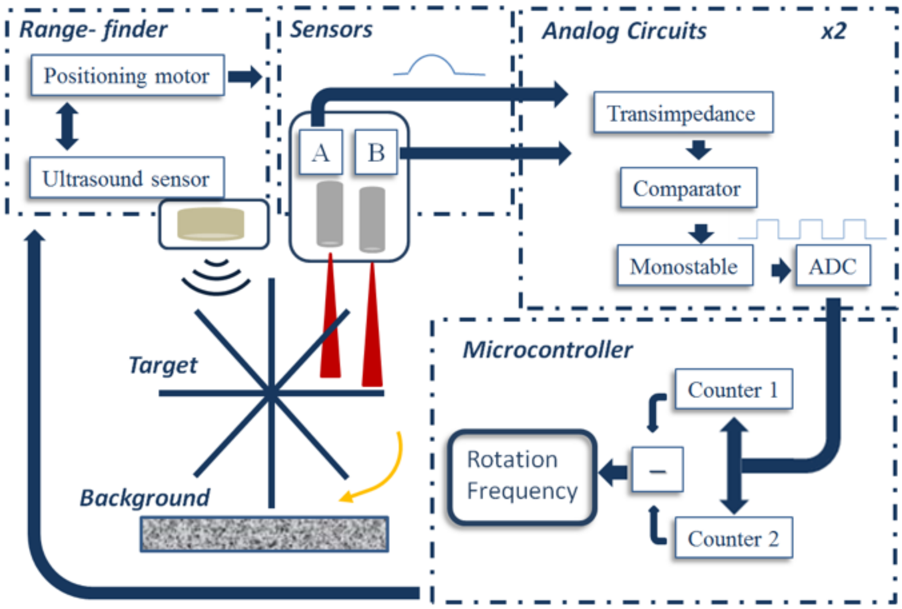

Fig. 7. System scheme: on the left, the range finder controls the step motor to select the working range of sensors. Laser A and B are aligned with the target blades. Two analog circuits return periodic square waves read and elaborated by the microcontroller.

can be used to acquire the second LD signal placed 10 mm away from the first one. The two parallel channels realized are driven and read by means of analog circuitry. At this point, the analog signal is digital converted and a microprocessor (STM32F4) calculates frequency by means of digital counters. As explained before, the self-mixing interferometry is based on a sort of homodyne detection and it is possible to use the same LD model for both sources. The trigger order of the two outputs can determine the rotation direction.

Fig. 6. Photo of the device under test is a washing machine spinner made by five spokes close to the background case.

Acquisitions return a trigger error on of 4 µs on a 14 ms period. We get rotation direction successfully demonstrating that two lasers do not interfere. Also, background rejection has been experimentally validated: object placed 3 cm after the focus was never detected.

V. Conclusions

A novel self-mixing sensor for proximity detection was designed and realized. The sensor revealed good performances in terms of background noise rejection, easy implementation and low-cost realization, a laser that shows self-mixing behavior costs not more than some euros. A sensor like this, due to its small size can be placed in environment where the size is one of the most important constraints.

Future developments will be to test deeply the proximity sensor under different condition in order to understand better its limits. Another one important development will be to put the sensor inside a real washing machine system of calibration, in order to test the machine before being sold, as depicted in Fig. 7. Since during the spin dry phase moving, the spikes moves at different positions due the vibration of the washing machine basket, an ultrasound sensor evaluates the best position of the proximity sensor, that is moved by a stepper motor controlled by a microcontroller in order to have the best measurements. This is a very demanding application because new washing machine arriving at 1400 round per minute are too fast for the normal commercial mechanical sensors that are subject to very high wear.

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