Contributed paper

OPTO-ELECTRONICS REVIEW 11(4), 313–319 (2003)

Low cost velocity sensor based on the self-mixing effect in a laser diode

L. KREHUT, J. HAST*, E. ALAROUSU, and R. MYLLYLÄ

University of Oulu, Optoelectronics and Measurement Techniques Laboratory and Infotech Oulu, 90014 University of Oulu, Finland

In this paper, a low cost velocity sensor based on the self-mixing effect in a laser diode is described. Theory of the self-mixing effect in the laser diode is shortly presented. Experimental velocity measurements are presented in order to evaluate the operation of the velocity sensor. In the design, the attention is focused to develop a budget sensor, which frequency response of the detection electronics is up to 85 MHz. This limits the maximum measurable velocity to 27.5 m/s. The total material costs of the velocity sensor were 234 euros. The experimental measurements conducted so far show that the linearity of the developed velocity sensor is at least as good as that of a mirror moved by a translation stage with velocities ranging from 1.0 to 48.5 mm/s. The velocity of the translation stage was controlled by a computer. When the mirror velocity is lower than 20 mm/s, the maximum relative precision with the mirror velocity is less than 3.5%. When the mirror velocity is higher than 20 mm/s the relative precision with the mirror velocity is below 0.5%. In an additional experiment with a vibrating loudspeaker's membrane, it is also demonstrated that a maximum Doppler frequency is clearly detectable over the noise level at 12.5 MHz.

Keywords: velocity sensor, laser diode, self-mixing effect, Doppler frequency.

1. Introduction

Measurement of a moving object's velocity has always been a very important factor in engineering. Different types of velocity sensors based on various physical mechanisms: mechanical, electrical, acoustical and optical have been invented. The challenge in the development of different velocity sensors is that the sensor should be able to measure the object's velocity from a far distance. On the other hand, it should be able also to detect very small changes in the velocity due to, e.g., vibration. Optical techniques offer a lot of potential to this challenge because their response to a stimulus is very fast and measurements can be performed from a far distance allowing contactless measurement. This is especially important in a turbulent industrial environment, where electromagnetic interference, heat, moisture or other factors do not allow using other type sensors.

One optical technique is interferometry that can be applied to velocity measurements by detecting the Doppler shift of the light scattered or reflected from the moving object. This so called laser Doppler technique is typically based on the use Michelson, Mach-Zehnder or Sagnac interferometer configurations or their modifications. The disadvantage of these configurations is that they comprise many optical components, which increase the price of the measurement instrument. Moreover, this also increases the size of the instrument. One very useful technique to implement a laser Doppler device is to apply the self-mixing effect that occurs in a laser in an optical feedback. The basic idea of self-mixing interferometry is to couple the light scattered from the moving object back into the laser cavity. In the laser cavity, the coupled and original laser beams interact with each other and cause the power fluctuations in the output optical beam of the laser. These fluctuations can be monitored using a photodetector placed on the back side of the laser cavity.

The self-mixing effect was discovered soon after invention of laser in 1960 [1]. It was noticed that external feedback into the laser cavity induces intensity modulation in the output of a gas laser [2]. A few years later, the first laser Doppler velocimeter implementing optical mixing in the laser cavity was presented [3]. It was also noticed that the fringe shift caused by an external reflector corresponds to the optical displacement of $\lambda/2$, where λ is the operating wavelength of the laser. In addition, the intensity modulation was noticed to be comparable to conventional interferometers. After this the self-mixing effect in a laser has been used in many different measurement applications for velocity [4–6], displacement, distance and vibration measurements [7–11] and ranging [12,13]. The self-mixing technique is also used for 3D imaging of a vibrating target [14].

In this paper, the velocity sensor that is based on the self-mixing effect in a 650-nm laser diode is presented. The theory of the self-mixing effect in a single mode laser diode is shortly presented. The results of velocity measurements in a velocity range 1.0–48.5 mm/s are also shown. The designed sensor is able, in principle, to detect the Doppler frequencies up to 85 MHz, which is limited by the frequency response (3 dB) of the detection electronics. 85 MHz corresponds to 27.5 m/s velocity. However, due to lack of an ap-

*e-mail: jukka.hast@ee.oulu.fi

propriate velocity reference, the measurements were limited to the velocity range 1.0–48.5 mm/s. A mirror mounted to a translation stage, which velocity was controlled by a computer, was used as the velocity reference. In this paper, it is shown also that a distinct maximum in the Doppler spectrum measured from a vibrating loudspeaker's membrane is detectable at 12.5 MHz. This equals to 4.1 m/s velocity.

