Two-focus chirp laser Doppler velocimeter using a powerful fibre-coupled green Nd:YAG ring laser

by

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ABSTRACT

The chirp heterodyne technique allows a directional discrimination of laser Doppler velocity measurements without the employment of additional frequency shift elements. The use of a chirp frequency-modulated solid-state-laser, emitting in the green spectral range is presented. The performance of realised green chirp laser Doppler velocimeter (LDV) is discussed in detail. The principle of the chirp heterodyne technique is based on a linear frequency modulation of a single-mode laser in combination with fibre delay lines. The use of different fibre delay lines, see Fig. 1, allows the distinguishing between different measuring volumes.
The advantage of the chirp heterodyne technique compared to other concepts is that only one laser source and a fibre network allows directional measurements of multiple velocities.

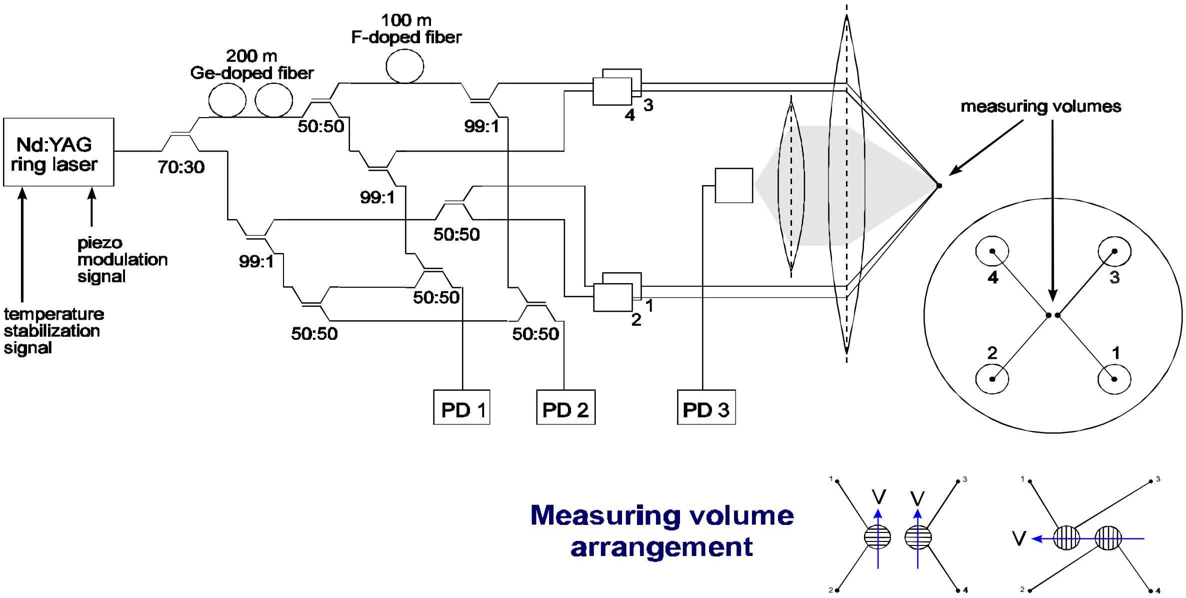

Fig. 1. Scheme of the two-focus chirp heterodyne laser Doppler velocimeter (LDV). Due to two fibre delay lines of different lengths, optical frequency differences are achieved. The scattering light from two measuring volumes is guided on one photo diode (PD3). The different carrier frequencies of the measuring signal are correlated with the two carrier-frequent reference signals. In result, two directional velocity values, corresponding to the two measuring volumes are achieved. The measuring volumes can be orientated parallel or serial. The first regime is interesting for the investigation of boundary layers.

1. Introduction

Directional heterodyne laser Doppler velocimeters (LDV) are frequently used in fluid mechanics. Conventionally, the directional discrimination of the laser Doppler velocity measurement is achieved by the use of frequency-shift elements, in general acousto-optic modulators (AOM, Bragg cell). Although Bragg cells are well-known as reliable devises, they also have some disadvantages: they are bulky, need a high-power rf-signal and they are alignment sensitive. Especially for the realisation of miniaturised LDV sensors, alternative methods for the directional discrimination are desirable. Towards these demand, several schemes were proposed in the last time, see e.g. (Plamann et al. 1998) and references inside. One promising method is the chirp heterodyne technique, Czarske et al. 1996: Using a chirp frequency modulation of a single-mode laser together with an optical delay line of a defined length, a frequency-shift between the two LDV beams can be achieved directly. The resulting heterodyne LDV signal allows the directional discrimination of the movement of the scattering particle. Up to now, these chirp heterodyne technique was usually implemented by the employment of diode lasers (Jones et al. 1984) and infrared Nd:YAG lasers (Czarske et al. 1996, 5]. However, single-mode diode lasers have a limited optical power of about 100mW. The available Nd:YAG lasers emit over 1W@1.3µm power, but the infrared emitting wavelength is not optimal for LDV measurements. Of course, a visible measuring point is easy to observe at its scanning through the fluid flow. Furthermore, the scattering coefficient increases with shorter wavelengths. In order to overcome this disadvantageous wavelength, frequency-doubled Nd:YAG lasers, emitting in the green spectral range can be employed. However, commercial powerful frequency-doubled solid-state lasers are usually working in the transverse multi-mode operation. Since some years fundamental-mode green lasers with multiple watts output power are also commercial available. By the use of etalons in linear cavities or by twisted-mode cavities, a longitudinal single-mode emission was achieved. These single-frequency laser types are today often applied in interferometry and spectroscopy. However, because of the intra-cavity elements, like the mode-selecting etalons, a tuning of the laser frequency tuning is difficult. Furthermore, the chirp-heterodyne LDV technique usually requires lasers, that have a frequency tuning rate in the kHz range. Recently, in the LZH a powerful green Nd:YAG laser was realised (Schneider et al. 1996), which fulfils this demand. In the next chapter the arrangement and the operation characteristics of this laser, respectively, are described. Using the green chirp modulated laser for LDV, directional velocity measurements can be accomplished without having to use frequency shift elements, chapter 3. Finally, the features and the potential of the chirp heterodyne LDV technique are concluded.

