Directional spatial-resolved laser Doppler velocimeter using a two-colour fibre laser

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ABSTRACT

A concept for the realisation of directional laser Doppler velocimeters (LDV), without having to use opto-electronic modulators like Bragg cells is presented. The concept is based on the use of a diode-pumped fibre laser, emitting at two different wavelengths. The two laser colours are used to generate two interference fringe systems in the measuring volume of the LDV system. The fringe systems have the same spacing d, but a phase shift of about d/4, see Fig. 1. Opposite motions of the tracer particle result in an opposite phase relation of the generated burst signals. The evaluation of the sign of the phase shift between these two signals gives the direction of the fluid flow. The main advantage of this directional discrimination principle is its complete passive arrangement. In consequence, a high miniaturization degree of the LDV measuring head can be achieved.

Besides the directional discrimination, the use of a two-colour laser allows the measurement of velocity gradients inside the measuring volume. A similar LDV system like in Fig. 1 was realised in order to obtain a spatial resolution of the velocity measurement. Due to the chromatic dispersion of the imaging optics, different spatial dependences of the spacings of two fringe systems are obtained. Employing two Doppler frequency measurements, a spatial resolved velocity measurement is achieved experimentally by a back-scattering differential LDV system for the first time to our knowledge. Both concepts will be combined for directional velocity measurements with spatial resolution, e.g. for the measurement of boundary layers.

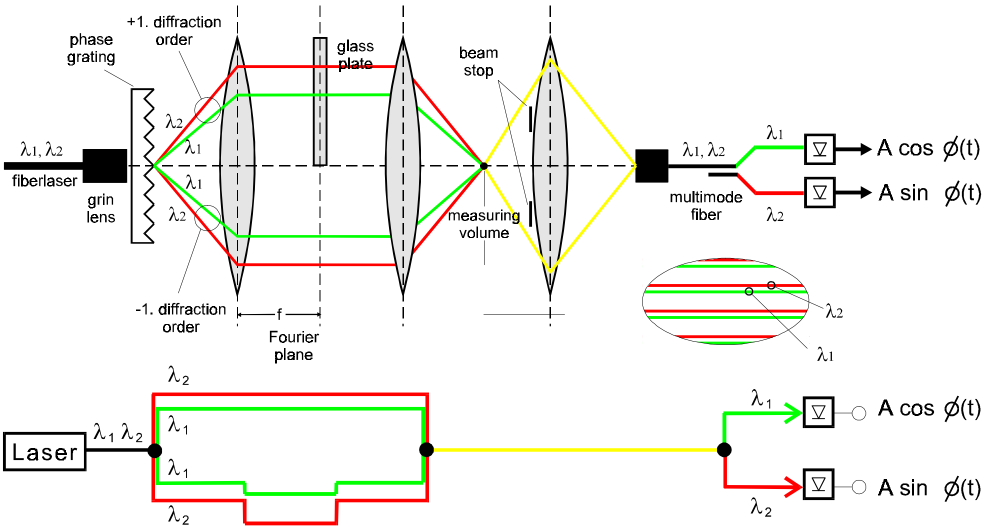


Fig. 1. Principle of the directional laser Doppler velocimeter using a two colour fibre laser. Top: Two equal distant fringe systems of different colour are generated by means of an achromatic imaging of a phase diffraction grating. Due to chromatic dispersion of a glass plate, employed in the lens focal plane, a defined phase shift between the two fringe systems is achieved. The scattering light is chromatical separated and generates a complex quadrature signal pair, i.e. sine-cosine signals. Their evaluation gives the directional Doppler frequency. Bottom: Mach-Zehnder interferometer scheme. After splitting the beam, different phase shifts of the two colours are generated. The combination of the beams in the measuring volume of the LDV systems results in a sine-cosine signal pair.

1. INTRODUCTION

Directional LDV systems are conventionally realised by the use of Bragg cells (acousto-optic frequency-shift modulators, AOM). Although Bragg cells have an undoubted reliability of work-function, their disadvantages like the high size and cost, the problematic electromagnetic compatibility and the optical power loss are also well-known. Especially, the miniaturisation of LDV measuring heads suffers, when a Bragg cell have to be integrated. Therefore, alternatives for the realisation of the directional discrimination were discussed. In principle, four directional discrimination methods can be applied:

1. Heterodyne technique. Besides the use of external modulators like Bragg cells or electro-optical modulators, the employment of several stabilised single-mode laser sources or a chirp frequency modulation of a single-mode laser allows a directional discrimination. These laser-based schemes allow the realisation of precise directional LDV systems. Furthermore, they can simply extended for multi-component velocity measurements. However, sometimes they are too complicated for LDV application fields.
2. Multiple measuring areas: The direction of motion can be determined by means of adjacent measuring areas, e.g. having fringe systems of different spacings. Using one photo detector, the defined change of the Doppler signal frequency allows a directional discrimination. However, a continuous observing of the motion direction is not possible, so that directional returns inside one measuring areas can not be detected. Furthermore, the determination of the Doppler frequency change can be uncertain. Applications of this method in the LDV technique are not known.
3. Imaging of the scattering particle: The position of a scattering particle is determined and its movement direction is detected, e.g. Plamann et al. 1998. For the imaging e.g. PSD elements (position sensitive detector, three-current photo-diode) or CCD camera are used. However, the noise properties of PSD elements are worst and the signal bandwidth of CCD cameras is generally too low for LDV signals.
4. Homodyne technique (Czarske et al.1994): Two fringe systems with the same spacing, but a shift of a quarter spacing are generated in the measuring volume, see Fig. 2. The physical discrimination between the two fringe systems can be done by different polarisations, different time intervals or different wavelengths. Two light wavelengths were used for the LDV system, see Fig. 1. In contrast to the other methods, the chromatic separation is reliable and has a low technical effort. As shown in Fig. 2, two corresponding signals, having a phase shift of 90^0 are generated. Such a quadrature signal pair allows the determination of the motion direction by detecting, which signal leads with respect to the other signal. The homodyne technique allows in contrast to the methods (2-3) a reliable detection of the motion direction also inside the measuring volume by using standard photo diodes. Compared to the method (1) no external modulator elements or expensive single-mode lasers are necessary. Therefore, a complete passive directional LDV system can be realised, see Fig. 1.