2. Materials and methods

2.1. Self-mixing effect in a laser diode

A three-mirror Fabry-Perot cavity is used to demonstrate the self-mixing effect in a single mode laser diode as presented in Fig. 1. The laser cavity, which length is L, is enclosed between mirrors M_1 and M_2. The external target M_{ext} is located along the optical z-axis at the distance of L_{ext}. Laser light in the external cavity E_2 interacts with the external target and is reflected or scattered back to the laser cavity. Inside the laser cavity, E_2 interacts with original laser light, E_1. If coherence conditions are fulfilled, interference between E_1 and E_2 occurs. The interference field E of E_1 and E_2 can be detected using a monitor photodiode (PD) that is placed behind the laser cavity on the opposite side to the primary light output of the laser diode.

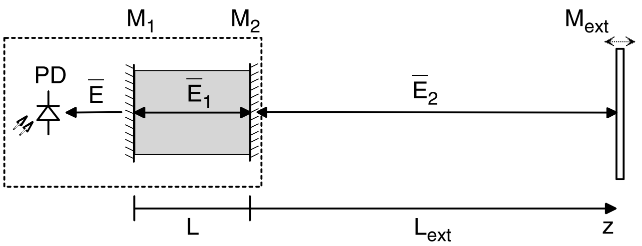

Fig. 1. Schematic arrangement of the self-mixing effect in a laser diode.

The basic theory of the optical feedback effect in a laser diode is considered in detail in reference [15]. It can be derived that the optical power fluctuations ΔP of the laser diode are related to gain variations and follow the equation

$$\Delta P \approx g_c - g_{th} = -\frac{\kappa_{ext}}{L}\cos(2\pi \nu \tau_{ext}), \tag{1}$$

where g_c is the threshold gain in optical feedback and g_{th} is the threshold gain without optical feedback. κ_{ext} is the coupling coefficient, which varies between zero and unity, defined as $\kappa_{ext} = (1-|r_{2s}|^2)r_{2ext}/r_{2s}$. Parameters r_{2s} and r_{2ext} are the amplitude reflection coefficients of an effective mirror M_{2s} and external target M_{ext}. M_{2s} is the effective mirror, which combines the laser cavity and the external cavity. τ_{ext} is the round trip time through the external cavity ($\tau_{ext} = 2L_{ext}/c$). The gain in the laser diode is produced by driving a high current density into the active area. Because external optical feedback causes gain variations, the self-mixing phenomenon can also be measured from the pump current of the laser diode [16].

A very important consideration in the optical feedback of a laser diode is the strength of the feedback. The feedback parameter C_{fb} of the self-mixing effect is defined as

$$C_{fb} = \frac{\tau_{ext}}{\tau_L}\kappa_{ext}\sqrt{1+\alpha^2}, \tag{2}$$

where τ_L is the round trip time thorough the laser cavity and α is related to the amount of stimulated emission. It is a ratio of the real to imaginary parts of the variation in the complex refractive index of the laser cavity [15]. When C_{fb} is much smaller than unity, the function ΔP varies sinusoidally. When C_{fb} increases, ΔP becomes more saw-tooth--like. When $C_{fb} > 1$, the operation of the laser is no longer stable, leading to increased noise and mode hopping [17].

When the external target moves with a uniform velocity v in the positive direction along the z-axis, then τ_{ext} varies as

$$\tau_{ext} = 2(L_{ext} + vt)/c, \tag{3}$$

where L_{ext} is the length of the external cavity at zero time and t denotes the time. Substituting this equation into Eq. (1), the power fluctuations become [18]

$$\Delta P \approx g_c - g_{th} = -\frac{\kappa_{ext}}{L}\cos(4\pi \nu \tau v t/c + 4\pi L_{ext} v/c), \tag{4}$$

When the target moves, the reflected or scattered light contains a frequency shift, which is proportional to the velocity of the moving target. According to the Doppler effect, the Doppler frequency ν_D is

$$\nu_D = \frac{2v}{\lambda}\cos(\varphi), \tag{5}$$

where v is the velocity of the moving target, λ is the operating wavelength of the laser diode and φ is the angle between the velocity vector of the moving target and the laser beam. If the measurement is perpendicular to the target, Eq. (5) is reduced to $\nu_D = 2v/\lambda$ and further, solving the velocity, $v = \nu_D\lambda/2$. Substituting this to Eq. (4) it can be seen that the power fluctuations of the laser diode are related to the Doppler frequency. Thus, it is possible to determine the velocity of the target measuring these power fluctuations. Moreover, when the velocity profile of the target is known, the displacement can be solved integrating the velocity profile as function of time.