2. Chirp heterodyne LDV system

The realised directional LDV system is based on the already presented chirp heterodyne technique, using a linear frequency modulated laser together with an optical path length difference of a Mach-Zehnder interferometer. This method is also known as ramp-modulation frequency-shift LDV technique. Here only a brief description of the realised LDV system is given, for details see Czarske et al. 1996, 4,5]. The Fig. 1 shows the optical arrangement of the LDV system. In Fig. 2 the principle of the generation of a carrier frequency by chirp laser frequency modulation is recapitulated.

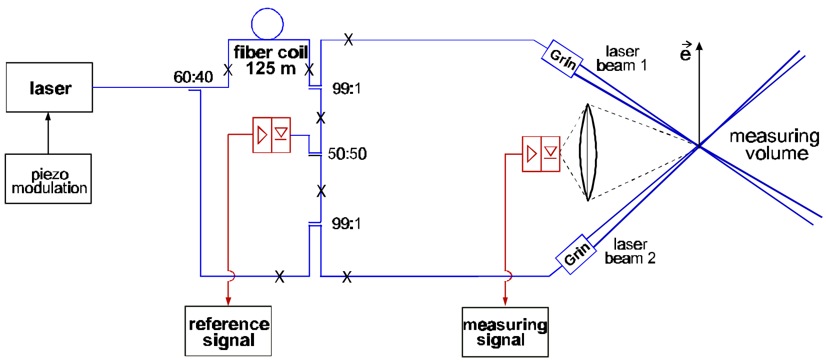

Fig. 1: Arrangement of the chirp heterodyne laser Doppler velocimeter (LDV). The scattering light of particles, moving through the measuring volume generates a carrier-frequent measuring signal. The measuring direction is given by the sensitivity vector $\vec{e}$ *. An accurate determination of the particle velocity is achieved by a correlation of the measuring signal with the reference signal, having the same carrier frequency. (X: fibre splice)*

2.1 Frequency-modulated green Nd:YAG laser

The used oscillator is a monolithic Nd:YAG ring laser with a fundamental-mode power of about 2W@1064nm and a spectral linewidth of less than 1kHz, Fig. 3. The ring laser arrangement enables a stable single-frequency emission, which can be mode hop free tuned over a range of approximately 10GHz by precise control of the laser crystal temperature. A faster frequency tuning can be accomplished by means of a piezo-element, which introduces mechanical stress to the Nd:YAG laser crystal. The piezo-electrical frequency modulation has a typical modulation coefficient of about 1.4MHz/V and can be accomplished to rates of about 100kHz. At higher modulation rates a resonance of the piezo-element occurs, so that a defined modulation is not possible. In Fig. 3 the scheme for generating visible laser light by means of an external laser frequency doubling is shown, for details see (Schneider et al. 1996). The laser beam first passes a Faraday isolator (>30dB extinction), which avoids optical feedback into the laser resonator. To obtain a dispersion-type error signal for locking the doubler cavity to the laser frequency, a resonant electro-optic modulator (EOM) is used. The semi-monolithic doubler cavity consists of a $MgO:LiNbO_3$ crystal and an external spherical mirror. The polished flat end faces are dielectrically coated, backside as high reflector for 1064nm as well as for 532nm and at the front-side in antireflection at both wavelengths. The external mirror is mounted upon a piezo-electric actuator and serves as an input coupler for the fundamental laser light and as an output coupler for the generated green light. The fundamental and the second-harmonic wave, respectively, are separated by a dicroic beam splitter with defined polarisation characteristics. The Pound-Drewer technique is used, to keep the external doubler cavity resonant with the laser frequency (Scheider et al. 1996). The above mentioned EOM is used for a phase modulation of the fundamental laser beam with 12MHz modulation frequency. The generated frequency side bands exhibit a phase shift due to the dispersion curve of the external resonator. The leakage wave of the resonator is detected by a pin photo detector, see Fig. 3. The AC component of the photo current is correlated with the 12 MHz carrier signal by a lock-in-amplifier arrangement. The resulting dispersion-type error signal is feeded back to the piezo-electric actuator via a servo-loop amplifier for active control of the cavity length. The external mirror arrangement ensures a large tuning range, so that there is no need for feeding the error signal back to the laser. In consequence, the defined frequency modulation of the Nd:YAG ring laser can be transferred to the second-harmonic emission. However, the control loop of the external-cavity usually can not follow fast laser frequency changes directly.