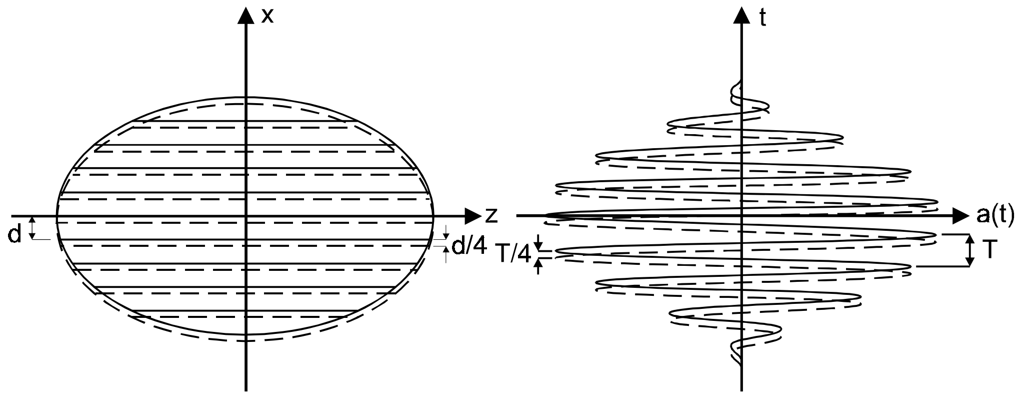


Figure 2: Principle of the two-colour directional discrimination technique. A pair of fringe systems with equal fringe spacing but a quadrature phase shift of 90^0 is generated in the measuring volume. The generated signal pair in the base band has a phase shift of $+/-90^0$, where its sign is dependent on the direction of the particle movement.

In the next chapter, the homodyne LDV technique is described in detail. A novel two-colour fibre laser is used for the generation of the two fringe systems. Besides the directional discrimination, the two-colour laser is also used for the spatial resolution of the velocity measurement. However, typical LDV measurements suffer from the missing distinguishing of tracer particle motions at different longitudinal positions along the measurement volume. As a consequence of this dilemma, short lengths of the measuring volume were realised for a spatial-resolved velocity measurement by LDV, see Mazumder, et al. 1981 By a mechanical scanning of the LDV device, distributed measurements were accomplished. Due to the scanning process, however, these measurement can not be performed in real-time. One solution was demonstrated by Strunck et al..1994, 1997. The principle is based on two measuring volumes, which are tilted against each other. Two symmetrically arranged reference LDV systems were installed. Each

LDV device measures the electrical beat frequency between the Doppler shifted scattered light and the non-scattered laser light, so that the tracer particle velocity component v_x can be determined. The time of flight Δt from one measuring volume to the other, allows the determination of the z-position of the tracer trajectory. It results to $z = v_x \Delta t / (2 \tan \Theta)$, where Θ is the half crossing angle of the two laser beams, see Strunck et al. 1994. However, the applied reference LDV technique has usually a lower accuracy than the differential LDV technique and requires higher alignment efforts. Furthermore forward-scattered light has to be used, which usually requires a detached receiving optics, implying a complicated adjustment. In order to realise a back-scattering receiving optic, the use of retro-reflectors was proposed by Strunck et al. 1997, but this can not be applied in standard LDV application fields. The main drawback, however, may be the dead-time, occurring between the two measuring volumes. As a result, only measurements of fluid flows, with a low fluctuation of the tracer particle velocity v_x can be accomplished.
In this contribution we propose a method for the spatial resolution of distributed velocity measurements in the measuring volume of a differential LDV system, using back-scattered light. No dead-time occurs, since only one measuring volume is used. The differential Doppler technique guarantees a high velocity measuring accuracy. Furthermore, the use of back-scattered light allows integration of the laser and the receiving optics in a single unit.

2. DIRECTIONAL DISCRIMINATION METHOD

2.1 Principle

In Fig. 1 the scheme of the homodyne LDV system, using a two-colour fibre laser was shown. The Figs. 3, 4 show the principle and design of the used diode-pumped up-conversion fibre laser, emitting two wavelengths.