The self-mixing interferometer is constructed into a budget (21 USD, June 2003) red laser diode (Toshiba TOLD9442M). The exact emission wavelength of the laser was measured using optical spectrum analyser (OPHIR

WaveStar V) and was equal to 648 ±0.5 nm. The optical power of the laser in continuous mode is 5 mW and it provides good single mode operation at this power. Laser diode and monitor diode pin connections are also suitable to obtain the self-mixing effect. The threshold current at 5 mW power without optical feedback is 35 mA.

2.2. Detection electronics and velocity sensor construction

The self-mixing signal that includes the Doppler frequency is picked by the photodiode detecting back laser beam. Very weak changes of the photocurrent are amplified in the broadband transimpedance preamplifier. This is DC-coupled structure consisting of three stages: transimpedance amplifier, voltage gain amplifier and output stage. Schematic diagram is shown in Fig. 2. The circuit is built of discrete components to avoid expensive and noisy high-frequency operational amplifiers.

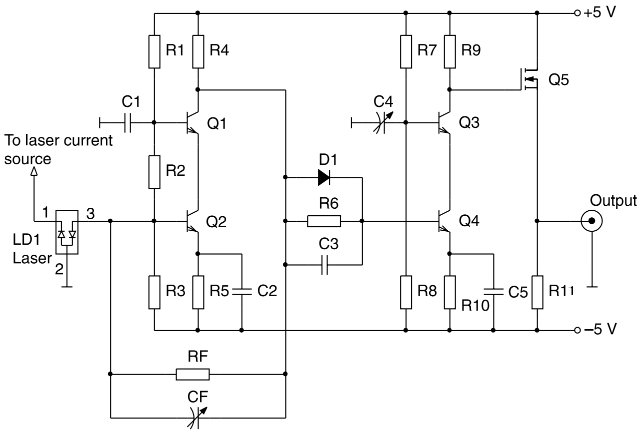

Fig. 2. Schematic diagram of the preamplifier.

The first stage (Q_1, Q_2) uses the cascade voltage amplifier with negative feedback – a structure widely used in high frequency circuits. Such construction guaranties low noise and low input capacitance. Transimpedance is defined mostly by the feedback resistor R_F which in this circuit is around 6.8 kΩ. The bandwidth is defined by the feedback loop. The cut-off frequency is around 50 MHz and can be accurately adjusted by capacitor C_F. The output of transimpedance amplifier is DC-coupled to the input of the second stage via temperature compensation network (D_1, R_6, C_3). The second stage (Q_3, Q_4) is also cascade structure but working as voltage amplifier. The cut-off frequency of this stage can be adjusted by capacitor C_4. To avoid gain reduction due to external load, which can be connected to the amplifier, the separation stage is needed. It is built using high-frequency MOSFET transistor Q_5 working as voltage follower (common-drain configuration). The gain of the whole preamplifier is 9.2 V/mA (79 dBΩ) with bandwidth ranging from 0 to 85 MHz. The measured frequency response of the amplifier is shown in Fig. 3. Measured output noise was around 1.1 mV_{rms} without laser. The input current range is from 0 to 250 μA that results in output voltage swing from –1.4 V to +0.9 V with nonlinearity less than 1%. The preamplifier is built of discrete surface-mounted components and enclosed in a shielding box.

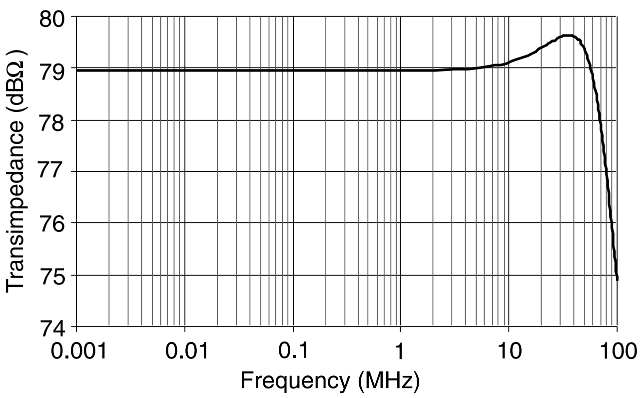

Fig. 3. Measured frequency response of the preamplifier.

Laser diode is driven by the constant current supplied from a regulated source. To avoid laser damage and guarantee good result repeatability, the temperature controlling must be provided. It is implemented using a Peltier thermo-electric element together with suitable heatsink and controller. Temperature controlling accuracy is ±1°C. Preamplifier and current source are mounted on a small printed circuit board close to the laser diode. Diode itself is mounted on a small metal holder and attached to the Peltier element. Such construction results in a compact sensor, which is easy to attach to any optical system. Power supply unit is built as a separate block connected to the sensor by a cable.