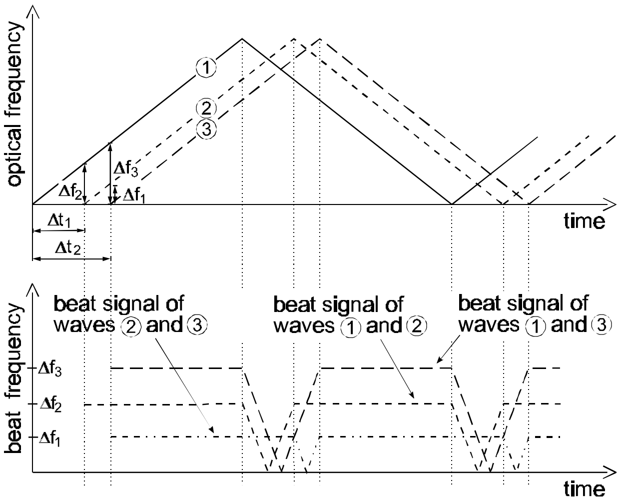

Fig. 2: Principle of the chirp heterodyne technique. The chirp frequency laser modulation generates an electrical carrier frequency by means of chirp frequency laser modulation together with an optical time delay.

For this purpose, a novel modulation scheme was applied. Two synchronous triangular signals, having different amplitudes and a phase difference, are used to modulate the laser and the doubler cavity, due to the control loop amplifier, see Fig. 3. In this operation, only small deviations between the laser frequency and the external-cavity resonance have to be minimised by means of a control. In consequence, a chirp frequency modulation of the green light with a modulation rate of several kHz rate can be achieved.

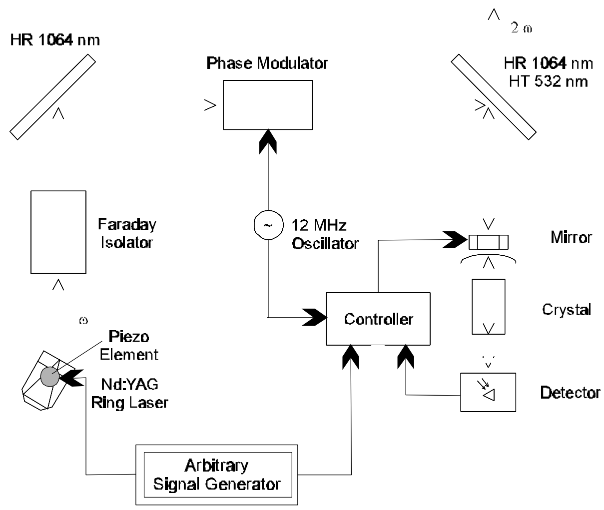

Fig. 3: Arrangement of the used green laser, according to (Schneider et al. 1996). An infrared single-mode laser of 2W@1064nm is piezo-electrical frequency modulated. By means of an external frequency doubling resonator an emission of 1.2W@532nm is generated. Due to a synchronous modulation of the laser and the external resonator, a fast frequency tuning of the green light can be accomplished without instabilities. (w: fundamental laser beam, 2w: frequency-doubled laser light, SHG: second-harmonic-generation).

2.2 Fibre-optical arrangement of the LDV system

The frequency-doubled Nd:YAG laser achieves about 1.2W@532nm fundamental mode power. In Fig. 1 the application of the frequency modulated laser for the LDV system is shown. The green light is launched into a single-mode fibre (fabricate 3M, FS-SN-3224, numerical aperture 0.12, mode field diameter ~4.2µm). Although the cut-off wavelength of the fibre is about 546nm and exceeds slightly the operation wavelength of 532nm, only the fundamental LP_{01} mode propagates within the fibre. By avoiding a strong bending of the fibre no mode conversion occurs. The fibre-guided light is splitted up by using a fused coupler. In one of the two ways a fibre coil of 125m length is introduced as an optical delay line, see Fig.1. Using gradient index (Grin) lenses, the two laser beams are focussed into the measuring volume. The available power in the measuring volume results as follows: The launching efficiency was about 65%, so that P_F~800mW@532nm as fibre optical power was achieved. Optical attenuation of fibre-guided waves occurs at the three fibre fused couplers (premium quality, each ~0.17dB), at the five thermal fibre splices (each ~0.1dB), at the fibre coil (~1.3dB) and at the two Grin lenses (each ~0.3dB). In sum, there is an optical loss of ~2.9dB. Hence, the optical power in the measuring volume was about $P_M \sim P_F/1.95 \sim 410$mW. The generated fringe system in the measuring volume has a spacing of $d \approx 7$µm and the diameter is approximately 110µm. These parameters were determined by an optical beam scanner.