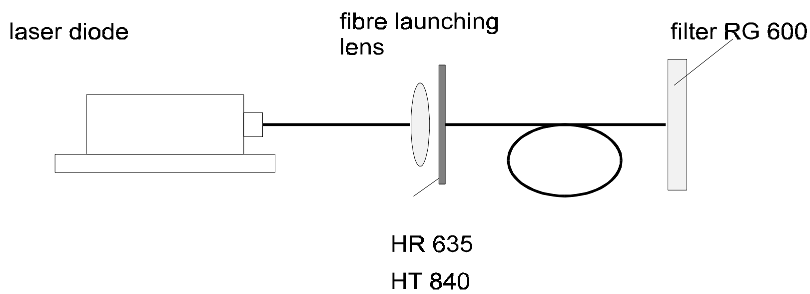


Fig. 3. Principle of a diode-pumped fibre laser, emitting at two wavelengths. A Pr/Yt doped glass fibre is pumped by a mopa diode laser of 840nm wavelength. Due to up-conversion processes, an emission wavelength of 635nm is achieved, see Zellmer et al. 1999.

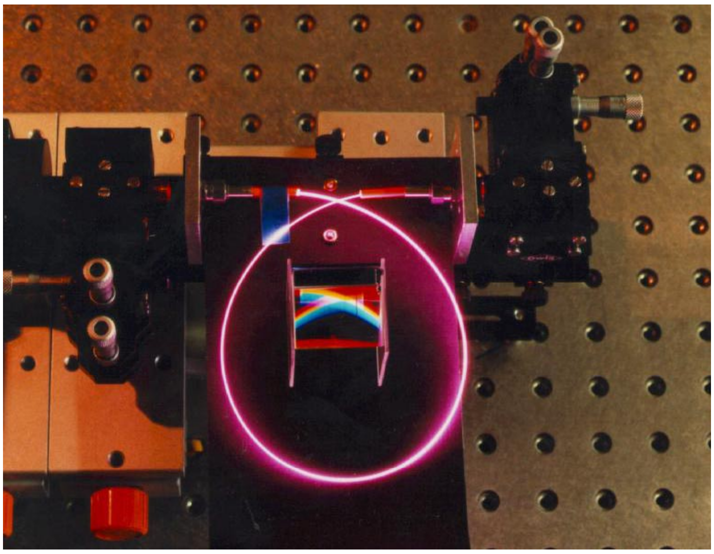


Fig. 4. Sketch of the Pr/Yt-doped fibre laser. The fibre laser is pumped by a mopa laser diode of 400mW@840nm *and emits about 50mW@635nm. The fibre-transmitted pump light of about 100mW is available at the output of the fibre laser. The single-mode fibre light guide guarantees an optimal combination of the two laser beams, having different wavelengths. However, other wavelengths besides 635nm line can be also excited in dependence on the used resonator mirrors. For illustration, in the middle of the fibre loop a prism shows the different spectral lines of the dopes fibre.*

The light of the fibre laser is collimated by means of a microscope objective and illuminates a diffraction grating. Two diffraction orders are used as beams for the illumination of the measuring volume. The homodyne technique has to fulfil two demands on the fringe systems of different wavelengths: 1. Same fringe spacing, 2. Shift of a quarter spacing against each other.
The first demand requires an achromatic fringe spacing. The imaging of the grating into the measuring volume fulfils this demand, see Czarske 1997. The second demand was achieved by a phase shift of the two beams in the Fourier plane of the imaging optics, see Fig. 1. Due to the chromatic dispersion of the used glass, different phase shifts for the two wavelengths occur. Applying a symmetrical tilting of two glass plate against each other, the relative phase shift of 90^0 was adjusted. In consequence, two fringe systems, having the same spacing, but a quadrature phase shift were generated.

2.2 Experimental results

An air stream with water particles of about 1.5µm diameter was used for the experiments. Their passage through the measuring volume, see Fig. 1 generates the quadrature signal pair in Fig. 5. The Fig. 6 shows the spectrum of the measuring signal. The enhancement of the noise floor at some 100 kHz and about 16 MHz is given by the relaxation noise of the fibre laser and the mopa diode laser, respectively.

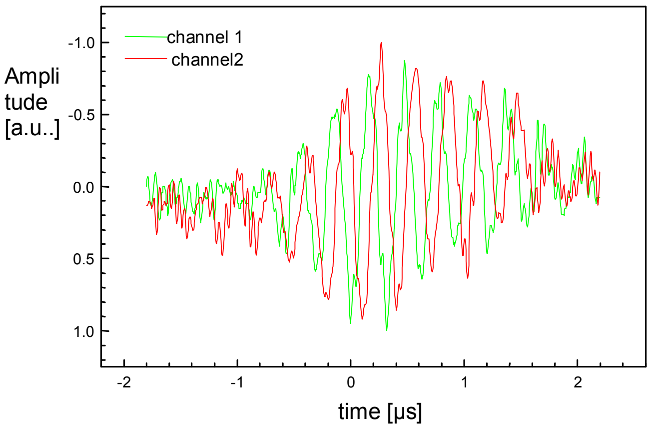


Fig. 5: High-pass filtered quadrature signal pair for one moving direction

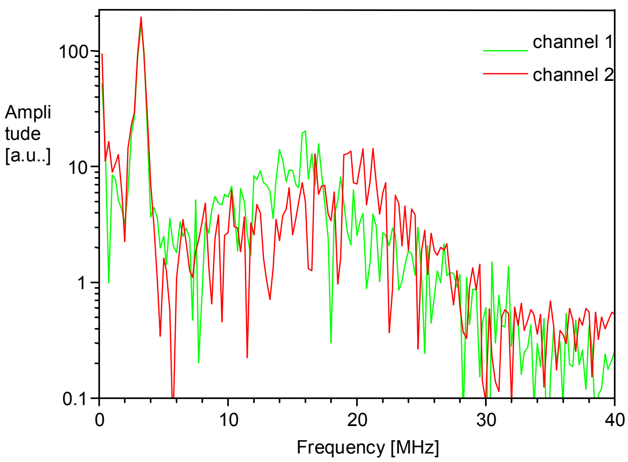


Fig. 6: FFT spectrum of the measuring signal from Fig. 5.

