Laser Vibrometry

Preparatory School on Applications of Optics and Photonics in Food Science

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3. Theory
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1. Introduction

The self-mixing effect is a phenomenon caused by a “parasite” feedback due to reflection (diffuse or not) on external surfaces, other than the mirrors of the laser resonator. It is a serious perturbation source, affecting both amplitude and frequency of the emitted beam.

It is stronger in lasers with high-gain active media, as laser diodes.

In most applications self-mixing effect is an undesirable effect that can be avoided by a careful optical design that includes the use of optical isolators.

Self-mixing effect is related to injection locking and synchronization effects.

1. Introduction

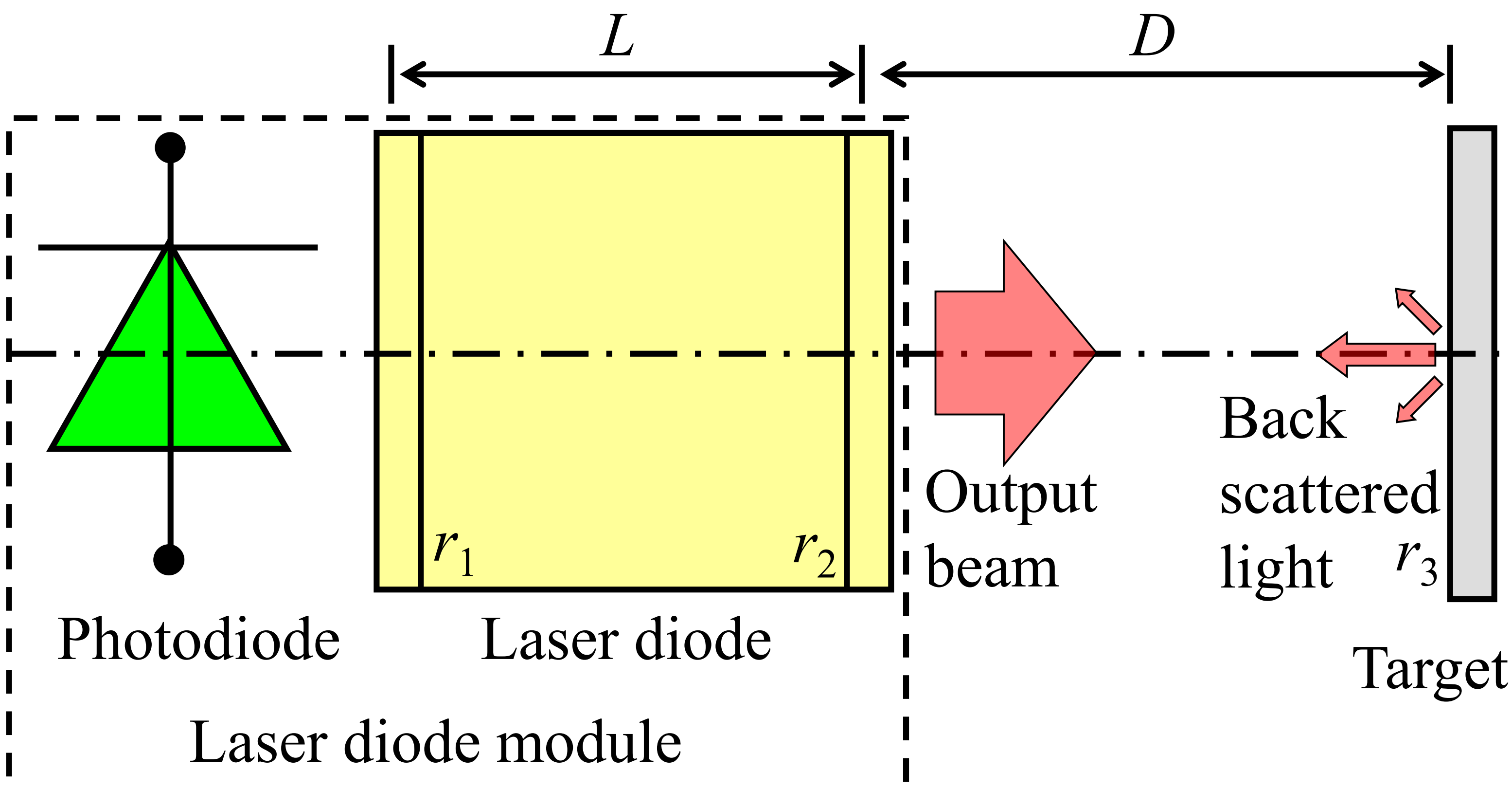
The application of feedback-induced phenomena for measuring optical path lengths was reported as early as in 1968. The first example of a fringe-counting device based on a feedback interferometer was reported in 1978. Frequency stabilization, longitudinal mode selection Displacement measurements, absolute distance measurements, velocimetry, and vibration measurement have being demonstrated.

M. J. Rudd, “A laser Doppler velocimeter employing the laser as a mixer-oscillator,” J. Sci. Instrum. 1, 723–726 (1968).
S. Donati, “Laser interferometry by induced modulation of the cavity field,” J. Appl. Phys. 49, 495–497 (1978).
S. Donati, L. Falzoni, and S. Merlo, “A PC-interfaced, compact laser diode feedback interferometer for displacement measurements,” IEEE Trans. Instrum. Meas. 45, 942–947 (1996)
P. A. Roos, M. Stephens, and C. E. Wieman, “Laser vibrometer based on optical-feedback induced frequency modulation of a single-mode laser diode,” Appl. Opt. 35, 6754–6761 (1996).
S. Merlo and S. Donati, “Reconstruction of displacement waveforms with a single-channel laser diode feed-back interferometer,” IEEE J. Quantum Electron. 33, 527–531 (1997).
G. Beheim and K. Fritsch, “Range finding using frequency modulated laser diode,” Appl. Opt. 25, 1439–1442 (1986).
S. Shinohara, H. Yoshida, H. Ikeda, K. Nishide, and M. Sumi, “Compact and high-precision range finder with wide dynamic range and its application,” IEEE Trans. Instrum. Meas. 41, 40–44 (1992).
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).
T. Shibata, S. Shinohara, H. Ikeda, H. Yoshida, T. Sawaki, and M. Sumi, “Laser speckle velocimeter using self-mixing laser diode,” IEEE Trans. Instrum. Meas. 45, 499–503 (1996).

1. Introduction

In this presentation we outline the basic principles of the laser vibrometry or self-mixing effect and present the theory, design and construction of an photothermal spectrometer based on this phenomenon for trace detection with specific uses in environmental research and food analysis.

