Multi-component LDA using coherence properties of semiconductor lasers

Michael Eggert, Gesine Grosche, Harald Müller, Martin Koch*

Physikalisch-Technische Bundesanstalt (PTB)
Bundesallee 100, 38116 Braunschweig, Germany
Phone: +49 531 4313, fax: +49 531 592 4305
e-mail: michael.eggert@ptb.de

*Technical University of Braunschweig
Institute for High Frequency Technologies
Schleinitzstr. 22, 38106 Braunschweig, Germany

ABSTRACT

We present a multi-component Laser-Doppler Anemometer, in which the channel separation is based on a new method of using the coherence properties of different semiconductor lasers, one for each LDA beam. Instead of requiring, for example, bulky multi-wavelengths lasers, additional opto-electronic components or very-large-bandwidth detectors, the compact LDA presented here uses three semiconductor lasers whose difference frequencies are controlled very accurately by a microcontroller frequency stabilisation system. In this way, the difference frequencies, which act as carrier frequencies for the measuring information, can be tailored very easily to the measuring task. Thus the signal to noise ratio can be optimised and the required bandwidth of the detection system may be kept small.

We correlate the LDA measuring signal – which contains the beat signals of the three Doppler shifted laser frequencies – with the two reference signals, given by the beat signals of the two laser beam pairs, one for each velocity component. Thus two LDA signals are obtained in the base band. These LDA signals, one for each velocity component, were low pass filtered and systematically analysed concerning their signal to noise ratio in dependence on the shift frequency bandwidths and differences.

Two dimensional velocity measurements were carried out in a free jet seeded with small water droplets with diameters of a few micrometers. The nozzle could be rotated to vary the flow direction systematically. Both the optical and electronic set-up were optimised to give a highly reliable system, achieving signal-to-noise ratios in excess of 30 dB. We explored the performance of the LDA in two operating modes:

a) using different shift frequencies to achieve channel separation and
b) setting identical shift frequencies and separating the measuring channels by using the fast frequency fluctuations arising for semiconductor lasers.

Already in operating mode (a) a significant reduction - by one order of magnitude compared to previous systems - in the required detection bandwidth was achieved. The system could be operated with all shift frequencies well below 100 MHz; no cross-talk was observed.
A new concept was realised in operating mode (b): for the first time with this technique, several velocity components can be separated unambiguously even if the mean carrier frequencies for the different components are nominally the same. Two-dimensional measurements with flow velocities between 0.17 m/s and 43 m/s were recorded; no cross-talk was observed. The required detection bandwidth is minimal, so that sensitive detectors can be used.
Theoretical and experimental analysis of the signal-to-noise ratio as function of system parameters and flow velocity shows that operating mode (a) can give better SNR if the bandwidth is adapted to the velocities to be measured, whereas mode (b) allows the measurement of high velocities and good SNR with limited band-width.

I INTRODUCTION

Many flow measuring applications require simultaneous multi-component velocity information. Ar^+ ion laser systems, using several wavelengths and/or additional optoelectronic instrumentation, are still common in multi-component systems despite their bulkiness and relatively high running costs. There have been on-going efforts to provide compact, reliable alternatives, based on semiconductor lasers, or small solid-state laser systems (Dopheide et al, 1990; Wang et al., 1994). Tunable, medium-power semiconductor lasers have made new sensors possible which are based on correlation techniques, using laser frequency differences, or "shift frequencies" which act as carrier frequencies for the separation of measuring components (Müller et al., 1996). However, such systems can be difficult to operate, which may reduce reliability. Also they required RF detection systems with a bandwidth of about 1 GHz, because a large difference in the carrier frequencies was needed to allow unambiguous separation of the signal components. We present a new multi-component LDA overcoming these difficulties.

II EXPERIMENTAL LDA DESIGN

We have developed a 2D-LDA system using three independent DBR-lasers forming two beam pairs. The three laser beams are focused into the measuring volume for measuring two orthogonal velocity components, the scattered light (see figure 1) is detected in forward (z-) direction. The optical set-up is shown schematically in figure 2a.

The lasers are operating at 851 nm with over 50 mW optical power each and a line-width of several MHz. One of the three laser diodes which was common for both LDA beam pairs was employed as master laser while the two other laser diodes were precisely tuned in their frequency to within a few MHz by a micro-controlled frequency stabilisation system. Reference optics and detectors provide two reference signals which are used for both frequency stabilisation and LDA-signal processing.