2.3. General measurement setup

The block diagram of the measurement setup is shown in Fig. 4. The velocity sensor was mounted on a precision XYZ-translation stage controlled by micrometers, which allowed accurate collimation adjustment of the laser light. After passing through the collimator (Melles Griot 06GLC003), the beam was directed to the mirror (Newport 10D10ER.1, reflectance >96% at 650 nm), mounted on the translation stage (Newport M-ILS200PP, precision of the stage satisfied ISO230 standard) controlled by PC via motion control unit (Newport ESP300). The mirror was positioned at the right angle to the beam direction, so the whole light was reflected back to the laser cavity. The length of the external cavity at zero time was fixed to 10 cm. The output signal from the velocity sensor was further amplified in the external precision amplifier (ORTEC Precision ac Amplifier 9452). Bandwidth of this amplifier could be adjusted to remove noises, e.g., floor vibrations. During the measurements, the low and high cut-off frequencies were

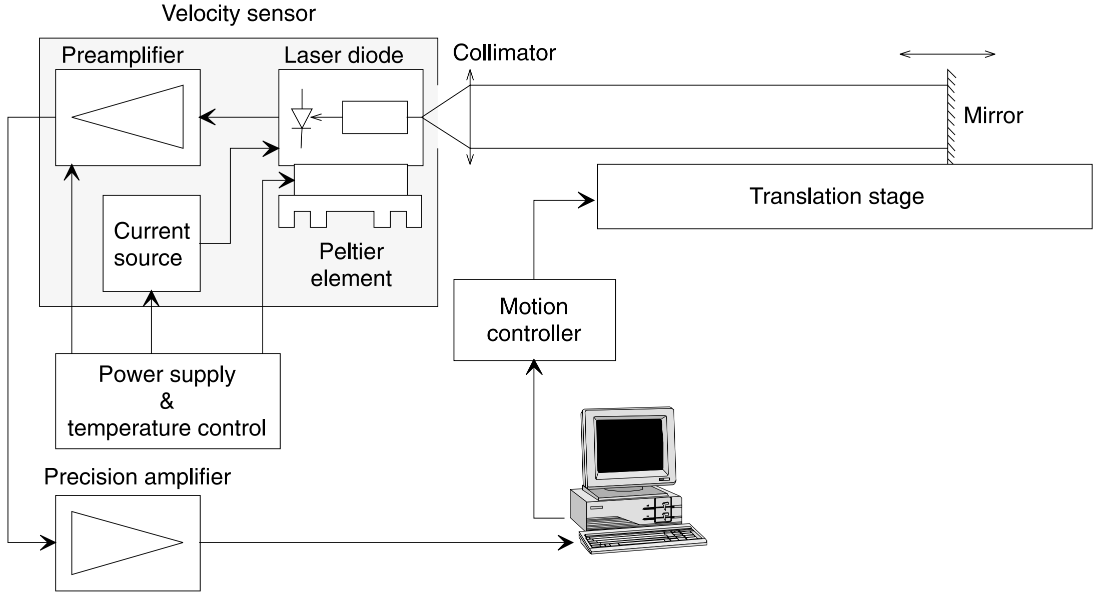

Fig. 4. The diagram of the measurement setup.

set to 100 Hz and 1MHz respectively. The analogue signal from the output of the precision amplifier was acquired by PC data acquisition card (National Instruments PCI6110E). The whole signal processing was made using LabView™ and Matlab™ softwares.

The mirror on the translation stage was driven following the pulse pattern shown in Fig. 5. The acceleration and retardation of the translation stage was 200 mm/s^2. The acceleration and the velocity of the mirror determine the rise time of the pulse. The constant velocity occurs during t_{on}. The fall time equals to t_r. The mirror is moved back and worth 10 times. More detailed parameters of the movement of the mirror are presented in Table 1.