An air stream with suspended water particles of some µm size was used for experimental verification. The back-scattered light was accumulated onto an avalanche-diode with a trans-impedance amplifier. The measured interference signal shows no polarisation fading effects, although non-polarisation-maintaining fibres were used. However, polarisation maintaining fibres would guarantee a higher signal modulation stability, but their optical losses and costs are significant higher than of standard fibres.

2.3 Results of the chirp laser frequency modulation

For a standing Wolfram-wire as the scattering object in the measuring volume, the photo detector signal is measured. Since the Doppler frequency is zero, the measured frequency is equal to the carrier frequency, Czarske et al. 1997. In Fig. 4 the Fourier spectrum of the measured beat signal is shown. The spectral line with a frequency of about 4.8 MHz corresponds to the desired carrier signal. The other spectral lines are due to the phase modulation of the laser beam, see Fig. 3. As described above, side bands with a 12MHz frequency spacing are generated on the fundamental beam. The frequency-doubling process yields the same time-domain-modulation on the second-harmonic beam. The Fig. 5 should explain the generation of the parasitic spectral lines in the beat signal. In the top of Fig. 5 the power spectrum of the two interacting laser beams is shown. Due to the application of the chirp heterodyne technique, see Fig. 2, an optical frequency shift by the amount of the carrier frequency occurs. The electrical beat frequency results as the difference frequencies of the two optical signals, see Fig. 5, bottom. These theoretical description is in good agreement with the measured spectrum, see Fig. 4. However, the measuring range of the Doppler frequency is limited by the parasitic spectral lines. This means that, the resulting beat frequency $f_B = f_C \pm f_D$ is limited by the half of the modulation frequency f_M=12MHz, see Fig. 5. Hence, the generated carrier frequency of $f_C \approx 4.8$MHz allows the measurement of a highest positive Doppler shift of $f_D \approx 1.2$ MHz. In order to enhance the Doppler frequency measuring range, an EOM with a higher modulation frequency should be used. Commercial EOM, allowing modulation frequencies of several 100 MHz are today available at low costs. Alternatively, the Pound-Drewer stabilisation technique can also be realised without laser beam modulation by the use of polarisation techniques (Hänsch et al. 1980). Furthermore, second-harmonic emission can also be effectively generated without an external resonator. Using the quasi-phase-matching (QPM) crystals, which allow great interaction lengths, a sufficient non-linear coefficient can be achieved (Reich et al. 1998). However, currently the maximum laser power before damaging the QPM-crystal is too low for the presented experiment.

By means of an electrical low-pass filter the carrier signal was separated from the modulation signal and the mixed signals (Fig. 4), respectively. The Fig. 6 shows the time-resolved frequency of the carrier signal in correspondence to the chirp modulation signal. The applied triangular-signal form theoretical yields a constant carrier frequency amount inside the modulation half periods. However, at the switches between the up-chirp and the down-chirp of the triangular modulation signal, a parasitic resonance oscillation of the piezo-element can be excited. In consequence, a low-pass-filtering of the modulation signal was accomplished. The laser modulation signal parameters were chosen as follows: $U \approx 390$V piezo modulation amplitude, $f_{MR}=3.5$kHz modulation rate, 10kHz low-pass filter frequency. The modulation of the serve-loop amplifier of the external-cavity was done by the same signal form, but having an effective phase shift of about 6°. A stable green light emission was observed for modulation rates up to about 7kHz. At higher modulation rates a parasitic laser power modulation occurs. However, the carrier frequency amount is currently limited to about 6MHz, due to the phase modulation arrangement (Fig. 3). Therefore, the above presented laser parameters can be viewed as to be optimal for the realised system.

The time-dependent carrier frequency function (see Fig. 6) should be interpreted. The small frequency ripples of about 100kHz modulation frequency result from oscillations of the piezo-element, which could not be completely suppressed. A significant frequency fluctuation, having a greater amount than the piezo oscillations, results from the hysteresis and the non-linearity of piezo-element and the piezo-mounting on the laser crystal. From Fig. 6 a carrier frequency fluctuation band from 4.3MHz up to 5.45MHz with an average of approximately $\langle f_C \rangle \approx 4.8$MHz can be seen. At the switching points of the modulation signal, the carrier frequency shows a strong change.