2. General considerations



Simplified scheme of a self-mixing interferometer with a laser diode module with encapsulated photodiode.

2. General considerations

Main features of a self-mixing interferometer with a laser diode with comments based on our experience.

1. No external optical component to the source is needed. *However, in some configurations, lenses and other optical components have to be added, for beam shaping or for increasing spatial resolution. These optical components may give some feedback perturbing that way the self-mixing detection.*

2. No alignment is necessary, since the laser itself filters out spatially the spatial mode that interacts with the resonator mode. *However, if the surface scatters light in a very narrow solid angle, alignment problems may arise because of the strong dependence of the feedback on the angle between the normal to the surface and the laser diode.*

T. Bosch, N. Servagent and S. Donati, "Optical feedback interferometry for sensing application," Opt. Eng. 40(1) 20–27 (2001).
G. Giuliani, M. Norgia, S. Donati and T. Bosch, "Laser diode self-mixing technique for sensing applications," J. Opt. A: Pure Appl. Opt. 4, S283–S294 (2002).

2. General considerations

Main features … (from the previous slide)

3. No external photodetector is needed, because the signal is provided by the monitor photodiode contained in the LD module. *However, some of the technical characteristics of the encapsulated photodiode may be inadequate for a specific application. For example, its bandwidth may be not large enough to accommodate the Fourier spectrum of the signal. In such a case, an external photodetector and additional optical components must be added.*

4. No stray-light filtering before the photodetector is needed. *This is true when we use an encapsulated photodiode for light sensing.*

T. Bosch, N. Servagent and S. Donati, "Optical feedback interferometry for sensing application," Opt. Eng. 40(1) 20–27 (2001).
G. Giuliani, M. Norgia, S. Donati and T. Bosch, "Laser diode self-mixing technique for sensing applications," J. Opt. A: Pure Appl. Opt. 4, S283–S294 (2002).

2. General considerations

Main features … (from the previous slide)

6. The beam can be sampled at different points, even at the same target.

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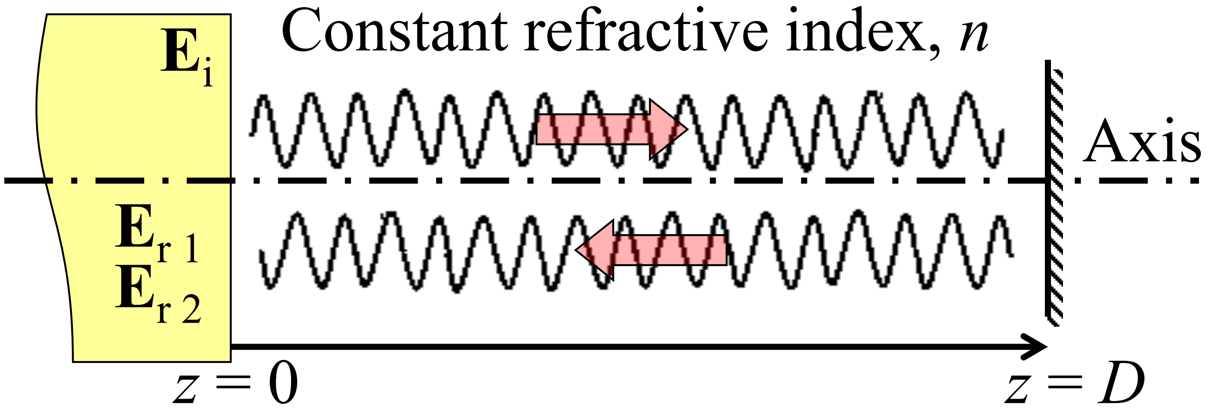
G. Giuliani, M. Norgia, S. Donati and T. Bosch, “Laser diode self-mixing technique for sensing applications,” J. Opt. A: Pure Appl. Opt. 4, S283–S294 (2002).

3. Theory

In the three-mirror cavity model the rear and the front facets of the laser diode (LD) and the target surface are considered as the mirrors of a laser resonator with reflection coefficients , respectively. The optical beam is back-scattered into the LD active resonator by the target, so that the laser operation is disturbed.



T. Bosch, N. Servagent and S. Donati, "Optical feedback interferometry for sensing application," Opt. Eng. 40(1) 20–27 (2001).
G. Giuliani, M. Norgia, S. Donati and T. Bosch, "Laser diode self-mixing technique for sensing applications," J. Opt. A: Pure Appl. Opt. 4, S283–S294 (2002).

3. Theory

The optical power of the LD with external feedback P_c and the optical power without external feedback P_s are linked by the formula:

$$P_c = P_s[1 + m' \cos(2\pi \nu_c \tau_D)]$$

where m', ν_c, and τ_D are the modulation parameter, the optical frequency of the emitted light with feedback and the round trip delay of photons, respectively.

For the case of stable, single mode operation the modulation parameter can be approximated as:

$$m' \approx r_3$$

Therefore the variations of the output power P_c are due to the changes of the optical path length nD.

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).

3. Theory. Photothermal effect.

When a medium is irradiated with a periodically modulated excitation laser beam with Gaussian profile the solution of the equation for the temperature rise in the sample is

$$\Delta T(r,t) = \frac{2P_e\alpha}{\pi\rho C_p\omega_{0e}^2}\int_0^t \frac{1}{1+2t'/t_c} exp\left[-\frac{2r^2}{\omega_{0e}^2(1+2t'/t_c)}\right] dt' \quad (1)$$

J. P. Gordon, R. C. C. Leite, R. S. Moore, S. P. S. Porto, and J. R. Whinnery, "Long-transient effects in lasers with inserted liquid samples,"Journal of Applied Physics, vol. 36, no. 1, pp. 3–8, 1965.

3. Theory. Photothermal effect.

The temperature rise in the sample can be obtained if t>>t_c

$$\Delta T(t) \cong \frac{\alpha P_e}{16.8\pi k} ln(\frac{2t}{t_c}),$$

The refractive index change with temperature

$$\Delta n(t) = n_0 + \frac{dn}{dT}\Delta T(t),$$

Then the refractive index change acts as an optical element changing the phase of a laser beam passing through it

$$\Delta\Phi(t) = \frac{2\pi}{\lambda_p} l \Delta n(t) = \frac{2\pi}{\lambda_p}\frac{dn}{dT} l \Delta T(t)$$
$$= \frac{0.12}{\lambda_p}\frac{dn}{dT} l \frac{\alpha P_e}{k} ln(\frac{2t}{t_c}),$$

J. P. Gordon, R. C. C. Leite, R. S. Moore, S. P. S. Porto, and J. R. Whinnery, "Long-transient effects in lasers with inserted liquid samples,"Journal of Applied Physics, vol. 36, no. 1, pp. 3–8, 1965.