The acceleration and retardation phases were cut off from the measurement data during data processing. Only the constant velocity that occurs during t_{on} was processed. Signal processing is based on calculation of discrete Fourier transform (DFT) that follows the equation

$$X(n) = \sum_{k=0}^{N-1} x(k)e^{-j2\pi kn/N}, \tag{6}$$

where $x(k)$ is the discrete time domain data sample and N is the length of this data vector [19]. The DFT is calculated with 512 points. Before applying DFT, the self-mixing signal is divided to appropriate time windows. Absolute values of the complex data points are calculated and squared and a power spectrum of the signal is determined. After the power spectrum is calculated, the frequency component that corresponds to maximum power, which equals to the Doppler frequency in the case of uniform motion, is selected and the velocity of the target is resolved using Eq. (5). Each scan of the mirror yields more than 300 power spectra. When the scans are repeated 10 times the total number of power spectra is more than 3000 in each mea-

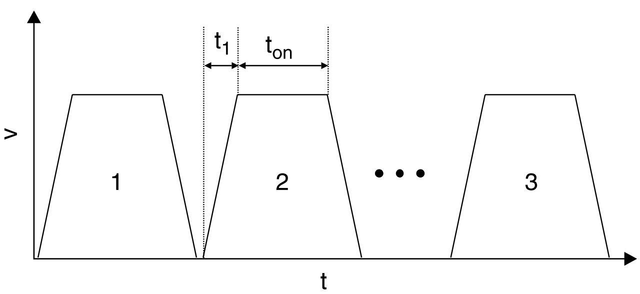

Fig. 5. Pulse pattern to control the movement of the mirror.

Table 1. The parameters of the mirror movement. The mirror velocity v is shown in the first column. Then the displacement of the mirror d, the rise time t_r, and t_{on}, which is the time when the velocity is constant, are shown. Last column is the sampling frequency F_s of the data acquisition board in the measurement.

v (mm/s)	d (mm)	t_r (s)	t_{on} (s)	F_s (kHz)
1.0	10	0.005	10.000	15.5
2.0	10	0.010	5.000	31.0
48.5	100	0.243	2.062	500.0
4.0	10	0.020	2.500	62.0
8.0	10	0.040	1.250	124.0
12.0	10	0.060	0.830	186.0
16.0	10	0.080	0.625	248.0
20.0	10	0.100	0.500	310.0
25.0	10	0.125	0.400	387.5
30.0	50	0.150	1.227	500.0
35.0	50	0.175	1.429	500.0
40.0	50	0.200	1.250	500.0

surement. Thus, each result is an average of large number of data. Average Doppler frequency $\langle f_D \rangle$, is calculated using equation

$$\langle f_D \rangle = \frac{1}{m} \sum_{j=1}^{m} f_{Dj}, \tag{7}$$

where m is the number of power spectra in the measurement and f_{Dj} is the Doppler frequency of *j-th* measurement. The standard deviation s of the maximum Doppler frequencies is also calculated using equation

$$s = \sqrt{\frac{1}{m-1} \sum_{j=1}^{m} \left(f_{Dj} - \langle f_D \rangle \right)^2}. \tag{8}$$

If the motion of a target is uneven, the averaged power spectra of the signal comprise a superposition of different Doppler spectra corresponding to different velocities. However, when an appropriate time-gaiting is performed, a distinct maximum can be observed in the Doppler spectra. For example, the power spectrum of a vibrating loudspeaker's membrane is shown in Fig. 6. The Doppler frequency peak can be located to 12.5 MHz, which corresponds 4.1 m/s velocity. The frequency peak is clearly visible 20 dB above noise level. Signal digitalisation in this experiment was done using a high-speed digital oscilloscope (Hewlett Packard Infinium) directly from the velocity sensor without using the precision amplifier. The loudspeaker was driven using a sinusoidal signal. The digital oscilloscope was triggered so that it recorded the power spectrum, when the driving signal had the highest gradient. This equals to the highest velocity of the loudspeaker's membrane.

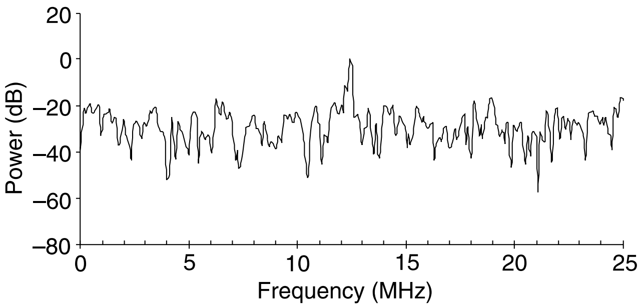

Fig. 6. Doppler spectrum from the vibrating loudspeaker's membrane.