In the switching time intervals Δt (Fig. 6), the Doppler measurement can not be accomplished. The theoretical delay time is given by $\Delta t = n\Delta l/c \approx 0.625\mu s$, where the fibre refraction index is $n \approx 1.5$ and the fibre length is $\Delta l \approx 125$m (c: vacuum light velocity). Based on the delay time and the frequency derivation df(t)/dt=[df/du][du(t)/dt] of the laser modulation f(t) c.f. the modulation voltage u(t), the carrier frequency amount results to (Czarske 1997): $\langle f_C \rangle = c_M \Delta t \, |du(t)/dt|$, with c_M = df/du as average modulation coefficient of the green laser frequency. This coefficient was determined to: $c_M \approx 2.81$MHz/V. It is twice of the modulation coefficient of the infrared laser frequency. Assuming the triangular modulation signal, the voltage derivation yields to: $du(t)/dt = 2\,U\,f_{MR} \approx 2.73\ 10^6$V/s. In result, the above mentioned average carrier frequency $\langle f_C \rangle$ can be calculated. However, the strong carrier frequency fluctuation of $\Delta f_C \approx 1.15$MHz, see Fig. 6, conventional limits the accuracy of the Doppler frequency determination. In the next chapter a signal processing technique, which allows a Doppler frequency measurement with nearly no influence of carrier frequency fluctuations, will be presented.

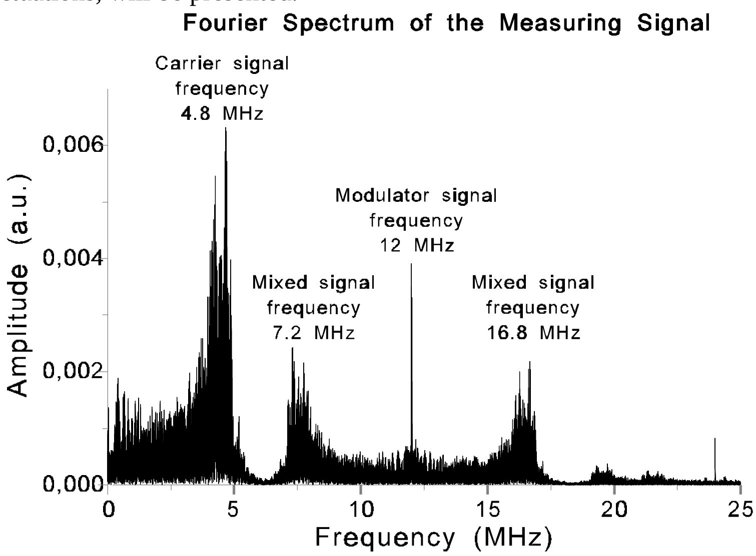

Fig. 4: FFT spectrum of the measuring signal for a standing scattering object in the measuring volume of the LDV system.

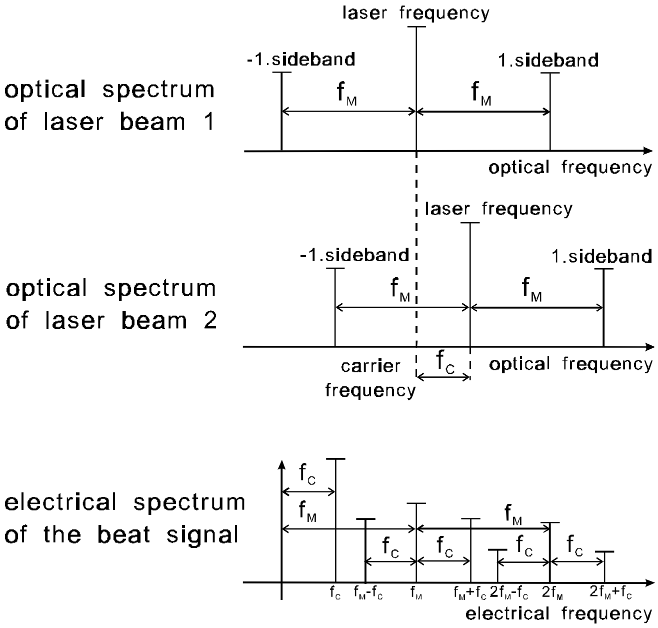

Fig. 5: Principle of the spectral line generation. The additional phase modulation for the locking of oscillator and external-frequency-doubler of the laser system, yields the parasite beat frequencies beside the carrier frequency f_C of about 4.8MHz, compare to Fig. 4. (f_M: laser phase modulation frequency of about 12 MHz, 2x f_M: frequency difference between the –1. and +1. side-bands, respectively).