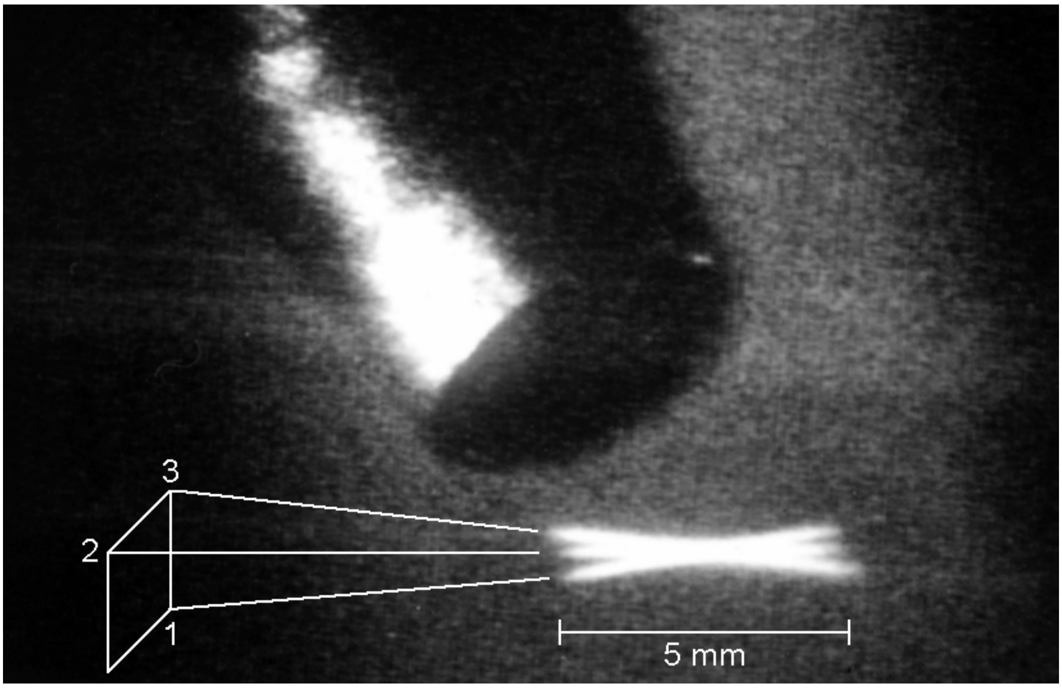

Figure 1: Three laser beams focused into the measuring volume, being scattered by particle flow.

By mixing the measured signal PD_M with the two reference signals $PD_{R\,1,2}$ (see figure 2b) we obtain two base band LDA signals suitable for conventional signal processing, one for each channel (direction). A similar concept was first demonstrated by Müller et al.(1996). Our new signal processing is described in section IV.

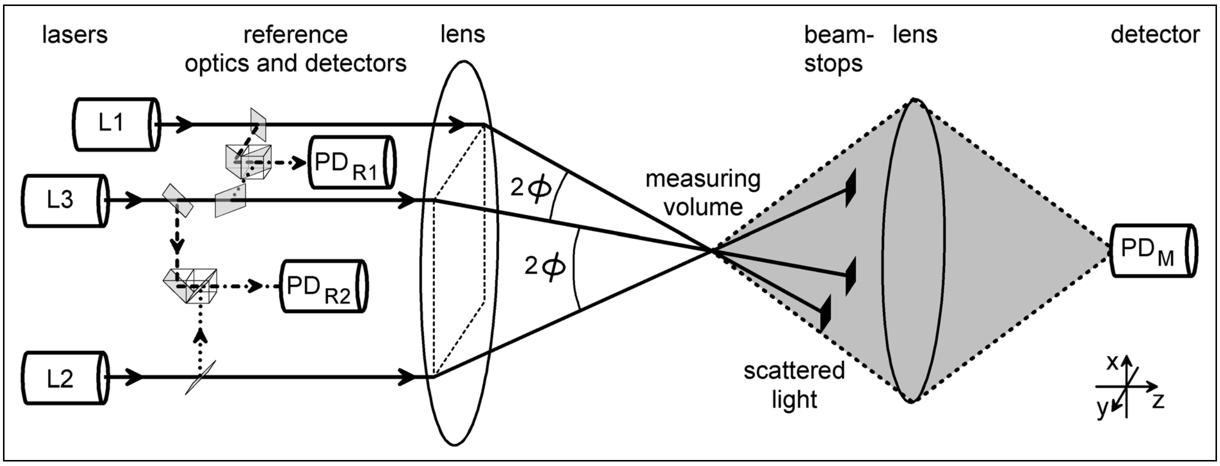

Figure 2a: 2D-LDA system using stabilised semiconductor lasers and coherent signal processing - optics -