3. Measurements and results

Velocity measurements were performed in the velocity range 1.0–48.5 mm/s. To obtain a good velocity reference, the before mentioned translation stage was used to yield constant velocity for the mirror. However, the properties of the translation stage limited the maximum available mirror velocity to 48.5 mm/s. Measurements of higher velocities can be performed using the loudspeaker's membrane as the

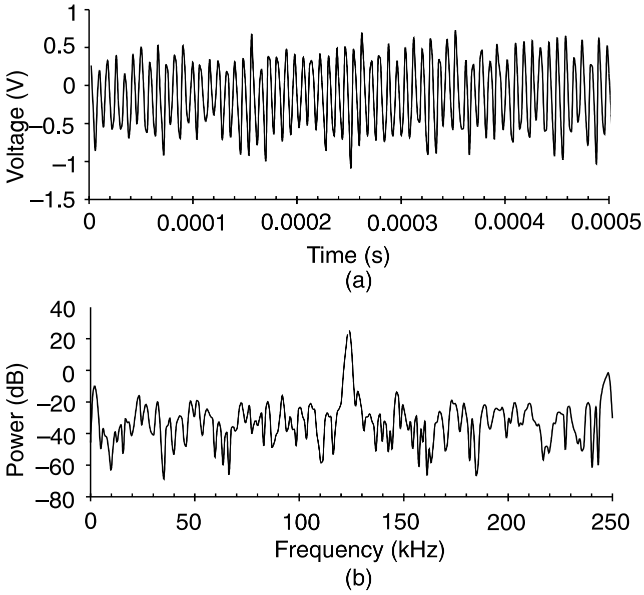

Fig. 7. Time domain Doppler signal (a) and corresponding Doppler spectrum (b). The mirror velocity is 40 mm/s.

target but there is no information about the actual velocity of the membrane. This is why only its Doppler spectrum is shown in Fig. 6.

The time domain Doppler signal and the corresponding Doppler spectrum are illustrated in Figs. 7(a) and 7(b). The time domain signal has a nice sinusoidal oscillation with approximately 1 V_{pp} voltage amplitude. The corresponding Doppler frequency can be obtained at 123 kHz about 40 dB above noise level. The measurements are summarized in Table 2. The total number of measurements was 12 from the previously mentioned velocity range.

Table 2. Summary of the velocity measurements. The second column indicates the velocities of the reference mirror v_M, and third one presents the corresponding theoretical Doppler frequencies f_{Th}. The measured Doppler frequencies $\langle f_D \rangle$, are shown in the fourth column, and the last one presents the standard deviations s, of the measured Doppler frequencies.

Meas. no.	v_M (mm/s)	f_{Th} (kHz)	$\langle f_D \rangle$ (kHz)	s (kHz)
1	1.00	3.09	3.16	0.24
2	2.00	6.18	6.38	0.33
3	4.0	12.36	12.12	1.23
4	8.00	24.72	24.87	2.47
5	12.00	37.08	37.20	2.08
6	16.00	49.44	49.92	2.76
7	20.00	61.80	62.00	2.94
8	25.00	77.16	77.34	2.30
9	30.00	92.59	92.14	3.43
10	35.00	108.02	107.77	3.42
11	40.00	123.46	123.11	3.31
12	48.50	149.69	148.45	3.72

The linearity of the velocity sensor compared to the mirror velocity set by the computer is shown in Fig. 8. The standard deviation is shown as vertical bars on each data point. The measured velocity is calculated from the measured Doppler frequency using Eq. (5). The trend line, fitted to the measured data points using the linear mean square approximation, follows the equation

$$\textit{measured velocity} = 0.9965 \times \textit{mirror velocity} + 0.0754, \quad (9)$$

where velocity is in millimetres per second. This result shows that the linearity of the measurement sensor within this velocity range is good and the velocity sensor can be easily calibrated using Eq. (9). If the linearity of the velocity sensor is also valid at 12.5 MHz, which was the Doppler frequency from the loudspeaker's membrane shown in Fig. 6, this correspond to 4.09 m/s velocity.

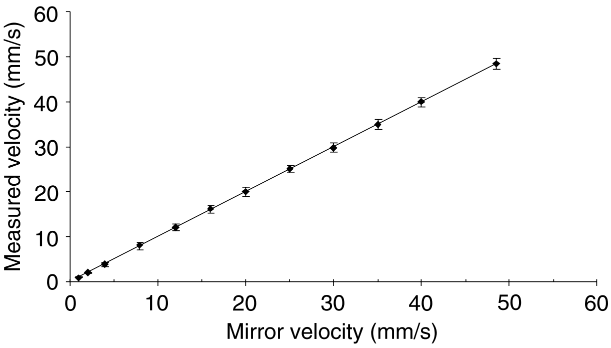

Fig. 8. Linearity of the velocity sensor.