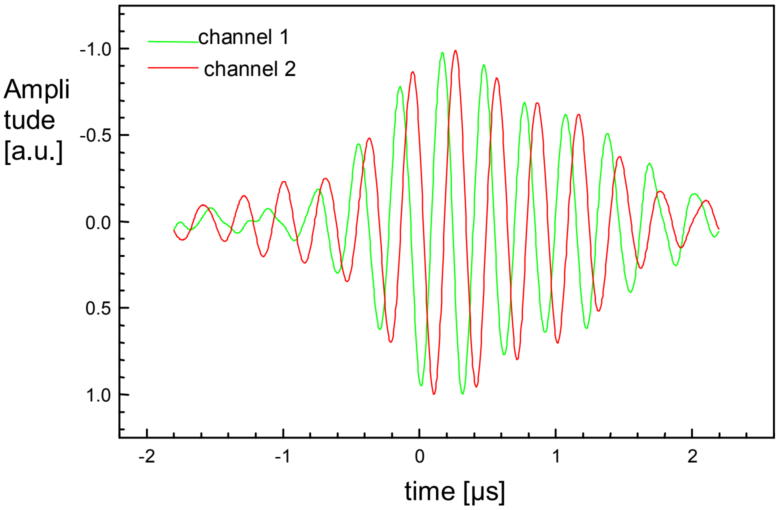


Fig. 7: Band pass filtered quadrature signal pair, compare Fig. 5.

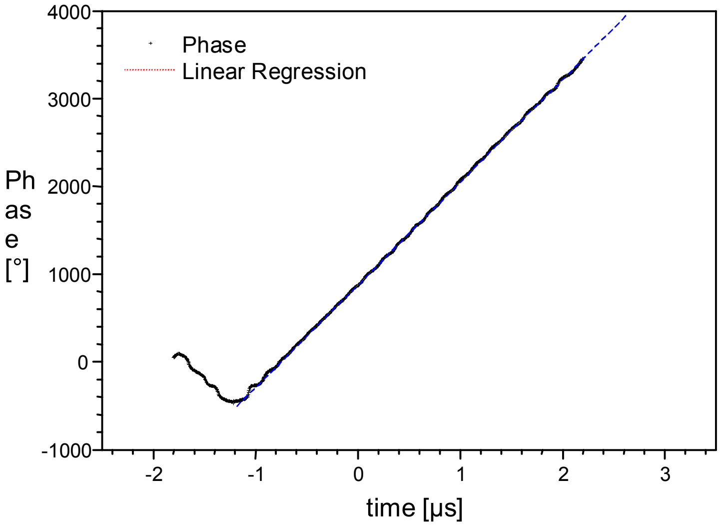


Fig. 8: Demodulated phase of the quadrature signal pair from Fig. 7. Using a straight regression curve, their slopes give the amount of the averaged Doppler frequency and the direction of motion.

The Fig. 7 was measured by using a band pass filter, so that the signal-to-noise-ratio is significantly higher than at Fig. 5. The Fig. 8 shows the measured phase curve of the signal from Fig. 7 by using the quadrature demodulation technique (QDT), see Czarske et al. 1999. As can be seen from Fig. 8, the phase curve has an opposite dependence for a time <-1µs. It corresponds to a phase shift between the signal pairs, see Fig. 7. The reason is the misalignment of the two fringe systems, due to chromatic aberrations of the imaging system.

The principle of the homodyne LDV system was demonstrated successfully. It was shown that precise velocity measurements can be accomplished by a homodyne LDV system. Since the homodyne technique does not need any active elements, a small measuring head can be designed. The use of the diffraction grating and the fibre laser allows the realisation of a miniaturised back-scatter LDV measuring head.

3. VELOCITY PROFIL SENSOR

The principle of the technique of spatial resolution is based on the deviation of the two fringe spacings gradients $d_i(z)$ from each other, i=1,2, Fig. 9. Their physical discrimination allows the separate measurement of the two Doppler frequencies $f_i=v_x/d_i$, i=1,2. The z position of the tracer trajectory is determined by means of the calibration function of the frequency quotient $z=\phi(f_1/f_2)$. Finally, the calculated z-position allows a correction of the distorted fringe systems, resulting in a precise velocity measurement.
The physical separation of the two measuring channels can be achieved, in principle, by laser pulses, orthogonal laser polarizations or different laser wavelengths (Drain 1980). The use of a high frequent pulsed laser source and the synchronous detection of the scattered laser pulses is technically complicated. The employment of different light polarizations is not possible, if depolarized scattering processes are involved. In general this is not fulfilled with the occurring Mie-scattering process. In contrast to these methods, the chromatic separation of two laser wavelengths allows a reliable discrimination between the two measuring channels. Further below it will be shown that this method can be employed for measurements of a chromatically coded measuring volume.