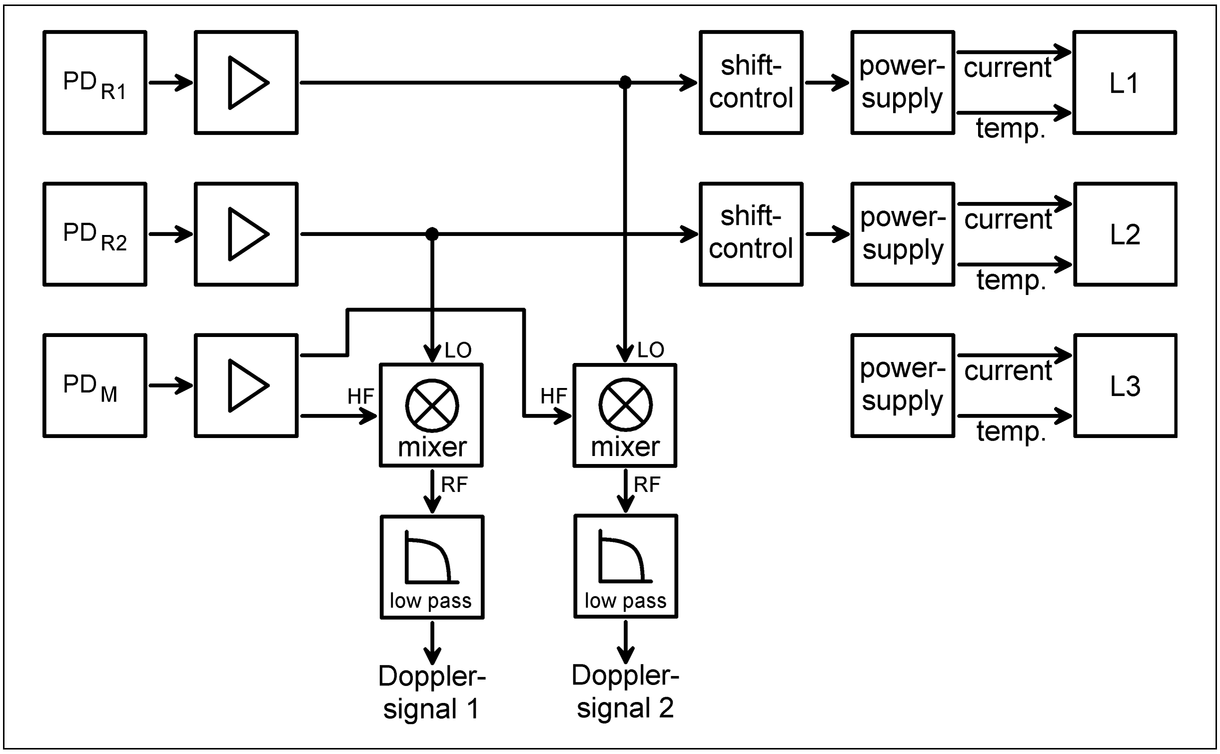

Figure 2b: 2D-LDA system using stabilised semiconductor lasers and coherent signal processing - electronics -

III SHIFT FREQUENCY STABILISATION

To control the shift frequencies for up to four separate lasers, we developed a microcontroller based stabilisation system using current tuning. In contrast to previous, analogue stabilisation circuits operating with large, fixed shift frequencies of several 100 MHz, with this stabilisation the shift frequencies of the lasers could be set to any value between 15 MHz and several hundred MHz for each channel. Thus it was possible to adjust the two shift frequencies for the two LDA signal channels systematically and with shift frequency fluctuations of less than 5 MHz, dominated by the spectral bandwidth of the lasers.

The stabilisation contains frequency counters to measure the shift frequencies with an accuracy of 200 kHz over a 0-1 GHz range, a microcontroller calculating laser current values and 24-bit digital-analogue-converters to drive the laser current by the laser power supplies. The whole system is working with an update rate of 3 kHz for each of up to three controlled lasers.