3. Theory. Photothermal effect.

By mixing in the laser cavity, the re-injected light perturbs the intracavity electric field, transferring this information from the TL effect, which then becomes measurable through the resulting variation in optical power described as follows

$$\frac{P_f - P_0}{P_0} = m\cos(\omega_f \tau),$$

where P_F is the laser power emitted, P_0 is the laser power without optical feedback

H Cabrera et al. "Pump-probe photothermal self-mixing system for highly sensitive trace detection" IEEE Sensors (2019) DOI:10.1109/JSEN.2018.2889600

3. Theory. Photothermal effect.

However, when the distance from the laser to the mirror M is greater than the coherence length of the laser, feedback phase loses are not important; the laser operates independent of feedback phase, but still depends on the feedback amplitude intensity m. Therefore we can write:

$$\frac{P_f - P_0}{P_0} = 0.24Bm\frac{1}{\lambda_p}\frac{dn}{dT}l\frac{\alpha P_e}{k}ln(\frac{2t}{t_c})$$

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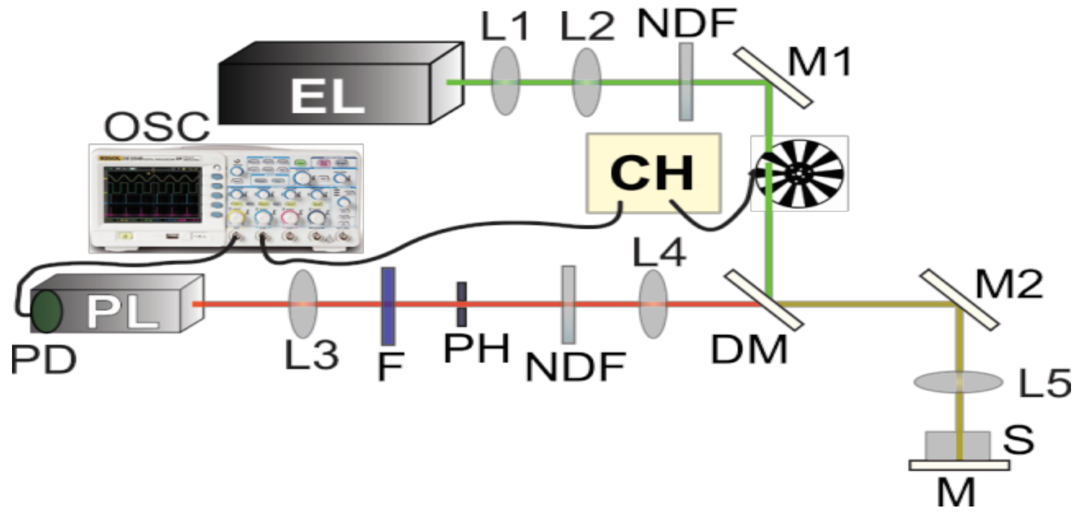
4. Application to trace detection



Scheme of the self-mixing pump-probe TL experimental setup. EL: excitation laser, PL: probe laser, PD: photodiode, L1, L2, L3, L4, L5: collimating lenses, M, M1, M2: mirrors, PH: variable pinhole, CH: chopper, F: filter, DM: dichroic mirror, NDF: neutral density filter, S: sample cell, OSC: oscilloscope.

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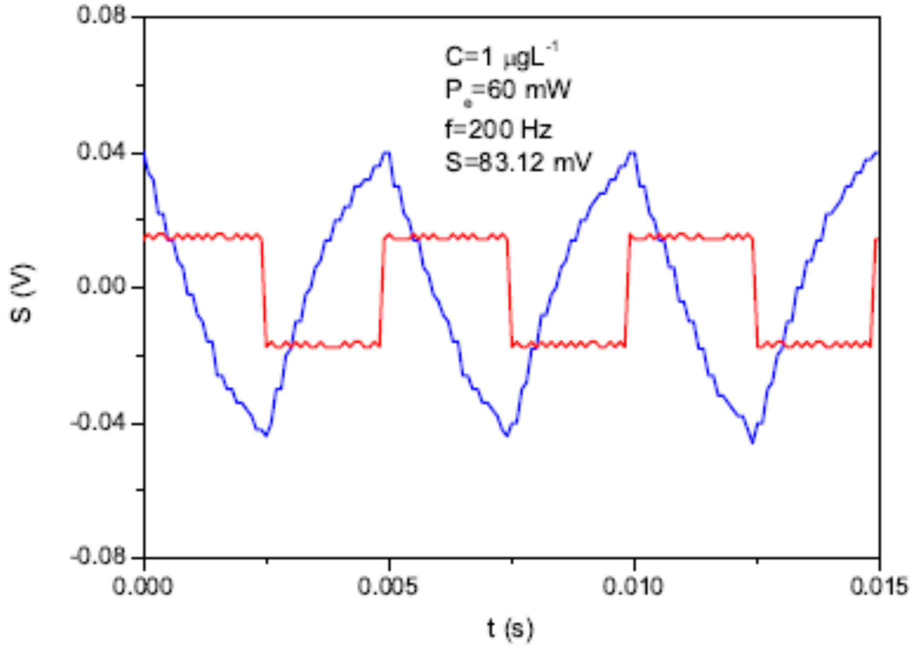
4. Application to trace detection



Self-mixing signal as a function of time for the concentration. The blue line is the signal due to the TL effect and the red line represents the modulated excitation.