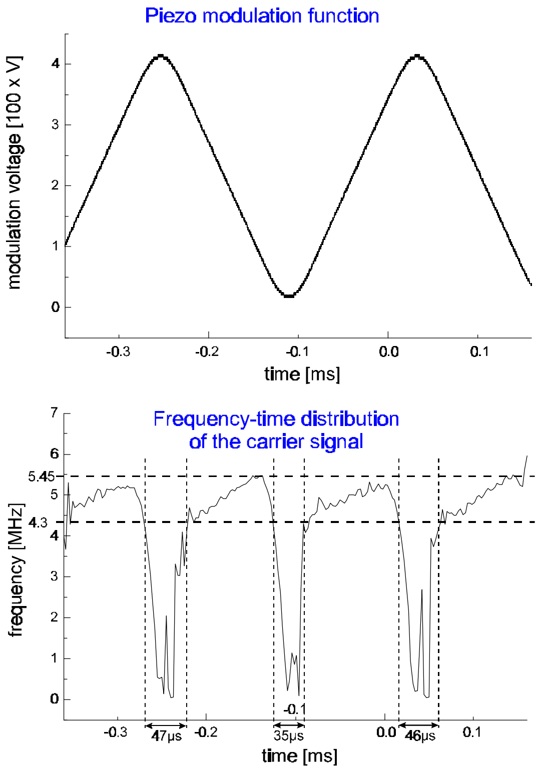

Fig. 6: On the carrier frequency of the measuring signal. Top: A nearly triangular modulation function is used for laser tuning. Bottom: Momentary frequency of the resulting carrier signal; to be compared with Fig. 2. The momentary frequency was calculated by a short-time FFT. Remark: The applied modulation signals of the laser and the servo-amplifier of the external cavity have a time difference. Therefore, the carrier frequency curve has a delay time compared to the curve in Fig. 2.

2.4. Signal processing technique

The processing of the photo-electrical measuring signal is accomplished by a well-known correlation procedure. e.g. Czarske et al. 1997, see Fig. 7. The measuring beat signal, having the frequency $f_B(t) = f_C(t) \pm f_D(t)$, is electrical mixed with a reference signal of the frequency $f_R(t)= f_C(t)$. After a low pass filtering the difference frequency of measuring and reference signal, respectively, the Doppler frequency base-band signal is achieved. In consequence, the carrier signal with its frequency fluctuations is eliminated in the measuring result. The Fig. 1 shows how the reference signal can be generated. A small part of the fibre-guided laser light is coupled out by fused couplers and interferes in a pin-detector. The resulting reference signal has a carrier frequency of $f_R= c_M \, \Delta t_R \, |du(t)/dt|$. In the case of an arrangement with equal optical difference lengths of the reference paths and the measuring paths, respectively, i.e. $\Delta t_R= \Delta t$, the same carrier frequency results. In practice, deviations of the fibre lengths of about 1 centimetres occur. This length deviation of 0.01m has to be regarded to the fibre delay line of Δl=125m length. In result, a frequency offset of $\Delta f \approx 0.01/125 \, \langle f_C \rangle \approx$ 380Hz exists, implying a velocity measuring error of $\Delta v = d \, \Delta f \approx$ 2.7mm/s, where a fringe spacing of $d \approx 7 \mu m$ was assumed (see above). Compared to the fringe spacing gradient in the measuring of several 0.1%, these error usually can be tolerated for fluid measurements. However, a reduction of the measuring error can be achieved by considering the frequency offset in the calculation of a corrected Doppler frequency. Furthermore, the laser frequency modulation can be linearised by using an arbitrary signal generator.

Remark: A change of the optical length of the measuring path could result from a vibration of the fibres, depending e.g. from the orientation in a wind tunnel. Hence, the two fibres of the LDV measuring head should be laid in close contact. Then, both fibres are influenced in the same way, so that their length difference and in consequence the carrier frequency change can be neglected.

The maximum velocity range is dependent on the carrier frequency of 4.8MHz and the half phase modulation frequency of 6MHz, see chapter 2.3. Theoretically the Doppler frequency measuring range is therefore given by –4.8MHz up to +1.2MHz. The Doppler frequency of 1.2MHz yields a velocity of v=8.4m/s. The relative resolution results to $\Delta v/v \approx 0.03\%$. A higher measuring range of the Doppler frequency generally requires a laser with a higher frequency tuning range. Meanwhile, a novel Nd:YAG crystal design and an optimised mounting of the piezo-element was realised. The frequency tuning range was successful enhanced to several GHz. One laser type, which has a much higher mode-hop-free tuning range up to several THz is the external-cavity diode laser (ECL), Wandt et al. 1998. However, currently the laser power of a ECL in the visible spectral range is significant lower compared to the presented Nd:YAG laser type.

The Doppler frequency signal processing is accomplished in the base-band, see above. However, in order to achieve a directional discrimination in the base-band, a quadrature signal pair has to be generated, see Fig. 7. Using a 90° phase shifter for the carrier-frequent reference signal, the sign of the quadrature phase shift of the generated signal pair is dependent on the movement direction, see Czarske et al. 1996, 5]. However, due to the carrier frequency fluctuations, a fixed phase shift is difficult to achieve. A suitable component is a hybrid coupler, which acts as a $0^0/90^0$ power splitter with low frequency dependence. Hybrid couplers with a phase shift unbalance below 3^0 within the interval of 3.5MHz to 4.5MHz are available, (mini-circuits). In Fig. 8 the digital processing of the quadrature demodulation technique (QDT) is shown. A brief description of the QDT will be done in the following, for details see