Using a microcontroller made it possible to build a system automatically scanning the current range of laser diodes for operation points and afterwards stabilising it. After an accidentally loss of stabilisation, e.g. in case of mode hop, scanning for new operation points is started automatically. Furthermore any parameter (of the PID-controller, the desired shift frequencies, current ranges, scan velocities) can be set precisely and reproducibly.

IV SIGNAL PROCESSING AND EXPERIMENTAL RESULTS

The LDA signals are derived by mixing the measuring signal with the reference signals (see figure 2b):
The light of all three lasers scattered in the measuring volume is superimposed on the measuring photodetector, similar to the beams pairwise superimposed on the reference detectors. While the reference photodetectors $PD_{R\,(i)}$ signals have the frequencies $f_{Ref\,(i)}$, the photodetector PD_M receives a superposition of different signals with Doppler-shifted reference frequencies $f_{Meas\,(i)} = f_{Ref\,(i)} + f_{Doppler\,(i)}$.

So mixing the measuring signal, containing components at $f_{Meas\,(i)}$ with the reference signal at $f_{Ref\,(i)}$ directly provides an LDA signal with the Doppler frequency $f_{Doppler\,(i)}$. On the other hand the contained measuring signals at frequencies $f_{Meas\,(j)}$ mixed with the reference signal at $f_{Ref\,(i)}$ for $i \neq j$ cause unwanted signal components at the frequency $f_{Ref\,(i)} - f_{Meas\,(j)}$. By using different shift frequencies with $|f_{Ref\,(j)} - f_{Ref\,(i)}| > 2\ f_{Doppler\,Max}$ the LDA signals with $|f_{Doppler}| < f_{Doppler\,Max}$ of both channels can easily be separated with lowpass filters at $f_{Doppler\,Max}$.

This is illustrated by the measurement shown in figure 3, recorded for slightly different shift frequencies of 27 MHz and 34 MHz. No cross-talk is detected.

A more intriguing domain is entered when the shift frequencies are nominally the same: because the lasers exhibit fast frequency fluctuations over time-scales smaller than the particle transit time through the measuring volume, even for nominally identical shift frequencies the correlation technique "picks out" the correct measuring signal. Mixing the reference signal at the fluctuating frequency $f_{Ref\,(i)}$ with the measuring signal component at the identically fluctuating frequency $f_{Meas\,(i)}$ gives a well defined peak at the correct Doppler frequency and mixing the signals with uncorrelated fluctuating frequencies $f_{Ref\,(i)}$ and $f_{Meas\,(j)}$ ($i \neq j$) only generates a slightly elevated noise floor.

This is illustrated by the measurement shown in figure 4, recorded for nominally identical shift frequencies of 32 MHz. No cross-talk is detected.

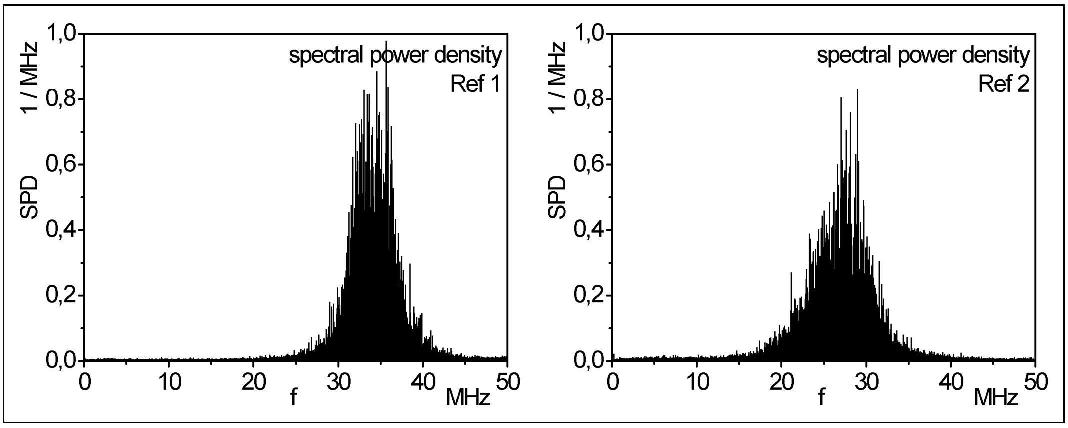

Figure 3a: Slightly different shift frequencies of 34 MHz and 27 MHz have been used.