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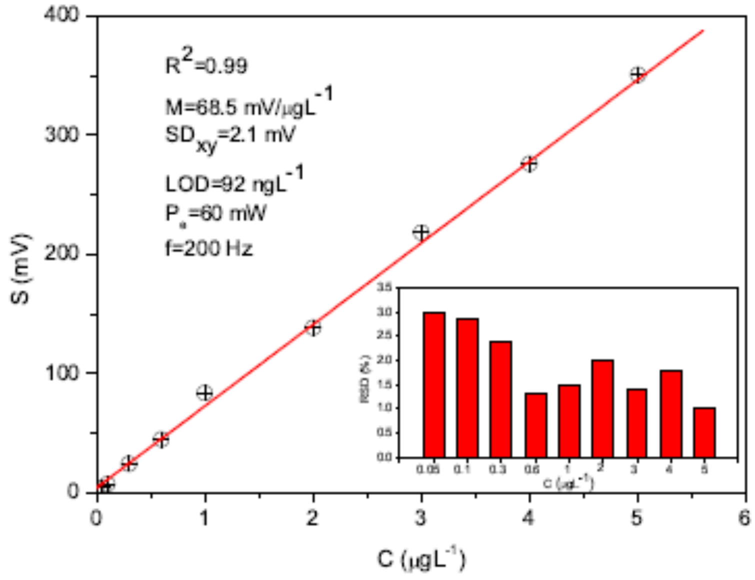
4. Application to trace detection



Calibration curve for Fe(II) concentrations in water-ethanol solution. The inset shows the RSD for each measurement point (n=7)

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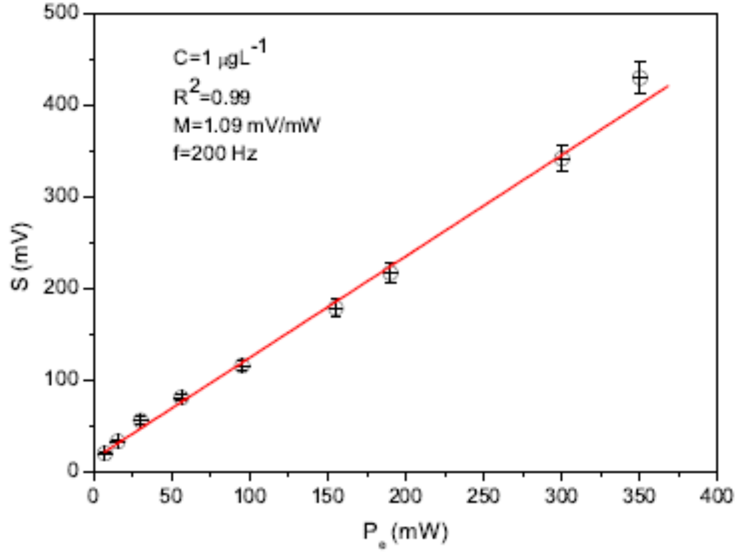
4. Application to trace detection



Power dependence of the self-mixing signal for the concentration. Solid line, least-squares linear fit of the experimental data

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5. Application to vibration measurement

Consider a sinusoidal vibration perpendicular to the target surface. Then the distance D can be written as:

$$D = D_0 + A_0 \cos(2\pi \frac{t}{T})$$

where D_0 is the mean position of the surface on the laser diode axis, A_0 - the amplitude and T - the oscillation period.

$$P_c = P_s \left\{ 1 + m' \cos[4\pi \frac{nD_0}{\lambda_c} + 4\pi \frac{nA_0}{\lambda_c} \cos(2\pi \frac{t}{T})] \right\}$$

where λ_c is the wave length.

Assuming a linear response of the photodiodes and a negligible distortion the captured signal has the form:

$$V_c = V_s \left\{ 1 + m' \cos[4\pi \frac{nD_0}{\lambda_c} + 4\pi \frac{nA_0}{\lambda_c} \cos(2\pi \frac{t}{T})] \right\}$$

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).

5. Application to vibration measurement

To extract the amplitude from the above expression we can use different "tricks". The simpler one is to count the number of peaks q between two consecutive symmetrical points of the signal. Then we obtain:

$$A_0 = \frac{q\lambda_c}{4}$$

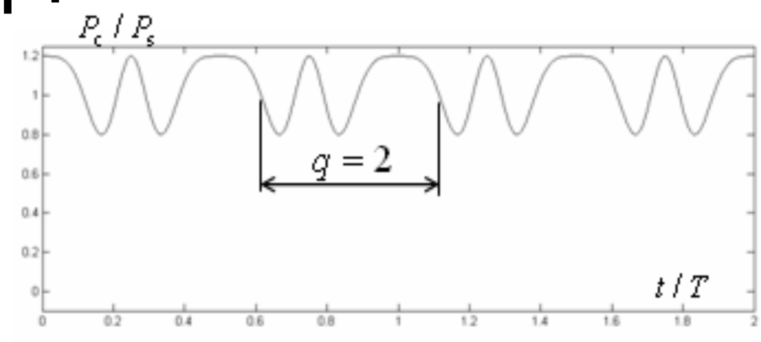
with a relative uncertainty:

$$\left|\frac{\Delta A_0}{A_0}\right| \leq \left|\frac{\Delta \lambda_c}{\lambda_c}\right| + \left|\frac{\varepsilon}{4q}\right|$$

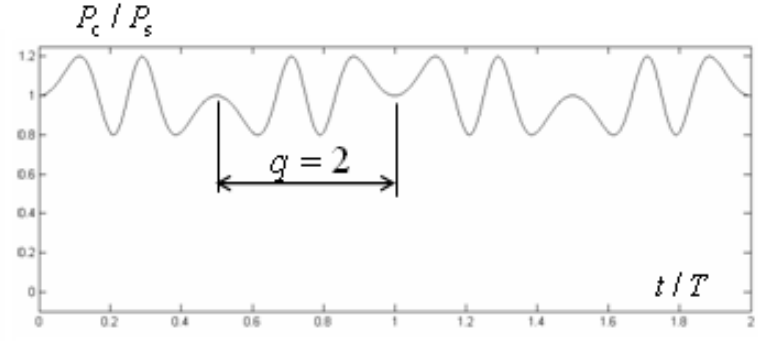
where $0 \leq \varepsilon \leq 1$ is the uncertainty of q.

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).

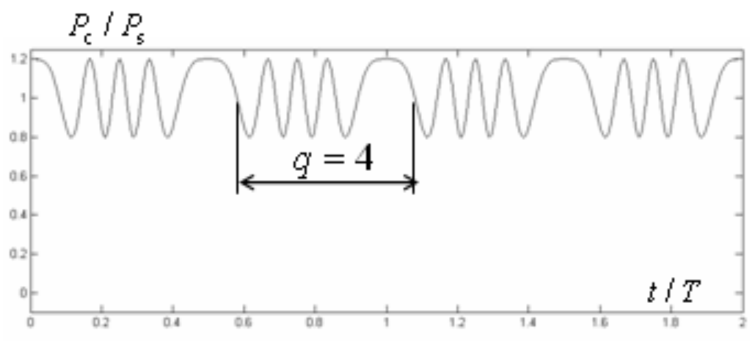
5. Application to vibration measurement



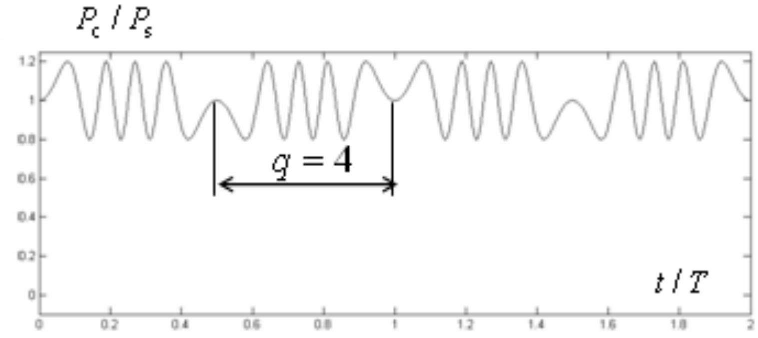
$A_0 = 0.5\lambda_0,\ 4\pi n D_0 / (\lambda_c c) = 2k\pi$