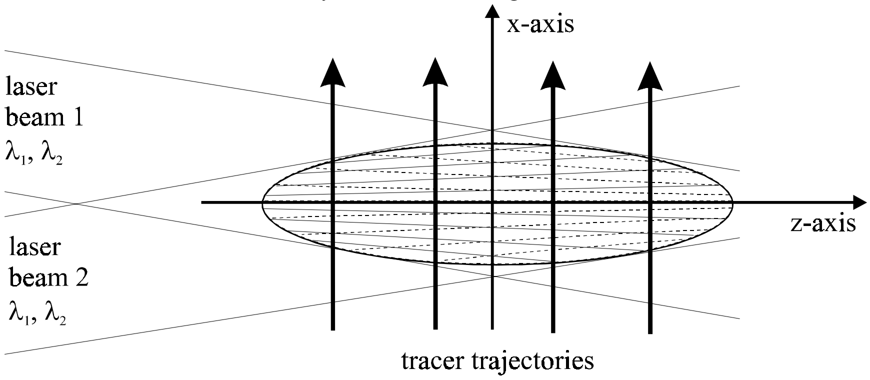


Fig. 9. Concept of the spatial resolution principle. Two fringe systems are generated with different spatial dependence of their fringe spacings along the z-axis. Their separate evaluation allows a spatial-resolved velocity measurement $v_x(z)$.

In Fig. 10 the technical solution of spatial-resolved distributed LDV system, using different wavelengths from two lasers is sketched. Two fiber-coupled laser diodes of 40mW@825nm (3nm linewidth) and of 80mW@860nm (0.7nm linewidth), respectively, are employed. The single-mode fiber-guided beams of the two lasers are combined by a fiber coupler. The light from the single-mode fiber, having a mode field diameter of D_1=7.7µm, is collimated by a Kepler telescope arrangement, using two aspheric diffraction-limited lenses of f_{L1}=4.5mm and f_{L2}=25mm focal lengths. In terms of geometric optics a gaussian beam results to a waist diameter of $D_2=D_1 f_{L2}/f_{L1}$=43µm. A transmission diffraction grating with a rectangular phase structure of a period of g=6µm splits up the beam into the –1. and +1. diffraction orders, which contain about 80% of the incident optical power. The other diffraction orders are blocked by a spatial filter. The resulting two laser beams are imaged into the measuring volume by incorporating a Kepler telescope arrangement, using two achromatic lenses with the focal lengths f_{L3}=10mm and f_{L4}=30mm, Fig. 10. The accomplished achromatic imaging of the diffraction grating guarantees a wavelength independent fringe spacing of $d=g\, f_{L4}/(2f_{L3})$=9µm in the measuring volume (Czarske et al. 1997), in the sense of geometric optics. In order to achieve a defined scattering signal, a velocity controlled chopper moves a tungsten wire with a diameter of 4µm through the measuring volume. The back-scattered light is coupled by incorporating a launching lens into a multi-mode fiber of 200µm diameter and a 0.16 numerical aperture. In the LDV device the scattered light is chromatically separated by a dichroic interference splitter onto two avalanche detectors. The generated burst signals are evaluated by FFT-technique (fast Fourier transformation). The center Doppler frequencies are interpolated by gaussian fits of the FFT spectra.

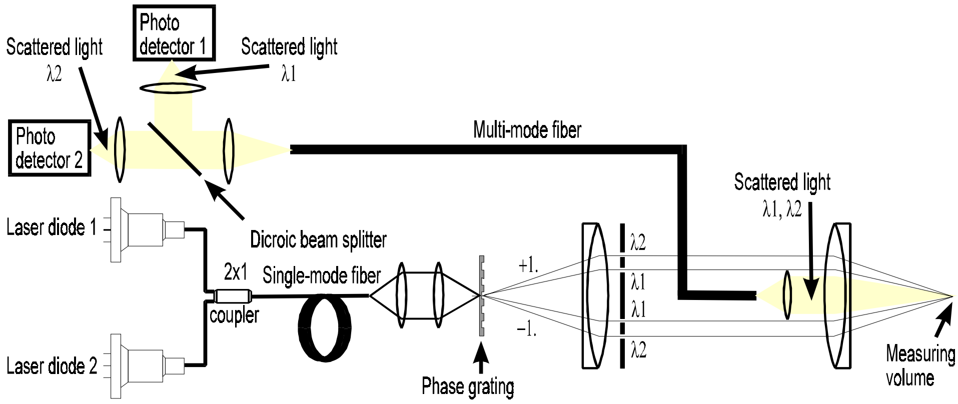


FIG. 10. Arrangement of the proposed LDV system, yielding a spatial resolution. Two laser diodes of different emission wavelengths are employed to generate the different fringe systems. The back-scattered light is chromatically separated into two detection channels. The evaluation of the two Doppler burst signals by FFT technique allows a determination of the x-velocity component $v_x(z)$ as a function of the z-position of the tracer particle trajectory.

