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Glass-fibre self-mixing diode-laser Doppler velocimeter

M H Koelink[†], M Slot[†], F F M de Mul[†], J Greve[†], R Graaff[‡], A C M Dassel[‡] and J G Aarnoudse[‡]

[†] University of Twente, Department of Applied Physics, PO Box 217,
7500 AE Enschede, The Netherlands
[‡] University Hospital Groningen, Centre for Biomedical Technology and Department of Obstetrics and Gynaecology, Oostersingel 59, 9713 EZ Groningen, The Netherlands

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Abstract. A novel diode-laser Doppler velocimeter based on self-mixing feedback of Doppler-shifted light in the laser through a single glass fibre is described. The instrument can be applied, for example, to the invasive measurement of blood velocities in blood vessels, and of other industrial fluids and solids. A model is presented to calculate modulation signals and the results of measurements are shown.

1. Introduction

We constructed an instrument [1] for the measurement of the velocity of moving objects or fluids, which is based on the self-mixing effect in a semiconductor laser [2,3]. Part of the light emitted by the laser is fed back into the laser after being scattered by a moving object. For the transport of the light from the laser to the object and back, use is made of a single glass fibre. When the object is moving, the light scattered by the object will be Doppler shifted:

$$\Delta f = 2vn\cos(\alpha)/\lambda \qquad (1)$$

where Δf is the resulting Doppler shift, v the velocity of the moving object, n the refractive index, α the angle between the optical axis viewing the moving object and the direction of the velocity of the moving object and λ the wavelength of the laser used.

Part of the back-scattered light that is fed back into the laser will interfere with the laser light in the laser cavity and will cause an amplitude modulation of the laser intensity. The frequency of the amplitude modulation equals the Doppler frequency Δf. The laser intensity can be measured from a photodiode situated behind the laser crystal in the laser housing.

No special demands are required concerning the coherence length of the laser with respect to the distance from the moving object to the laser, since measurements can be performed with a multi-mode laser at several metres distance. The maximum distance at which self-mixing measurements can be performed for a multi-mode laser is apparently limited by the spectral width of each of the single modes. The self-mixing signal vanishes if the distance from the moving object to the laser clearly exceeds the coherence length corresponding to the spectral width of each of the single modes.

The back-scattered light which re-enters the laser cavity takes part in the amplifying process in the laser cavity, so only very small amounts (~1% relative to the laser power) of back-scattered light lead to detected signals, as seen in figure 2(*a*) [4]. It is very difficult to

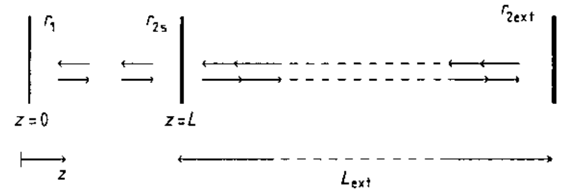

Figure 1. Model for a semiconductor laser with optical feedback. (Further explanation is given in the text.)

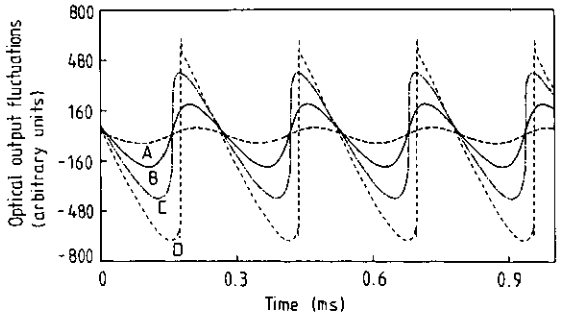

Figure 2. Shape of the self-mixing signals as a function of C: $c=0.12$ (Curve A); 0.5 (B); 1 (C); 1.66 (D). For increasing values of C the self-mixing signal changes from sinusoidal towards saw-tooth-like.

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give an absolute value for the amount of back-scattered light necessary for a detectable signal, since one cannot determine the fraction of the back-scattered light which is actually coupled into the laser cavity in front of the laser facet [5]. The signal amplitudes in a self-mixing set-up exceed comparable signals in a heterodyne detection set-up by a factor of three (considering the absolute maximum signal amplitudes for heterodyne detection) [5,6]. We have developed a theoretical description of velocimetry using self-mixing in a semiconductor laser which will be published elsewhere [7]. A short outline of this now follows, but for further details we refer the reader to this publication.