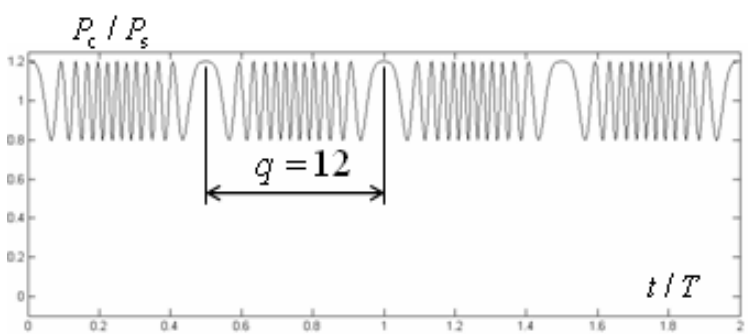
$A_0 = 0.5\lambda_0,\ 4\pi n D_0 / (\lambda_c c) = (2k+1)\pi / 2$



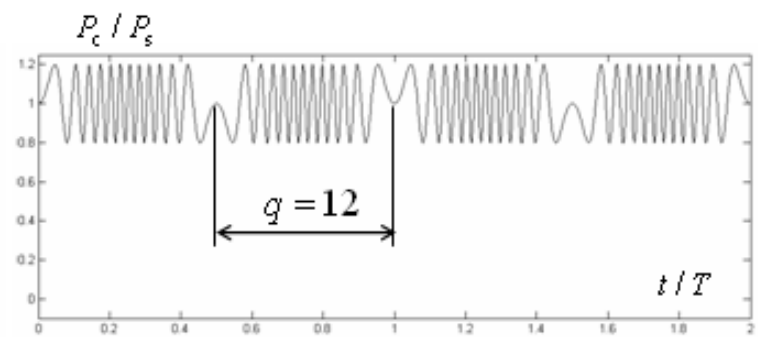
$A_0 = \lambda_0,\ 4\pi n D_0 / (\lambda_c c) = 2k\pi$



$A_0 = \lambda_0,\ 4\pi n D_0 / (\lambda_c c) = (2k+1)\pi / 2$



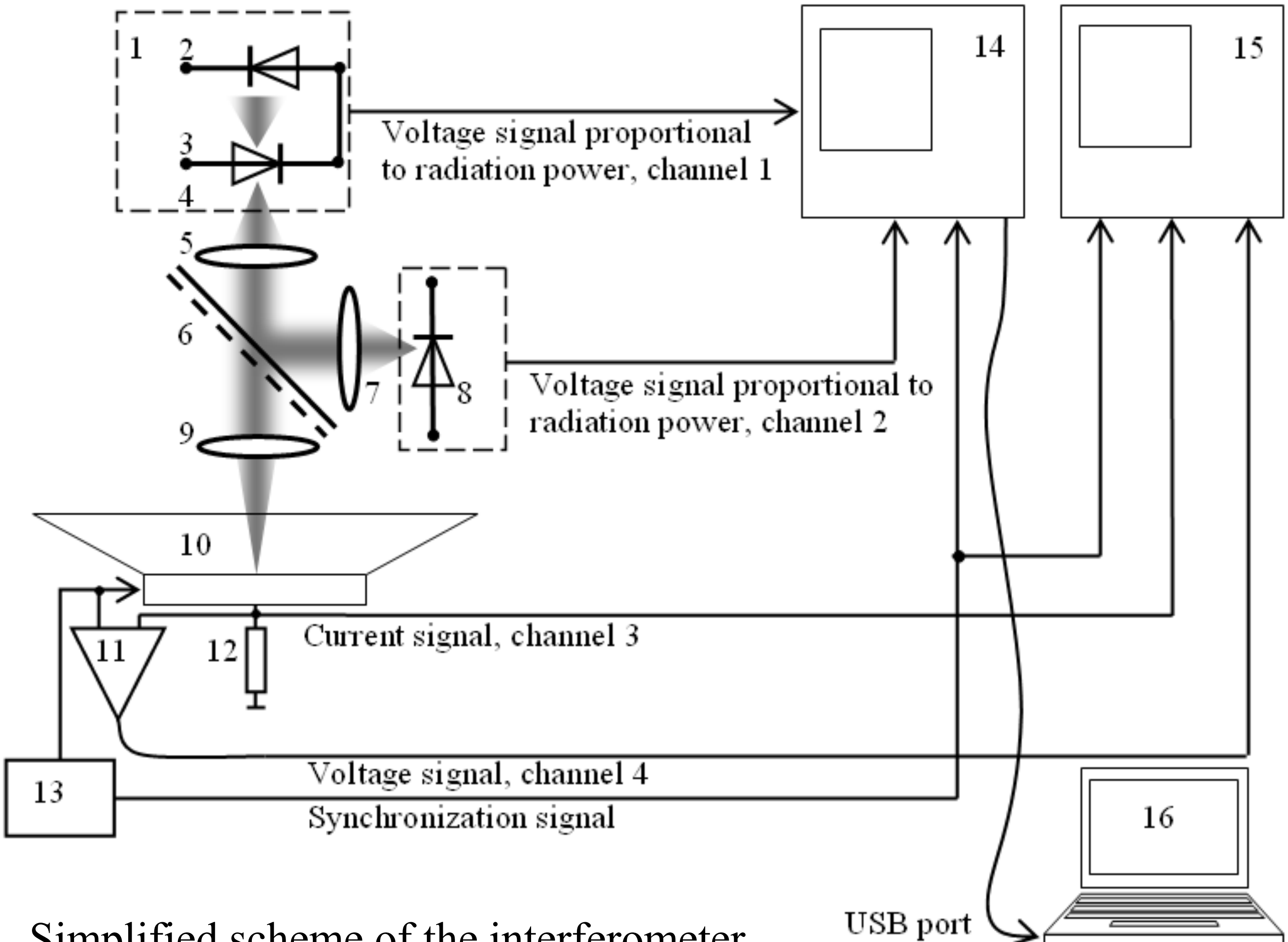
$A_0 = 3\lambda_0,\ 4\pi n D_0 / (\lambda_c c) = 2k\pi$



$A_0 = 3\lambda_0,\ 4\pi n D_0 / (\lambda_c c) = (2k+1)\pi / 2$

Plots of the normalized power versus normalized time for $m' = 0.2$.