The principle of the spatial-resolution-technique, based on a chromatic coding, has briefly been described above. Now, this technique shall be explained with respect to the realised arrangement, Fig. 10. The applied spatial-resolution-procedure is based on four steps:

1) Generation of two differing fringe systems, Fig. 9, 10. The fringe spacing between adjacent fringes in the x-direction is determined by the curvature of the wave fronts of the gaussian laser beams (Miles et al. 1996). In consequence, the fringe spacing gradient in z direction depends on the position of the gaussian beam waist. The variation of the fringe spacing along the longitudinal axis is given by (Miles et al. 1996): $d(z)= [1+(z \cos^2\Theta(z \cos^2\Theta - z_w))/(z_R^2 \cos^2\Theta - z_w(z\cos^2\Theta - z_w))]\ \lambda/(2 \sin\Theta)$, where λ is the laser wavelength, Θ is the half beam crossing angle, z is the longitudinal coordinate in the measuring volume, z_w is the position of the gaussian beam waist relative to the beam crossing point z_c and $z_R=\pi w_0^2/\lambda$ is the Rayleigh length; w_0 being the radius of the $1/e^2$ intensity contour at the beam waist position.

In order to achieve a different fringe spacing gradient d(z), the positions z_{wi}, i=1,2 of the gaussian beam waists have to be longitudinally shifted against each other. However, the collimation of the two-wavelength light by singlet-lenses, exhibits a chromatic aberration. Hence, different beam waist positions result for the two wavelengths. The beam waists are achromatically focussed into the measuring volume, as follows: λ_1=825nm: w_{01}=53µm, z_{w1}=−5.5mm and λ_2=860nm: w_{02}=43µm, z_{w2}=−2.65mm. According to the equation above, different longitudinal dependences are obtained for the respective fringe spacings.

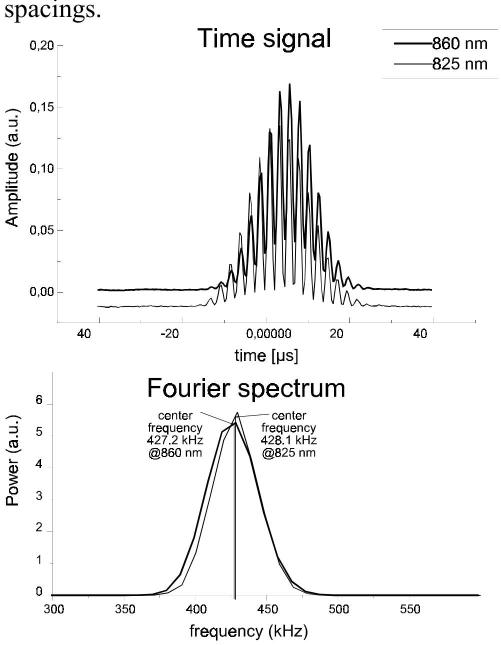
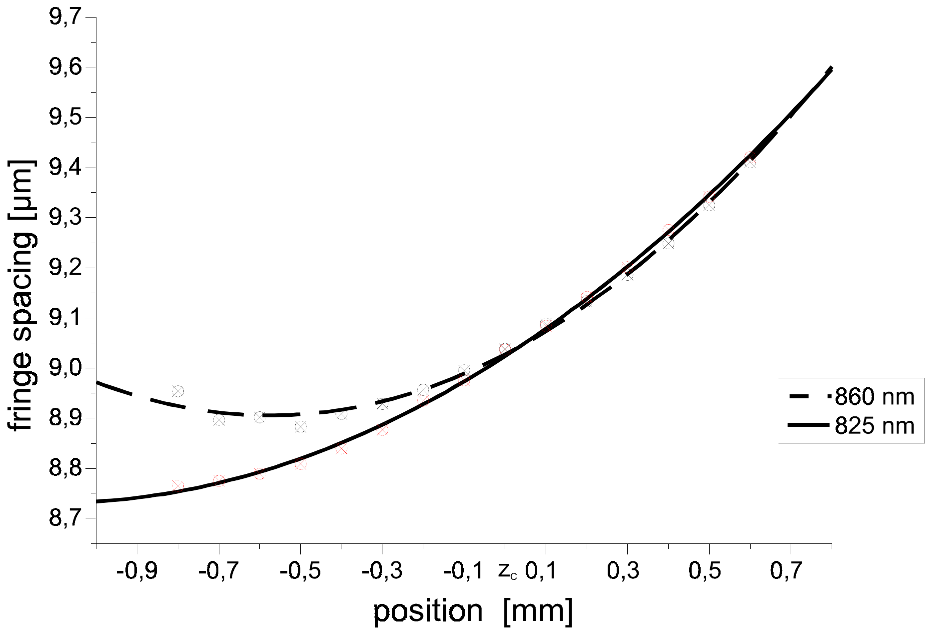


FIG. 11. Measuring results from the two channels for a single longitudinal position ($z=z_c$-0.05mm) Top: Burst time signal; bottom: FFT spectra of the Doppler frequencies.

2) Accomplishment of two separated Doppler frequency measurements, Fig. 10, 11: The simultaneous determination of two variables, refering v_x and z, requires two measurements. The use of two laser wavelengths allows the detection of two chromatically separated measurands. Different discrimination methods are principally possible: the use of (i) color filters, (ii) dispersive elements, like diffraction gratings or prisms, and (iii) dicroitic interference elements. However, the wavelength separation by colour filters has a not sufficient isolation. The method (ii) can be problematically, if scattering light with a high numerical aperture occurs, since it can result in overlapping diffraction orders. In contrast, the method (iii) provides good isolation of the two light wavelengths from each other. In consequence, a dielectric interference coating element was used. The light of the wavelength 825nm is split into the two detection channel, as follows: 80 (a.u.) at channel 1 and 4 (a.u.) at channel 2. A cross-talk of 4.8% results. For the wavelength of 860nm, a value of 5.5 (a.u.) for channel 1 and of 130 (a.u.) for channel 2 is obtained, i.e. 4.1% cross talking occurs. Hence, an average isolation of approximately 13.5dB between the two detection channels results. This discrimination of the two wavelengths guarantees a reliable function of the LDV system. However, further improvement of the isolation is desirable yet. It is obtained by a greater wavelength difference and by an optimized design of the dicroitic interference filter.