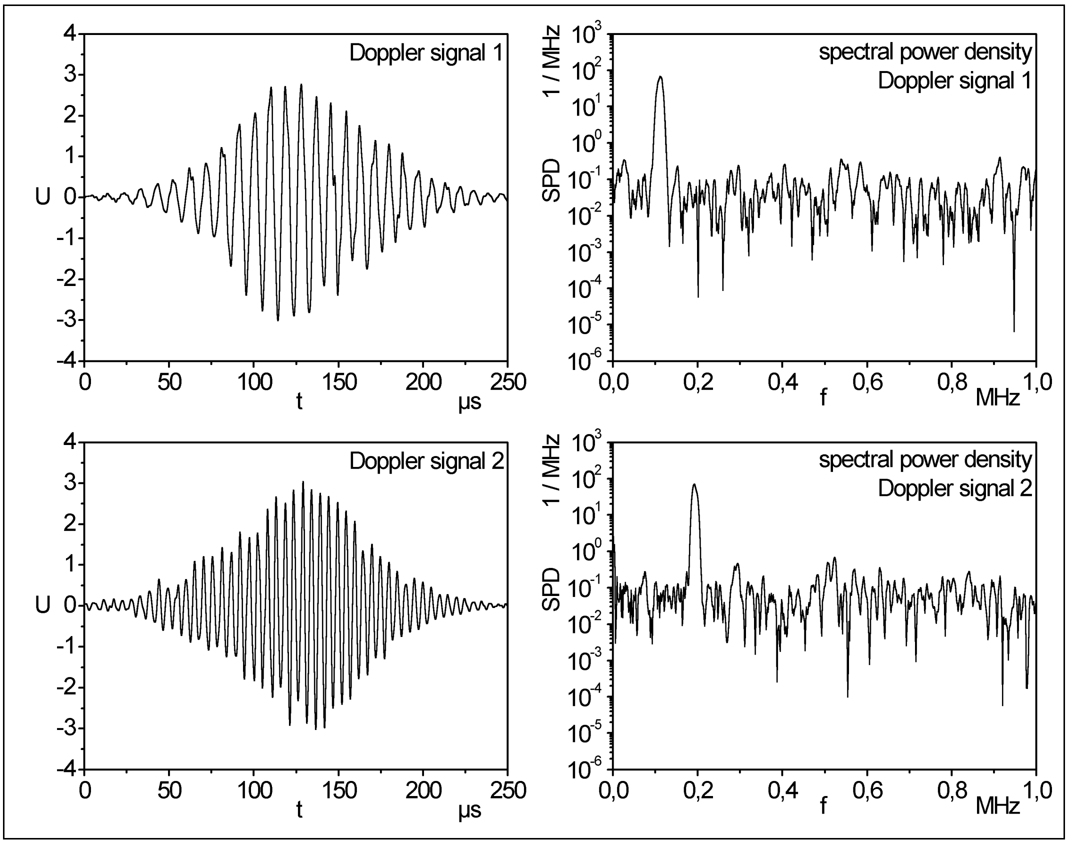

Figure 3b: LDA signals in time and frequency domain, separated by the different shift frequencies.

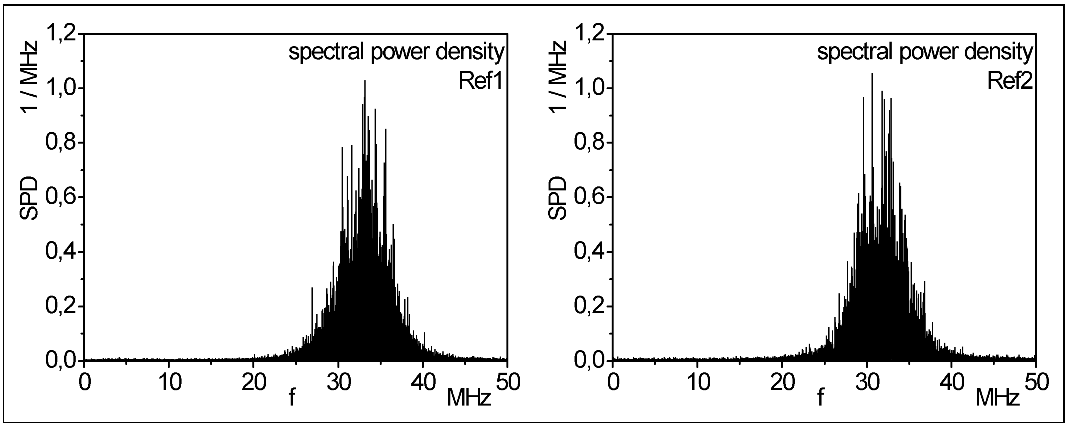

Figure 4a: Nominally same shift frequencies of about 32 MHz have been used.