Precision of the measurement sensor compared to theoretical one as a function of measured velocity is show in Fig. 9. It is calculated using equation

$$error(\%) = \sqrt{\left(\frac{f_{Th} - \langle f_D \rangle}{f_{Th}}\right)^2} \times 100. \quad (10)$$

It can be seen that the relative error is higher at lower velocities and decreases when the velocity increases. Similar results were also obtained by Bosch *et. al.* [20]. The relative error is around or less than 1% when the mirror velocity exceeds 4.0 mm/s velocity. Above 20 mm/s the relative error is less than 0.5%.

4. Discussion

The self-mixing effect is a very useful phenomenon and it offers a lot of potential to different velocity measurement applications. There are several special features that are advantages for this effect. Firstly, the interferometer is easy to use because there is only one optical axis to control. Secondly, it is simple because basically only laser itself is needed. Thirdly, it is a cheap technique and the interferometer can be build into a small size and a compact package. Self-mixing technique offers a lot of potential to velocity and displacement measurements, especially fascinating, in different Micro-Electro-Mechanical System (MEMS) and BioMEMS applications. When using a self-mixing interferometer one must be very careful with optical feedback to the laser. As it was discussed in section 2.1 the shape of the self-mixing signal depends on the strength of the feedback field. Too strong feedback causes unstable operation of the laser. So the optical properties of the measured target must be carefully considered. An interesting situation occurs, when the self-mixing signal has the saw-tooth behaviour. Then it changes its inclination in respect to the phase of the external target. Thus, this phenomenon can be used to detect the direction of the moving target [21].

In this paper, the self-mixing effect in a laser diode was used to develop a budget velocity sensor, which frequency response (3 dB) is up to 85 MHz. Theoretically, this Doppler frequency corresponds to 27.5 m/s velocity. Total material costs of the developed sensor were 234 euro, which includes power supply, temperature controller, current source to laser and preamplifier with the laser diode. Due to lack

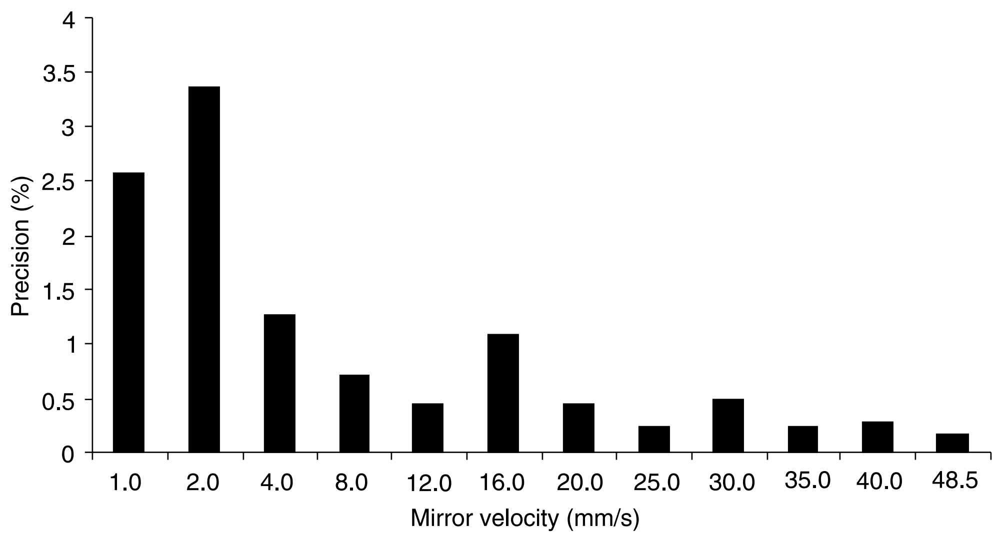

Fig. 9. The relative error of the measurement sensor as function of the mirror velocity.

of appropriate velocity reference, the measurements in this case were limited to the velocity range 1.0–48.5 mm/s. However, it was shown that, when using appropriate time-gating, the Doppler frequency at 12.5 MHz is detectable from the moving loudspeaker's membrane, and its maximum velocity can be determined. It was found out that the velocity sensor has a very good linearity compared to the mirror velocity set by the computer in the velocity range 1.0–48.5 mm/s. The precision with the mirror velocity is higher, above 1%, at low velocities, while at velocities above 20 mm/s it is less than 0.5%.

In future, measurements will be performed in a much wider velocity range with corresponding Doppler frequencies is up to 85 MHz. The length of the external cavity will be increased so that the velocity measurement will occur from a distance of several tens of meters. In addition, different velocity profiles will be measured. It is also interesting to show that this sensor is capable of measuring displacements of the target of order $\lambda/2$. The transimpedance amplifier will be also developed so that the frequency range of the sensor will be doubled to 170 MHz. This corresponds to 55 m/s velocity.