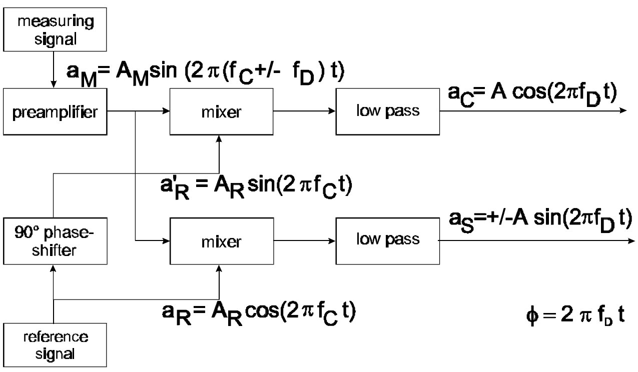

Fig. 7: Lock-in-amplifier for the correlation of the measuring signal and the reference signal, respectively.

(Czarske et al. 1997). The quadrature signals are sampled and transformed into polar coordinates, so that the incremental phase results. The directional counting of the incremental phase jumps allows a phase-unwrapping, resulting in an absolute phase time function $\phi(t)$. Using a linear regression the Doppler frequency can be determined. For example, the centre Doppler frequency $\langle f \rangle$ of a time interval can be estimated by fitting to the phase curve the straight regression line: $\hat{f} = 2p\hat{f}t$, where the regression slope $\hat{f}$ is equal to the centre frequency. The QDT-scheme was implemented on a digital signal processor (DSP: TMS320C50).

The triggering of the laser Doppler signals was done two-fold: First, a triggering on the signal amplitude was accomplished and second, defined validation intervals, regarding to the laser modulation function were considered. The validation intervals are given in Fig. 2 as the available measuring time for the Doppler frequency. As can be seen, close to the switching points no stable carrier frequency exists. These dead time duration are between 35µs and 47µs, respectively (Fig. 6). Regarding to the period of the modulation signal of $1/f_{MR}$=286µs, a relative available measuring time of 72% results. In comparison with Fig. 2, the measured dead time is almost two magnitudes larger than the theoretical value Δt, see chapter 2.1. One reason is the low-pass filtering of the triangular signal, so that the slopes are more smoothed. Furthermore, the stability of the laser modulation is not yet fully optimised. However, the relative measuring time of 72% limits the achievable burst data rate. By means of an optimising of the modulation function, it can be improved to values over 90^0, Czarske et al. 1996. Additionally, the burst duration is limited to half of the laser modulation period of 143µs.

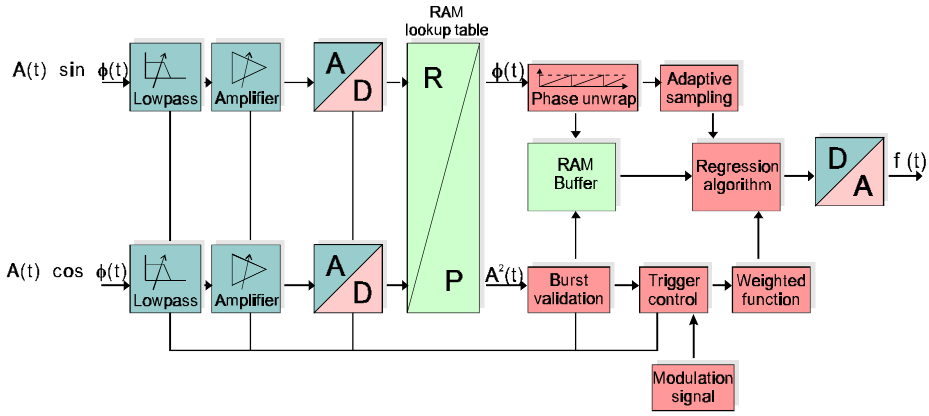

Fig. 8: Quadrature signal processing technique (QDT): The phase of the quadrature signal pair is demodulated. By a linear regression the directional Doppler frequency f(t) is calculated.

In conclusion, the validation signal is implied from the laser modulation signal by recognising the resulting available measuring time intervals. By a logical combination with the signal triggering, the resulting triggering of the signal is accomplished. As a preliminary result, a measured quadrature signal pair is shown in Fig. 9. As scattering particles, water spheres in an air flow have been used. Based on the DSP-QDT the phase of the quadrature signal pair is demodulated. The determined slope of the regression lines (75.8rad/200µs) yields the centre Doppler frequency of the signal to: <f>=+60.3kHz. In result, the particle velocity of <v>=d<f>=+0.42m/s was measured (d=7µm: fringe spacing).