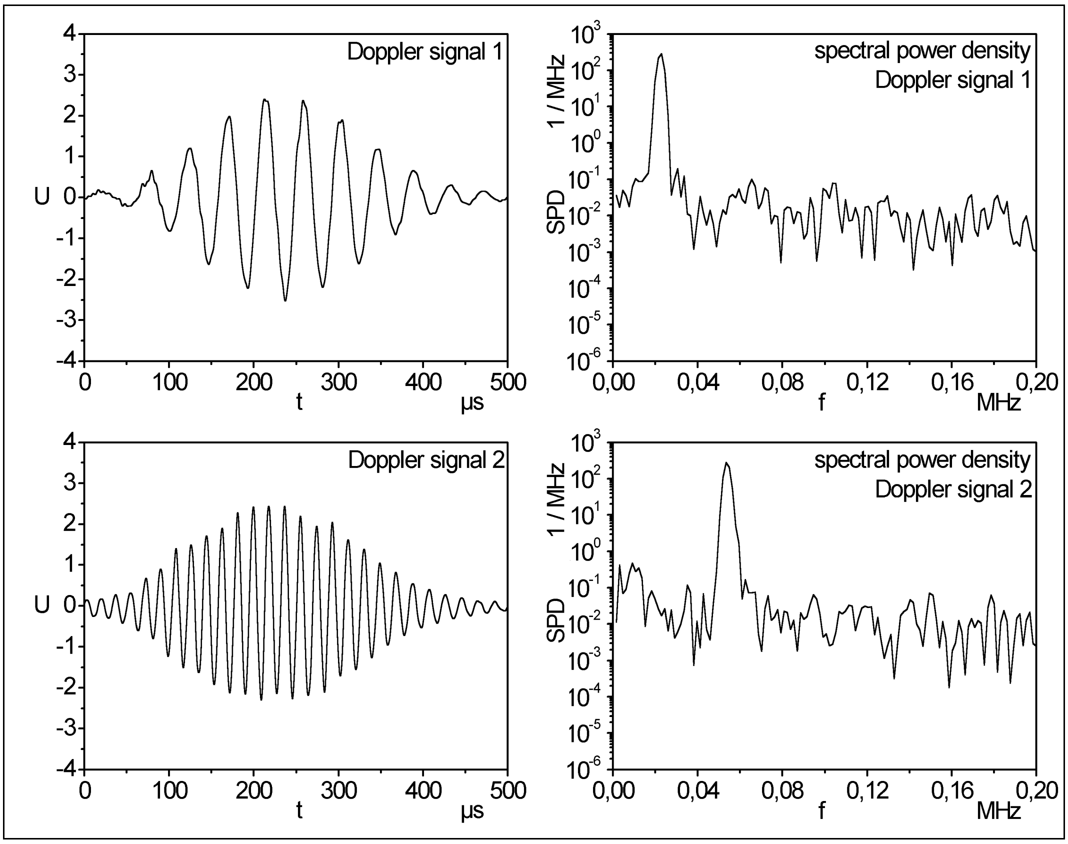

Figure 4b: LDA signals in time and frequency domain, separated only by the reference frequency fluctuations.

V THEORETICAL ANALYSIS OF SNR

By analysing the system quantitatively, taking the shift frequency spectral power density into account, we can calculate the optimal signal-to-noise ratio (SNR, given as the ratio of maximum spectral power density of the Doppler signal to noise-spectral density). We have found that the SNR is mainly a function of the line-width of the shift frequency, given as $\sigma_{f\,Ref}$, and the transit time of the particle, given as $\sigma_{t\,Doppler}$.

In multi-dimensional LDA systems using carrier frequencies, base band noise is not only caused by photodetector noise and laser amplitude fluctuations, but also by mixing the reference signal with other channels' measuring signal. Figure 5 shows such uncorrelated reference and measuring signals and the resulting mixing product in the base band.