2. Theory

In this section a short outline of self-mixing will be given, partly following Petermann [8]. Self-mixing or backscatter-modulation is based on the optical feedback of Doppler-shifted light into the laser cavity. The optical feedback modulates the optical output of the laser by influencing some internal laser parameters. This will be elucidated in the following.

A self-mixing set-up can be seen as a three mirror set-up with an external cavity that is large compared with the (diode) laser cavity itself. The first mirror facet is positioned at $z=0$ with an amplitude reflection coefficient r_1, the second mirror facet is positioned at $z=L$ with an amplitude reflection coefficient r_{2s}, and the scattering object is positioned at $z=L+L_{\mathrm{ext}}$ with an amplitude reflection coefficient $r_{2\mathrm{ext}}$ (see figure 1). We replace the mirror at $z=L$ and the mirror at $z=L+L_{\mathrm{ext}}$ by an effective mirror at $z=L$ with an amplitude reflection coefficient r_2 given by:

$$r_2(\nu)=r_{2s}+(1-|r_{2s}|^2)\,r_{2\mathrm{ext}}\exp(-\mathrm{i}2\pi\nu\tau_{\mathrm{ext}}) \qquad (2)$$

where ν is the optical frequency and τ_{ext} is defined as the round-trip delay time equal to $2L_{\mathrm{ext}}/c$ (where c is the speed of light). In this equation we ignore multiple reflections in the external cavity since we assume that $|r_{2\mathrm{ext}}| \ll |r_{2s}|$.

When the laser is in a stationary state, the propagating wave inside the laser has to satisfy both a phase and an amplitude criterion. When substituting equation (2) into these criteria, the fluctuations ΔP in the optical output of the laser under self-mixing conditions can be written as [8]:

$$\Delta P \approx -\frac{\kappa}{L}\cos\left[2\pi\nu(\tau_{\mathrm{ext}}+2vt/c)\right] \qquad (3)$$

where κ is a feedback constant proportional to the reflection coefficient of the moving object:

$$\kappa=\frac{r_{2\mathrm{ext}}}{r_{2s}}(1-|r_{2s}|^2) \qquad 0<\kappa<1 \qquad (4)$$

L is the length of the laser cavity, ν is the operating laser wavelength, τ_{ext} is the laser-light round-trip time from the laser to the moving object and back to the laser in the initial position (at zero time), v is the velocity of the moving object and t is the time. The actual laser frequency ν at a given time is defined as:

$$\nu=-\nu_{\mathrm{th}}+\frac{\kappa\sqrt{1+\alpha^2}}{2\pi\tau_1}\sin\left[2\pi\nu(\tau_{\mathrm{ext}}+2vt/c)+\arctan\alpha\right] \qquad (5)$$

where ν_{th} is the frequency of the laser without optical feedback, α is a constant depending upon the laser semiconductor crystal and τ_1 is the laser-light round-trip time in the laser cavity. Equation (5) is a non-linear equation and can only be solved numerically. Equation (5) has only one solution for ν if the parameter C defined as:

$$C=\frac{\tau_{\mathrm{ext}}}{\tau_1}\kappa\sqrt{1+\alpha^2} \qquad (6)$$

satisfies $C \lesssim 1$.

For very small values of C, the fluctuations ΔP in the optical output of the laser are sinusoidal. For larger values of C, the fluctuations ΔP in the optical output become more saw-tooth like (see figure 2). If C becomes larger than a value of about unity, equation (2) has two or more solutions for the laser frequency ν and in such a situation the laser has more than one wavelength for stable operation. This will result in increasing noise and so-called mode-hopping. Of course this situation has to be prevented. C is linearly proportional to both κ and to τ_{ext}. This means that, for stable operation under self-mixing conditions, the moving object may not reflect too much light back into the laser and may not be positioned at too large a distance from the laser. When using a fibre coupled to the laser, the fibre ends also contribute to the value of κ since they also reflect a small part of the light back into the laser. If necessary anti-reflection coatings can be applied to the fibre ends.

In our experiments using fibres of several metres length, C was limited to values well below unity.

3. Measurements

In figure 3 our experimental set-up is given. We used a Sharp LT080MD0 5 mW single-mode laser diode at 780 nm and a threshold current of 38 mA. The actual laser supply current was 44 mA. The self-mixing signal was monitored with the built-in photo-diode of the laser package and after amplification recorded with a Hameg HM208 oscilloscope and a Hewlett-Packard HP3561 spectrum analyser. This built-in photo-diode is usually used to monitor the laser intensity and drive the laser current in a feed-back circuit so as to verify a stable intensity. Our laser is driven at a constant current without any feed back. The electronic noise of the laser current supply and the optical noise of the laser of our set-up are negligible.