3) Determination of the z-position of the tracer trajectory, Fig. 12,13: The principle is based on the determination of two Doppler frequencies f_1, f_2 of one tracer particle motion in x-direction. Assuming two fringe spacings d_1, d_2 for the respective wavelengths λ_1, λ_2, the Doppler frequencies are given by $f_i=v_x/d_i$, i=1,2. Their quotient $q=f_1(z)/f_2(z)=d_2(z)/d_1(z)$ depends only on the z-position of the tracer trajectory, due to the chromatic coding. Since q is independent of the velocity, the z-position can be calculated by a calibration function $z=\phi(q)$, assuming a defined calibration function, having no equal values throughout the whole measuring volume. In Fig. 12 the determined fringe spacings are shown with respect to the laser wavelengths. Fig. 13 presents the calibration curve of the spatial-resolution-procedure. However, the z-position of the tracer trajectory can be calculated definitely only over a limited range ($z=z_c-0.8$mm...$z_c+0.4$mm) . The reason why the gradients of the fringe spacings d_1, d_2 are equal $z=z_c+0.4$mm, Fig. 12. It should be pointed out that no physical limitation of the measuring range exists. A larger longitudinal separation between the two beam waist positions z_{w1}, z_{w2}, results in a defined calibration function in the whole measuring volume.

The reproduceability of the determined quotient q is shown in Fig. 13 for three exemplary z-positions. As can be expected, at the centre of the measuring accuracy is higher than at its tailing regions, i.e. the outer z-positions. The burst Doppler signals from the boundaries have a low signal-to-noise-ratio and show disturbances. A mean accuracy of approximately 120µm for the z-position in the measuring range from $z=z_c+0.4/-0.8$mm was achieved. Therefore, a relative spatial resolution results of about 10% within the longitudinal measuring range of 1.2mm. Improvement of the accuracy will be achieved by suppression of the laser power fluctuations, which are caused by the digital power supply. Furthermore, the small number of occurring periods, see Fig. 11, results in a low frequency measuring accuracy of the FFT technique. A larger measuring volume, containing a higher number of fringes will improve the measuring



accuracy.

Fig. 12: Experimental curves for the fringe spacings in the measuring volume as a function of the beam waist positions as follows: z_{w1}=-5.5mm, z_{w2}=-2.65mm, longitudinal measuring volume dimension (1/e^2 intensity level): z_c-0.8mm...z_c+0.6mm.

4) Determining the x-velocity-component v_x of the tracer trajectory, Fig. 11: Based on the calculated z-position by step 3), the fringe spacings d_1, d_2 are known. Hence, the two Doppler frequency measurements f_1, f_2 allow a determination of the average velocity $v_x=0.5(f_1d_1+f_2d_2)$ as the arithmetic mean. In contrast to the known methods for a discrimination of two simultaneous measurements (Jones 1997), an iterative procedure was applied. First, both frequency measurements were used for the calculation of the z-position and second, based on these result, the velocity v_x was determined.
In addition to the desired fringe spacing gradient in z-direction, also a transverse gradient in x-direction results. In order to reduce it, the longitudinal distance between of the two beam waist positions should be limited. Furthermore, the used different wavelengths result in considerable fringe spacing changes for conventional LDV systems, with a partial-reflecting mirror as beam splitter. To avoid this chromatic effect, a diffraction grating was used as a beam splitter, Fig. 10. The generated achromatic fringe systems reduce the change of the fringe spacings in transverse direction. Furthermore, the imaging of the diffraction grating into the measuring volume, results in a fully symmetrical interferometer arrangement. Therefore, low-coherence lasers like the used one, can be employed easily. However, in order to achieve a definite beam waist position, longitudinal single-mode lasers should be employed in the future.
It should be remarked that the occurring transverse change of the fringe spacing can be evaluated by the quadrature demodulation signal processing technique (QDT, Czarske et al. 1999) Realising a heterodyne LDV system, e.g. by using an acousto-optic modulator, a sine-cosine quadrature signal pair can be generated. The QDT allows a time-resolved Doppler frequency measurement of the signal pair, incorporating an incremental counting of the signal periods, i.e. fringes. Consequently, the gradient of the fringe spacing in x-direction can be measured by QDT. Additionally, the discrimination of the direction sense of the tracer movement is achieved. By an extension to a three-dimensional velocity measurement, whole-field velocity measurements can be done. Therefore, the three-dimensional LDV system with a spatial resolution, can be regarded as an alternative to whole-field measuring techniques, like three-dimensional particle image velocimetry (3D-PIV, Bücker 1996, Hinsch 1993).