If we mix two uncorrelated, Gaussian signals, centered at $f_{Ref\,(i)}$ and $f_{Meas\,(j)}$ $(i \neq j)$, each with normalised power and $\sigma_{f\,Ref}$ we obtain Gaussian baseband signals with variance $\sqrt{2}\,\sigma_{f\,Ref}$ and power ½ each at the corresponding frequencies $\pm f_{Max\ noise} = \pm (f_{Ref\,(i)} - f_{Meas\,(j)})$ resulting a maximum noise level $SPD_{Max\ noise} = 1 / (4 \sqrt{\pi}\ \sigma_{f\,Ref})$.

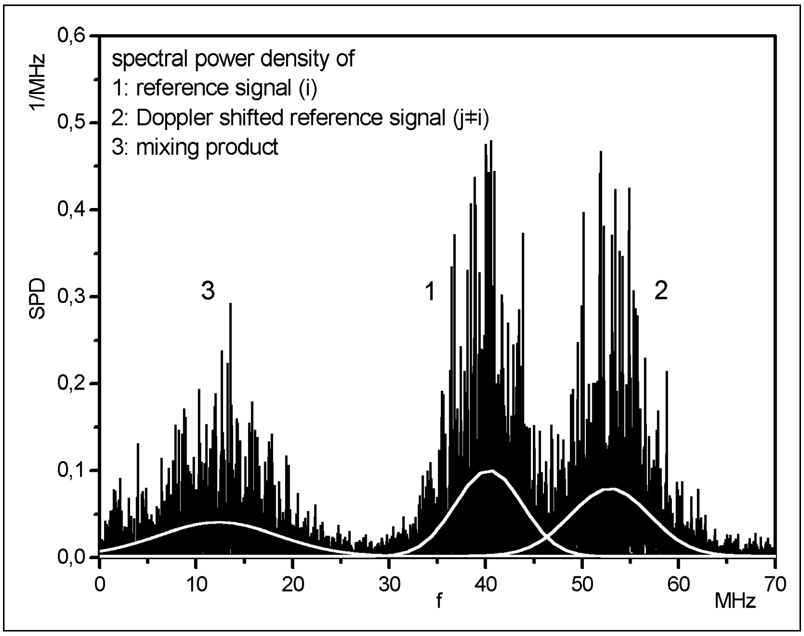

Figure 5: Uncorrelated reference and measuring signal and their mixing product (positive only).

In mode (a), using different shift frequencies for channel separation, the shift frequencies are set with a difference at least twice the maximum Doppler frequency: $\Delta f_{Shift} = f_{Ref\,1} - f_{Ref\,2} \geq 2\ f_{Doppler\ Max}$. In this case, the frequency of maximum base band noise exceeds the Doppler frequency range: $f_{Max\ noise\ a} \geq f_{Doppler\ Max}$. Within the Doppler frequency range, the noise is greatest at the maximum Doppler frequency. The worst case happens if $f_{Doppler\,(1)} = f_{Doppler\ Max}$ and $f_{Doppler\,(2)} = -\ f_{Doppler\ Max}$, where the noise maximum is close to the measured Doppler frequency.

The worst case noise level for mode (a) can be described as:
$SPD_{worst\ noise\ a} = SPD_{Max\ noise} \exp\left(-\tfrac{1}{2} (\Delta f_{Shift} - 2\ f_{Doppler\ Max})^2 / 2\ \sigma_{f\,Ref}^{\ 2}\right)$.

In mode (b), using the uncorrelated frequency fluctuations for channel separation at identical mean shift frequencies, the maximum base band noise occurs at $f_{Max\ noise\ b\,(i)} = f_{Doppler\,(j)}$, which is zero in the worst case, so the maximum noise level doubles to $SPD_{worst\ noise\ b} = 2\ SPD_{Max\ noise}$.

In either case, the maximum spectral power density of the Doppler signal is given by $SPD_{Max\ signal} = 2\sqrt{\pi}\ \sigma_{t\ Doppler}$, determined by the particle transit time.

Consequently the SNR can be calculated as follows:

$SNR_{Min}(a) = 8\ \pi\ \sigma_{Doppler}\ \ \sigma_{f\ Ref}$

for mode (a) with minimum shift frequency difference ($2 \bullet f_{Doppler\ Max}$). The SNR rises exponentially with $(\Delta f_{shift} - 2\ f_{Doppler\ Max}) / \sigma_{f\ Ref}$. As the maximum noise density is outside the Doppler frequency range, the SNR within the Doppler frequency range can be increased by large shift frequency differences and small shift frequency fluctuations.