The laser was coupled into an optical fibre using a microscope objective (NRC, MD-plan 10X). The laser light was guided through the fibre to a rotating wheel covered with white paper. The same fibre was used to collect scattered light from the rotating wheel and guide

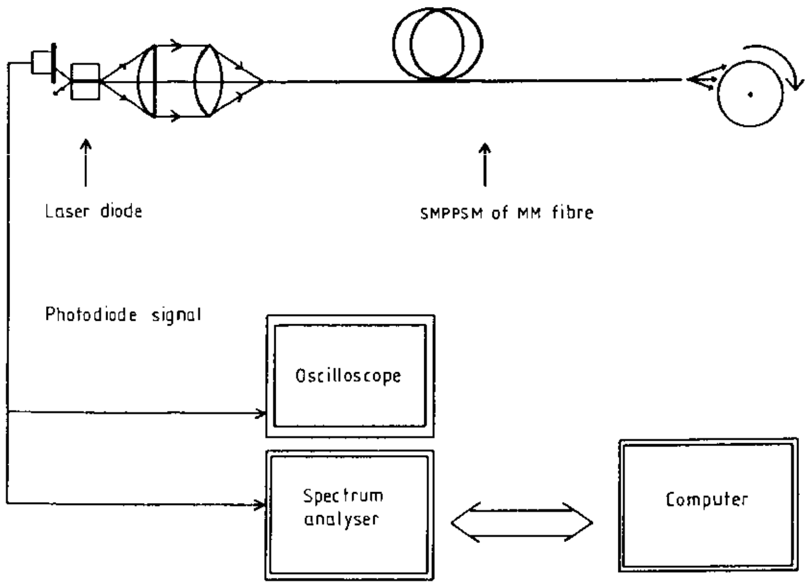

Figure 3. Experimental set-up for the experiments. In this set-up, a solid moving object is shown. The fibre can also be injected into liquids, e.g. moving blood, both *in vitro* and *in vivo*.

it backwards into the laser cavity. Figure 4 shows a measurement of the self-mixing signal in both the time and the frequency domain. No focusing optics were used to collimate the light from the fibre onto the wheel since good results had already been obtained when the fibre was positioned close to the wheel. In the frequency domain, higher harmonics from the Doppler frequency can be seen. This can also be seen in the time domain where the signal is not sinusoidal but slightly saw-tooth like. This is caused by a non-linear response from the laser in the case of large optical feedback (for more details see [6]). The frequency of the Doppler peak is indeed related to the velocity of the moving object according to equation (1). Figure 5 shows a similar

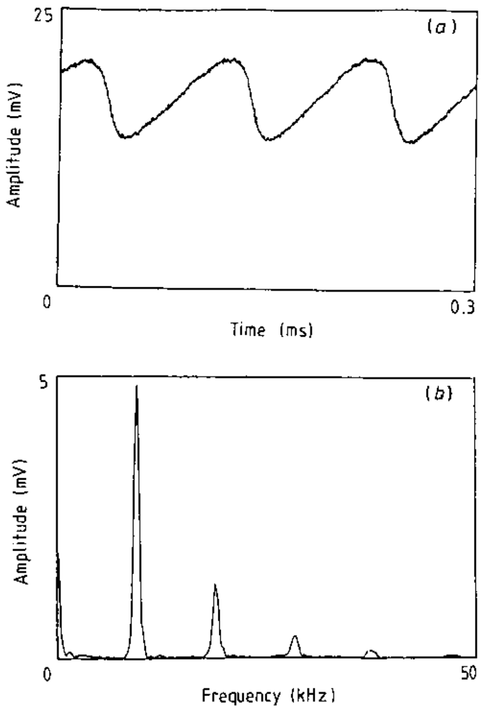

Figure 4. Typical self-mixing signals for a moving object: (*a*) time domain; (*b*) frequency domain. The velocity of the moving object was 4.8 mm s^{-1}, angle α (see equation (1)) was 40°, the wavelength λ was 780 nm and the resulting Doppler frequency was 9.8 kHz.