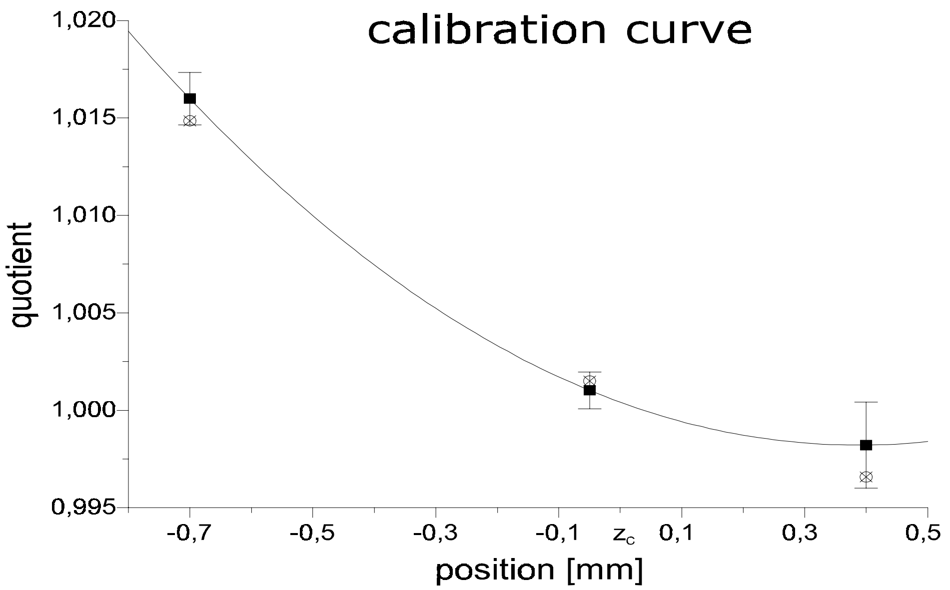


FIG. 13. Experimental calibration curve. The quotient of the fringe spacings $q=d_2/d_1$ as a function of the z-position is shown. The validation range of the spatial resolved velocity measurement results to z_c-0.8mm to z_c+0.4mm. The error bars depict the accuracy of the measured quotient q at three arbitrary z-positions (5 repeated measurements).

A novel differential laser Doppler velocimeter has been reported, which allows distributed velocity measurements with spatial resolution. Due to a chromatic coding, different measuring scales were generated in the measuring volume. Through chromatic separation, two Doppler frequency measurements were obtained. In result, the longitudinal position and the lateral velocity of the tracer particle were determined. As a preliminary result a spatial resolution of about 120µm was achieved. A higher laser stabilization, an improved FFT frequency interpolation and corrected spherical lens aberration will improve the spatial resolution significantly. Especially fluid flows, having high velocity gradients like boundary layers can be measured. Due to the achievable high data processing rate, also velocity fluctuations, e.g. at the transition from laminar to turbulent flow, can be determined.

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References:

Brücker, C.: 3-D PIV using a scanning light sheet and stereoscopy: Study of flow development around a spherical cap, Appl. Sci. Res. 56(2-3), pp.157-179, 1996.

Drain, L.: The laser Doppler technique, Wiley, Chichester, 1980.

Czarske, J., Müller, H., Hock, F. (1994). "Verwendung von Beugungsgittern als Strahlteiler für die Laser-Doppler-Anemometrie", Technisches Messen 7 , pp.311-316

Czarske, J., Zellmer, H., Tünnermann, A., Welling, H., Müller, H. (1997) "Novel high-power laser Doppler anemometer using a diode-pumped fiber laser", Appl. Phys. B, 64, Rapid Communication, S.119-122, 1997

Czarske, J., Zellmer, H. and Welling, H. (1999) "Directional achromatic heterodyne fiber laser Doppler anemometer", Optics Communications, Vol. 132, pp.421-426,

Hinsch, K.: The many dimensions of optical flow diagnostics, Proc. of the 5th Int. Conf. On Laser Anemometry – Advances and Applications, 23-27 August 1993, Koningshof, Veldhoven, The Netherlands, pp. .63-78.

Jones, J.: Review of fibre sensor techniques for temperature-strain discrimination, OSA Technical Digest Series Volume 16, 12th Intern. Conf. on Optical Fiber Sensors, October 28-31, 1997, pp.36-39.

Mazumder, M. K.; Wanchoo, S.; McLeod, P. C.; Ballard, G. S.; Mozumdar, S.; Caraballo, N. (1981): Skin friction drag measurements by LDV. Appl. Opt. 20, pp. 2832-2837

Miles, P., Witze, P.: Evaluation of the Gaussian beam model for prediction of LDV fringe fields, Eighth Intern. Symposium – Applications of laser techniques to fluid mechanics, July 8th-11th, 1996, Lisbon, Portugal, paper 40.1.

Plamann, K., Zellmer, H., Czarske J. and Tünnermann, A.: Directional discrimination in laser Doppler anemometry (LDA) without frequency shifting using twinned optical fibres in the receiving optics, Measurement Science and Technology, 9, 1998, pp. 1840-1846.

Strunck, V., Grosche, G., Dopheide, D.: Scanning laser Doppler probe for profile measurements, Seventh Intern. Symposium – Applications of laser techniques to fluid mechanics, 1994, Lisbon, Portugal, paper 17.1.

Strunck, V., Kisters, T., Dopheide, D.: Dual forward reference scattering LDA probe with high spatial resolution used a backscatter configuration, Proc. of the 7th Int. Conf. on Laser Anemometry – Advances and Applications, 8-11 September 1997, Karlsruhe, Germany, pp. 17-24.

Zellmer, H., Riedel, P., Tünnermann, A. 1999 "Visible upconversion lasers in praseodymium-ytterbium-doped fibers", Appl. Phys. B 69, pp.417-421.