Acknowledgements

Authors would like to thank professor Alexander V. Priezzhev for fruitful comments and revising the English of the manuscript. Second and third author would like to thank Infotech Oulu graduate school for financial support during this work.

References

1. T.H. Maiman, "Stimulated optical radiation in ruby", *Nature* 187, 493–494 (1960).
2. P.G.R. King, and G.J. Steward, "Metrology with an optical maser", *New Sci.* **17**, 180 (1963).
3. M.J. Rudd, "A laser Doppler velocimeter employing the laser as a mixer-oscillator", *J. Physics E-Scientific Instruments* **1**, 723–726 (1968).
4. S. Shinohara, A. Mochizuki, H. Yoshida, and M. Sumi, "Laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode", *Appl. Opt.* **25**, 1417–1419 (1986).
5. T. Shibata, S. Shinohara, H. Ikeda, H. Yoshida, and M. Sumi, "Automatic measurement of velocity and length of moving plate using self-mixing laser diode", *IEEE T. Instrum. Meas.* **48**, 1062–1067 (1999).
6. S.K. Özdemir, T. Takasu, S. Shinohara, H. Yoshida, and M. Sumi, "Simultaneous measurement of velocity and length of moving surfaces by a speckle velocimeter with two self-mixing laser diodes", *Appl. Opt.* **38**, 1968–1974 (1999).
7. S. Donati, G. Giuliani, and S. Merlo, "Laser diode feedback interferometer for measurement of displacement without ambiguity", *IEEE J. Quantum Electron.* **31**, 113–119 (1995).
8. T. Gharbi, A. Courteville, and A. Chebbour, "Backscatter-modulated laser diode for low-frequency small-amplitude vibration measurement", *Appl. Opt.* **36**, 8233–8237 (1997).
9. F. Gouaux, N. Servagent, and T. Bosch, "Absolute distance measurement with an optical feedback interferometer", *Appl. Opt.* **37**, 6684–6689 (1998).
10. G. Mourat, N. Servagent, and T Bosch, "Distance measurement using the self-mixing effect in a three-electrode distributed Bragg reflector laser diode", *Opt. Eng.* **39**, 738–743 (2000).
11. P.J. Rodrigo, M. Lim, and C Saloma "Optical-feedback semiconductor laser Michelson interferometer for displacement measurements with directional discrimination" *Appl. Opt.* **40**, 506–513 (2001).
12. G. Beheim, and K. Fritsch, "Range finding using frequency modulated laser diode", *Appl. Opt.* **25**, 1439–1442 (1986).
13. P.J. de Groot, G.M. Gallatin, and S.H. Macomber, "Ranging and velocimetry signal generation in a backscatter-modulated laser diode", *Appl. Opt.* **27**, 4475–4480 (1988).
14. E. Gagnon and J.F. Rivest, "Laser range imaging using the self-mixing effect in a laser diode", *IEEE T. Instrum. Meas.* **48**, 693–699 (1999).
15. K. Petermann, *Laser Diode Modulation and Noise*, Kluwer Academic Publishers, Tokyo, 1991.
16. K. Meigas, H. Hinrikus, J. Lass, and R. Kattai, "Pulse profile registration using self-mixing in a diode laser", *Proc. IEEE/EMBS* **4**, 1875–1878 (1998).
17. G.A. Acket, D. Lenstra, A.F. den Boef, and B.H. Verbeek, "The influence of feedback intensity on longitudinal mode properties and optical noise in index-guided semiconductor lasers", *IEEE J. Quantum Electron.* **QE20**, 1163–1189 (1984).
18. M.H. Koelink, M. Slot, F.F.M. de Mul, J. Greve, R. Graaff, A.C.M. Dassel, and J.G. Aarnoudse, "Laser Doppler velocimeter based on the self-mixing effect in a fibre-coupled semiconductor laser: theory", *Appl. Opt.* **31**, 3401–3408 (1992).
19. E.C. Ifeachor and B.W. Jervis, *Digital Signal Processing: A Practical Approach*, Addison-Wesley Publishing Company, New York, 1993.
20. T. Bosch, N. Servagent, and S. Donati, "Optical feedback interferometry for sensing application", *Opt. Eng.* **40**, 20–27 (2001).
21. W.M. Wang, W.J.O. Boyle, K.T.V. Grattan, and A.W. Palmer, "Self-mixing interference in a diode laser: Experimental observations and theoretical analysis", *Appl. Opt.* **32**, 1551–1558 (1993).