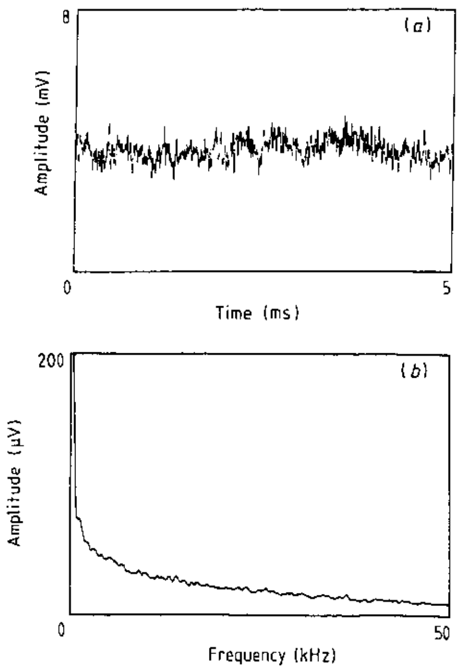

Figure 5. Typical self-mixing signals for a stationary object: (*a*) time domain; (*b*) frequency domain. The velocity of the moving object was 4.8 mm s^{-1}, angle α (see equation (1)) was 40°, the wavelength λ was 780 nm and the resulting Doppler frequency was 9.8 kHz.

measurement in both the time and frequency domains measured with the same wheel in a stationary position.

In our experiments, we used multi-mode (graded index, Philips, $NA = 0.2$, core 50 μm, length about 2 m), single-mode (NRC F-SF, $NA = 0.1$, core 5 μm, cladding 125 μm, length about 2 m) and polarization-preserving single-mode fibres (NRC F-PF, NA = 0.1, core 3.25 μm, cladding 125 μm, length about 2 m). All fibres gave good signals with comparable signal amplitudes. We succeeded in measuring blood velocities in a human blood vessel both *in vitro* and *in vivo*.

Due to multiple scattering and the small penetration depth of laser light (800 nm) in blood, the signal processing is more difficult than in measurements on solids as described above. The spectrum of measurements in blood does not show one single frequency of the Doppler frequency as shown in figure 4, but shows a whole spectrum of frequencies. Such a spectrum is given in figure 6. Figure 6 also does not show higher harmonics of the Doppler frequencies since the signal energy per frequency interval is so small that the laser gives a linear response (see figure 2 for small values of C).

From measurements, it turns out that the cut-off frequency (defined as the frequency where the signal spectrum statistically vanishes into the noise of the spectrum obtained with zero velocity) in the frequency spectrum can be used as a measure for the Doppler frequency corresponding to the velocity of the undisturbed flow. The cut-off frequency of the signal spectrum has already been used previously and similarly defined by other researchers [9]. The viewing angle α in equation (1) is assumed to be zero. This is in fact correct, even for multiple scattering, since the Doppler shift of a photon scattered by several moving particles all with the same velocity (speed and direction) will only depend on the initial situation (before any scattering took place) and the last scatter event. So, in our set-up, no larger Doppler shift could occur than for $\alpha = 0$ in equation (1) for a single scatter event. A penetration depth of the laser light larger than the disturbed area of the blood flow is of course a necessary condition for such a measurement. This was taken care of in our experiment. Figure 7 shows the cut-off frequency as a function of the blood velocity in an *in vitro* experiment, together with the calculated Doppler frequency of the undisturbed flow obtained from an external velocimeter. It shows good agreement.

Apart from this, the velocity can also be obtained from the normalized first moment of the signal-frequency power spectrum [10]. The normalized first moment of the signal spectrum does not automatically lead to the Doppler frequency of the undisturbed flow and a calibration is necessary in such a case.

In figure 8, the measurement of the blood flow in muscle tissue (between the shoulders) of a healthy rat is

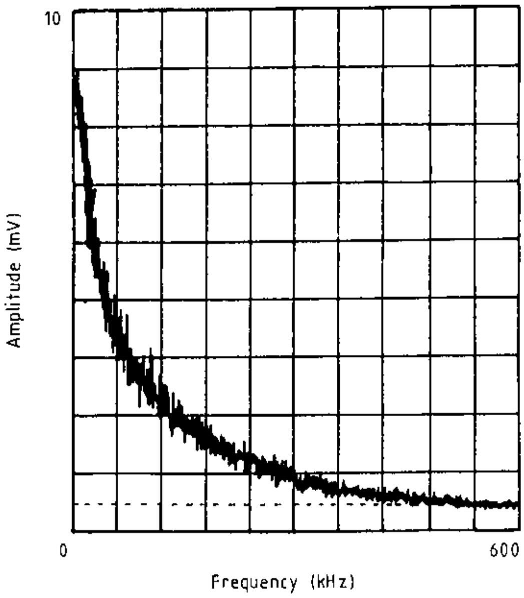

Figure 6. Self-mixing signal spectrum of an *in vitro* experiment in human blood using an optical fibre (level of the noise spectrum at zero velocity: line at 0.4 mV, indicated by the dashed line.)