5. Vibrometer



Simplified scheme of the interferometer

5. Vibrometer

1. Optical block.

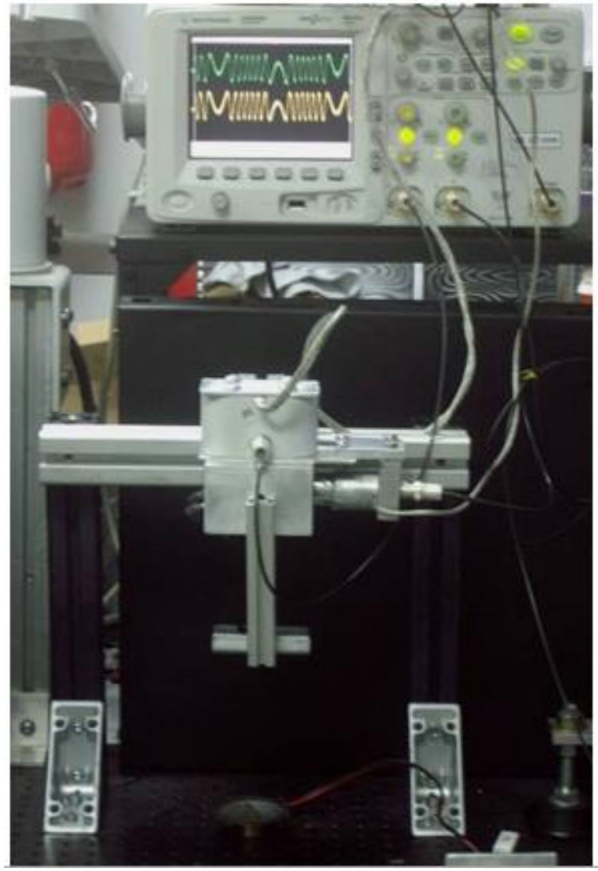
The laser diode module (1) HL6738MG (35mW, 680nm, single mode, from Hitachi) contains the photodiode (2) and the laser diode (3). Both devices are fed by a stabilized power supply (model IPS4303 from Isotech) and have an ad hoc circuitry, not shown in fig. 4. The large divergence in the fast axis of the beam (4) is
corrected by the beam shaping optics (5) to obtain a collimated beam. The 50% beam splitter (6) samples the beam, sending a fraction to the collecting lens (7), which in turn focuses it on the photodetector (8). The photodetector (8) is a commercially available photodiode with an ad hoc circuitry, not shown in fig. 4. The lens (9) focuses the beam
on the surface of a professional loudspeaker (10).

5. Vibrometer

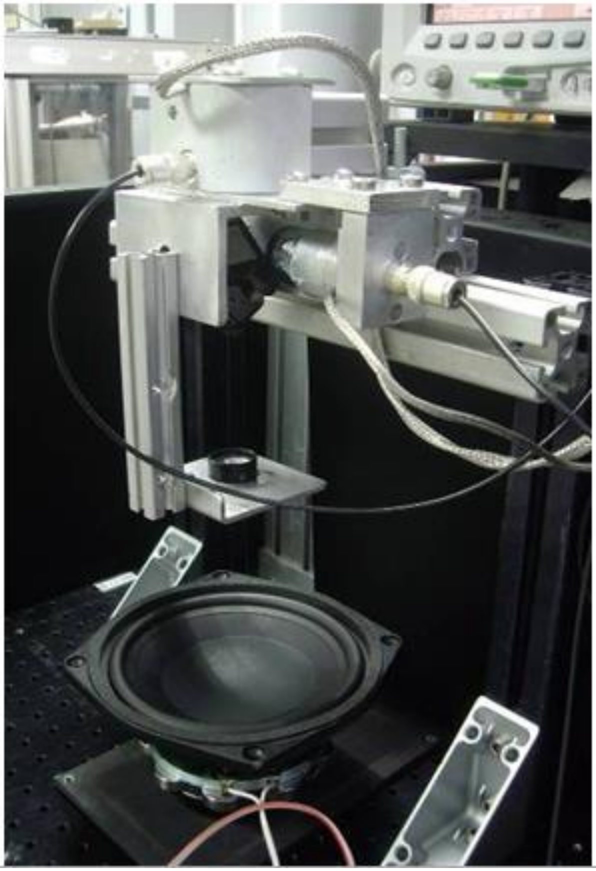
2. Electronic block.

The voltage differential amplifier (11) senses the input voltage delivered by the function generator (13) (model GFG 8216A from Isotech) to the loudspeaker. The resistance (12) samples the current flowing through the loudspeaker. The signals coming from the photodiode 1 (PHD 1, channel 1), the photodiode 2 (PHD 2, channel 2), are introduced into the dual trace digital oscilloscope (14) (model DSO 6052A from Agilent), while the current signal (channel 3) and the voltage signal (channel 4) – to the dual trace oscilloscope (15) (model PM 3335 from Philips). If we want to record digitally the current and voltage signals, the channel 3 and 4 are connected to the oscilloscope (14) and the channels 1 and 2 to the oscilloscope (15). Other connection schemes are possible. A TTL synchronization signal from the function generator (13) is introduced into the oscilloscopes (14) and (15) for obvious purposes. The digital signals at the oscilloscope (14) can be saved as images, ASCII files or excel files in a personal computer (16) or in a flash memory via the USB port.