$SNR_{Min}(b) = 4\ \pi\ \sigma_{t\ Doppler}\ \ \sigma_{f\ Ref}$

for mode (b) with identical medium shift frequencies. As the maximum noise density is within the Doppler frequency range, the SNR can be increased by deliberately using large shift frequency fluctuations.

VI COMPARISON WITH EXPERIMENTAL RESULTS

Both the theoretical prediction and measured values for the mode (b) SNR are shown in figure 6

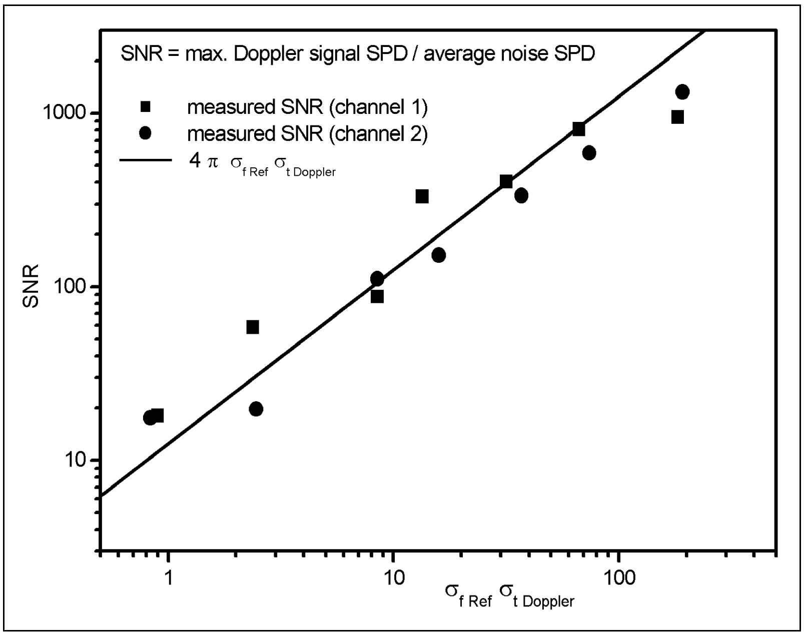

Figure 6: Calculated minimum and measured base band Doppler SNR for different transit times $\sigma_{t\ Doppler}$ and shift-frequency line-widths $\sigma_{f\ Ref}$. Measurements were taken with identical shift frequencies and over a velocity range of 0.17 m/s to 43 m/s.

Though the same shift frequencies were used for both channels, an SNR of over 30 dB could me measured for low velocities. With high velocities, 43 m/s producing Doppler frequencies of about 5 MHz and 10 MHz, still 12 dB SNR were achieved. This could be furthermore increased by increasing the laser linewidth, e.g. by random current modulation.

VII CONCLUSIONS

We have verified a new method of channel separation for multi-component LDAs, using several lasers whose difference frequencies are controlled very accurately by a microcontroller frequency stabilisation system.

Via this stabilisation, in the range of the laser line-width, we have shown that for channel separation by different shift frequencies, the frequency difference could be reduced to twice the Doppler bandwidth per channel. Compared to previously presented systems, the required detection bandwidth could be reduced by an order of magnitude.

The new method is based on using the fast frequency fluctuations of semiconductor lasers with typical line-width in the MHz range. For the first time with this technique several velocity components can be separated unambiguously even if the carrier frequencies for the different components are nominally the same. This permits to use the same frequency range for several channels, reducing detector bandwidth to twice the Doppler bandwidth overall.

We have presented experimental results and discussed the signal-to-noise properties for different system configurations. Channel separation by frequency fluctuations, using twice the Doppler bandwidth overall, provides only marginal less SNR than separation by different frequencies with twice the Doppler bandwidth per channel.

Using this new approach, compact, reliable LDA systems using highly sensitive detectors become available, that allow multi-component velocity measurement with excellent SNR.

The stabilisation system could also be useful for altogether different flow characterisation instrumentation: for example, just by adapting the software, the shift sweep function could be implemented to characterise absorption cells for DGV-systems.

VIII ACKNOWLEDGEMENTS

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