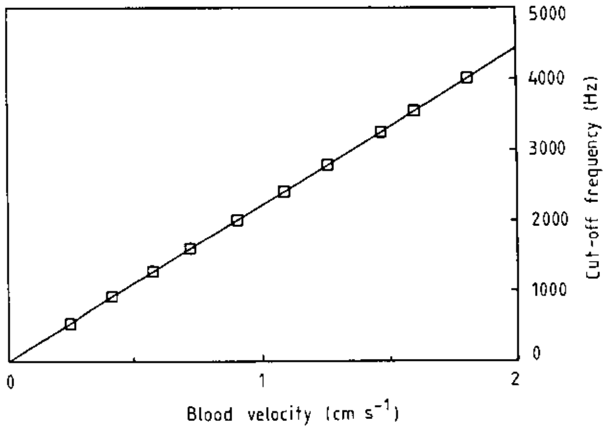

Figure 7. The cut-off frequency of the self-mixing signal spectrum as a function of the blood velocity. The measurement was performed in an *in vitro* experiment using full human blood with a normal haematocrit and the flow running towards the fibre facet. The squares denote measurements, while the line indicates the calculated Doppler frequency of the undisturbed velocity from an external calibration and shows good agreement.

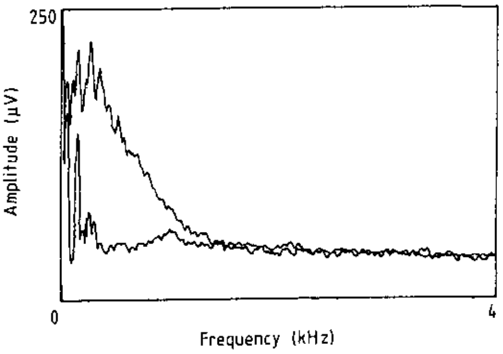

Figure 8. Self-mixing measurement of blood flow in muscle tissue of a healthy rat (between the shoulders). The upper spectrum is the signal spectrum, the lower spectrum is the noise spectrum. Further explanation is given in the text.

shown. The cut-off frequency is about 500 Hz, corresponding to 0.2 mm s^{-1} (from equation (1) with $\alpha=0$). Figure 9 shows the flow in an artery of the left rear leg of a healthy sheep. Here, the cut-off frequency is 50 ± 5 kHz, which means about 2 cm s^{-1}. However, this plot has been averaged over some time, comprising alternating pulsed flow and stationary blood.

Moreover, the fibre was inserted at an angle of less than 30° and in the vicinity of the wall of the blood vessel. Therefore, the velocity value of 2 cm s^{-1} should be corrected to about 8 cm s^{-1}, a value to be expected physiologically for this kind of vessel.

4. Conclusions

We have developed a laser Doppler velocimeter based on self-mixing in a fibre-coupled semiconductor laser. The instrument enables remote and non-destructive measurements of the velocities of fluids and solids to be made. According to the results of the *in vivo* measurements of the blood flow in sheep, the possibility of performing invasive measurements of blood velocities in human blood vessels seems likely. The small diameter of the glass fibre ensures a minimum disturbance of the actual blood flow and penetration of the fibre into small vessels.

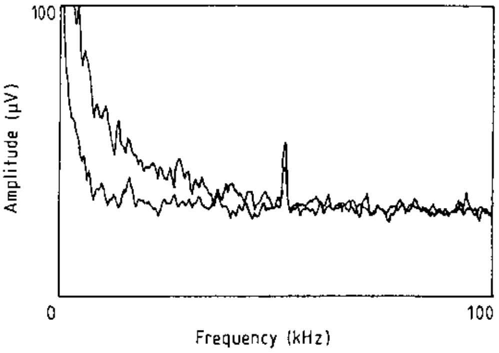

Figure 9. Self-mixing measurement of blood flow in a large artery of the left rear leg of a healthy sheep. The upper spectrum is the signal spectrum, the lower spectrum is the noise spectrum. Further explanation of the figure is given in the text. The peak at 52.2 kHz is electronic noise.

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