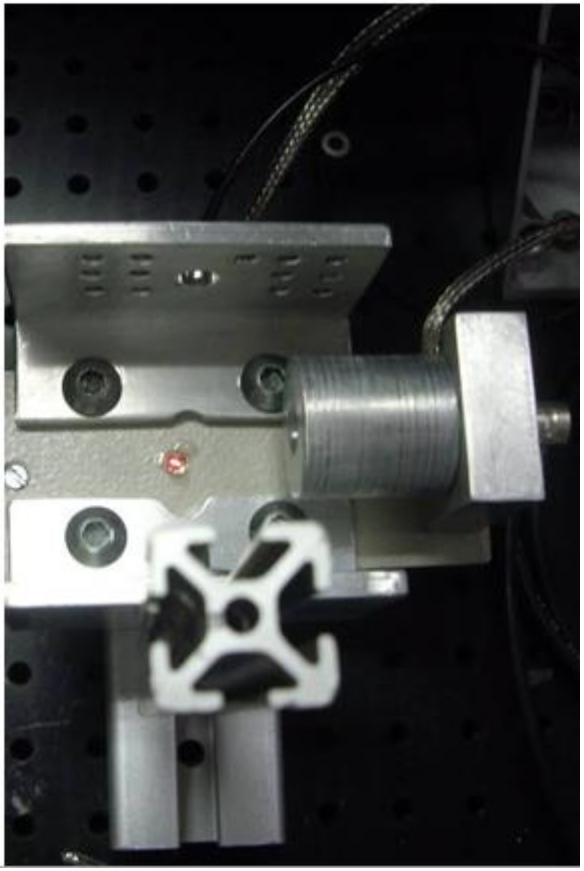
5. Vibrometer



Front view

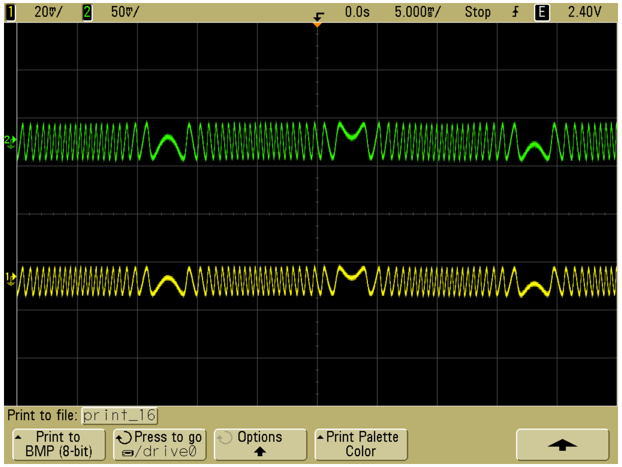


Focusing lens and loudspeaker

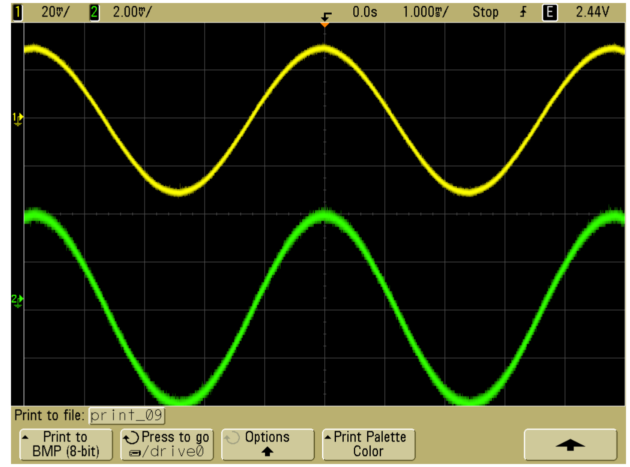


Laser diode and with beam shaping optics and photodiode in its housing

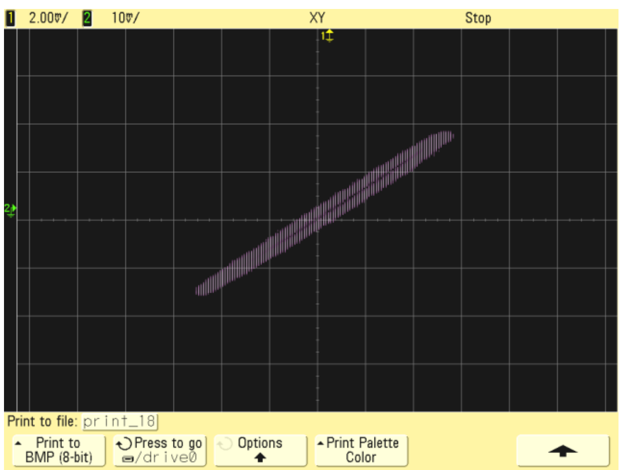
5. Vibrometer



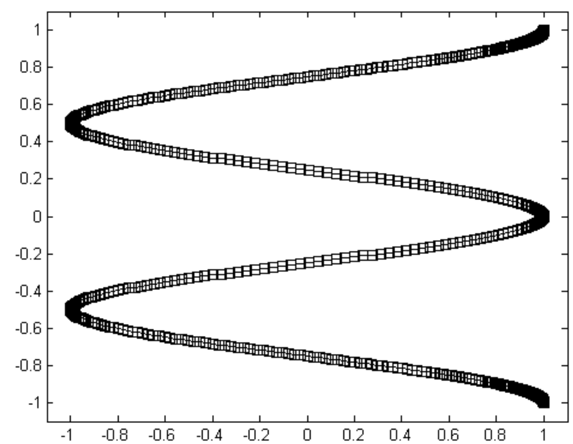
Green trace – PHD 2,
Yellow trace – PHD 1



Green trace – current signal
Yellow trace – voltage signal



Lissajous figure of the signals from the loudspeaker.



X axis – normalized current signal
Y axis – normalized signal PHD 1.

6. Signal processing

Numerical techniques of phase unwrapping should be applied to extract the amplitude. Here we describe a simpler but not so precise technique to extract the amplitude.

The main drawback of the counting method is that the relative uncertainty of q, ε/q approaches to unity as the amplitude tends to zero. To palliate it let us consider the recurrence transformation:

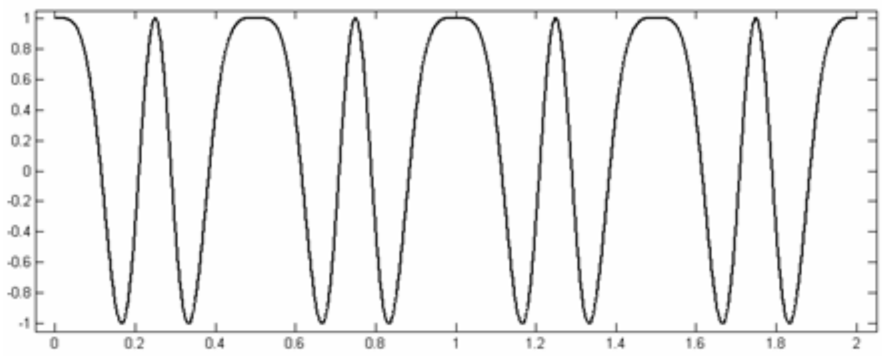
$$f_{g+1} = 2(f_g^2 - 0.5),\ g = 1, 2, 3, \ldots$$

$$f_1 = \cos[4\pi D_{\mathrm{n}} + 4\pi A_{\mathrm{n}} \cos(2\pi t_{\mathrm{n}} + \varphi_0)]$$

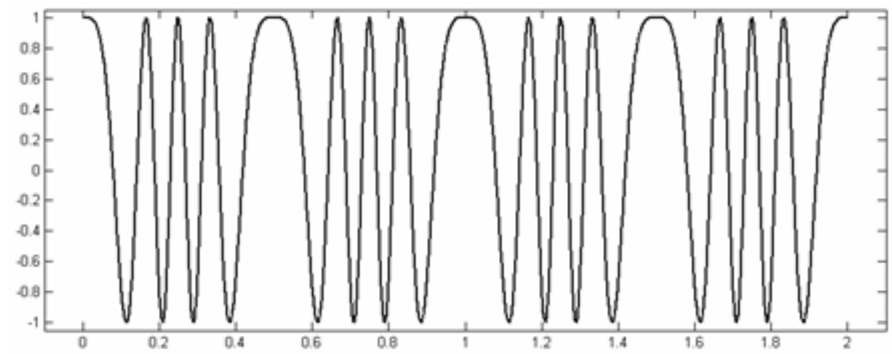
where f_1 is the normalized captured signal without the DC term and

$$D_{\mathrm{n}} = D_0 / \lambda_{\mathrm{c}},\ A_{\mathrm{n}} = A_0 / \lambda_{\mathrm{c}},\ t_{\mathrm{n}} = t / T$$

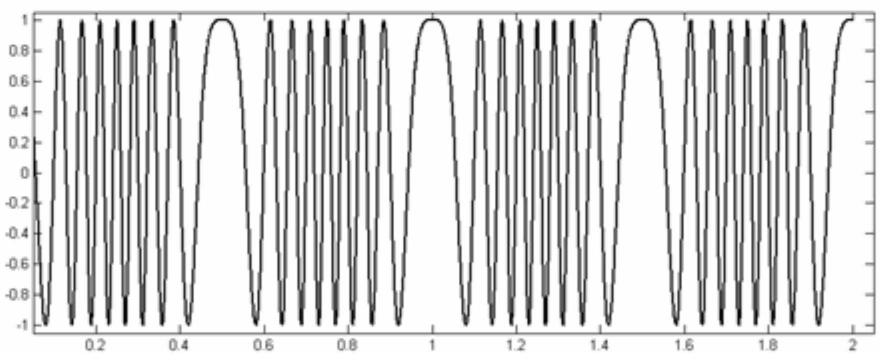
6. Signal processing



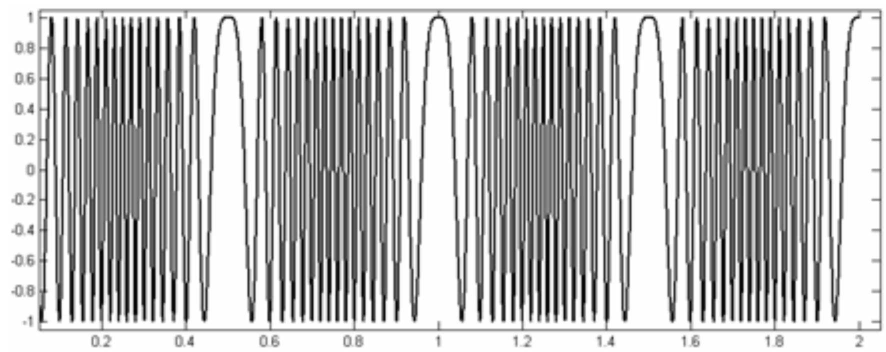
f_1, 2 peaks



f_2, 4 peaks



f_3, 8 peaks



f_4, 16 peaks

Recurrence transformations for $A_0 = 0.5\lambda_c$.

6. Signal processing

It can be shown that the number of peaks Q_g is

$$Q_g = 2^{g-1} q$$

where q is the number of peaks of the function f_1.

Consequently, the amplitude can be calculated as

$$A_0 = \frac{Q_g \lambda_c}{2^{g+1}}$$

This procedure has two advantages:

First, the peaks of the function fg, are narrower than the peaks of the function f1; it reduces the uncertainty of the peak counting.

Second, peak counting on the function reduces uncertainty propagation to the amplitude.

6. Signal processing

To show the latter we consider that for peak counting on function f_g, the relative uncertainty of the amplitude is

$$\left|\frac{\Delta A_0}{A_0}\right| \leq \left|\frac{\Delta \lambda_c}{\lambda_c}\right| + \left|\frac{\varepsilon}{2^{g+1} Q_g}\right|$$

Assuming a similar uncertainty ε for Q_g we obtain a reduction of the contribution of the counting to the amplitude uncertainty of

$$\frac{q}{2^{g+1} Q_g}$$

For $g \geq 3$ the contribution of the relative uncertainty of peak counting to the relative uncertainty is negligible. Since the typical relative wavelength uncertainty is 0.02 we may expect an amplitude uncertainty of 0.01.

7. Conclusions

Features of a novel photothermal self-mixing system were demonstrated experimentally and also the corresponding theoretical model which includes the TL effect.

It was demonstrated that the output power of the probe beam on the photothermal parameters is linear for the particular experimental conditions employed here.

Therefore, the use of the self-mixing signal facilitates the determination of the amount of trace concentration in water samples.

The experimental results have high accuracy with a RSD around 3%, and high sensitivity, which provides a LOD for the determination of Fe(II) of 92 ng/L concentration.

The photothermal system described here has the attributes of simplicity, compactness and ease of operation. Future uses of this new device could include imaging of cells, photothermal material characterization, etc.

7. Conclusions

A laser vibrometer based on the self-mixing effect in an LD has been demonstrated. A prototype instrument has been designed, built and tested in the vibration measurement of professional loudspeakers. In addition, a variant of the peak counting method for amplitude measurement have been described.

The self-mixing laser vibrometer can find application in cases where non-contact operation is required, for monitoring of soft or lightweight structures. Other applications involve vibration measurement of delicate biological objects as the tympanic membrane.

The proposed laser vibrometer is intrinsically low cost since it is made of simple, off-the-shelf optical components, and uses a straightforward signal processing, owing to the simplicity and effectiveness of the self-mixing interferometric scheme.

In the near future we plan to improve the technical characteristics of the presented prototype to increase its sensibility and accuracy.


Thank you!