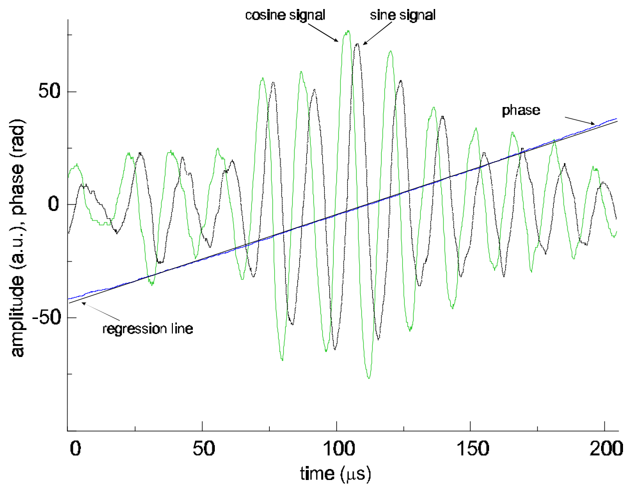

Fig. 9: Measured burst signal pair for one direction of the fluid flow. By means of the applied QDT the signal phase is demodulated and fitted to a straight regression line. The line slope determines the burst centre frequency, which is proportional to the averaged fluid flow velocity in the LDV measuring volume.

3. Discussion

One important choice for the chirp heterodyne LDV technique is the laser wavelength. However, regarding to fluid mechanics applications, visible light usually is preferred. One reason is the possibility of an easier working. The traversing through the measuring volume can be directly observed and furthermore, light, which is reflected e.g. at a wall, can be seen. The physical reasons for the use of visible light are the high scattering coefficient, especially of small particles and the good transmission in water (Tropea 1995). Tracer particles with a diameter, which is small compared to the light wavelength, exhibit Rayleigh scattering. The Rayleigh scattering coefficient goes with the fourth power of the frequency, so that e.g. a doubling of the laser frequency results in a 16-times higher scattering light power. However, for the particle sizes close to the laser wavelength range, Mie-scattering occurs. Their scattering coefficient does not show a clear monotone dependence on the wavelength, e.g. (Grosche et al. 1998). Furthermore, the whole LDV system has to be considered regarding the optimal light wavelength. Besides the scattering process, the photo detector efficiency is wavelength dependent. The quantum efficiency of silicon pin diodes is optimal in the wavelength range of 800nm. However, the responsitivity (dimension A/W), giving the detector current with respect to the light power, is more important, since the resulting photo current value determines the signal quality. However, the realisation of the chirp heterodyne LDV technique generally requires a defined frequency modulated laser source. Therefore, a comparison of the available optical power of the presented Nd:YAG ring laser type for different wavelengths seems to be suitable. This laser type emits about 2W@1064nm power, see above, and by other dielectrical coatings of the Nd:YAG resonator a power of about 1.5W@1357nm was generated (Freitag et al. 1997). By a frequency-doubling of the 1064nm emission about 1.2W@532nm power was achieved, see above. Using a three-level transition of the Neodymium-ion an emission at 946nm was achieved and by frequency-doubling about 0.5W@473nm power in the blue spectral range occurs (*Bode et al 1997.).* A further frequency-doubling into the ultra-violet (UV) spectral range was also realised, but with significant lower power levels. Additionally, in the UV the quantum efficiency of common photo diodes is insufficient and the alternative use of more efficient photo-multipliers is because of their bulky size and complicated power supply not recommendable. Recapitulating the above mentioned dependence of the light scattering coefficient especially for small particle diameters, the employment of a green Nd:YAG laser system seems to be the right choice for the chirp heterodyne LDV technique.

However, in the case of scattering particles with a diameter larger than the laser wavelength, the advantages of a short spectral range are not significantly, see e.g. (Grosche et al. 1998). Then, the responsitivity of the photo detector can dominate. Using light of 532nm wavelength a responsitivity for silicon diodes of 0.35A/W occurs (New Focus) The 1064nm and 1357nm light has a responsitivity of about 0.65A/W and 0.825A/W, respectively, assuming an InGaAs diode.

Furthermore, the realisation of the fibre-optical arrangement is easier to accomplish in the near-infrared spectral range. At telecommunication wavelengths like 1.3µm, low-loss components are available at low-costs. In the green spectral range the linear fibre losses due to Rayleigh scattering are more one order of magnitude higher and additional non-linear fibre losses like stimulated Brillouin scattering (SBS) increase. For SBS the non-linear efficiency increases with the square of wavelength (Agrawal et al.). Hence, higher laser wavelengths have a lower attenuation in the fibre delay line.

4. Conclusions

We have presented the application of a powerful green Nd:YAG laser for the chirp heterodyne LDV technique. The realised directional LDV system consists of a passive fibre optical arrangement and did not employ any frequency shift elements. The laser frequency modulation results in a reliable carrier frequency signal of 4.8MHz, which allows directional Doppler frequency measurement in the range of –4.8MHz to 1.2 MHz, respectively. However, in the future the amount of the carrier frequency and in consequence the Doppler frequency i.e. velocity measuring range should be increased, respectively. The employment of longer fibre delay lines and the use of lasers with higher frequency tuning range will enhance the velocity measuring range.

The green laser emission wavelength is mainly useful for LDV measurements in the Rayleigh scattering regime, i.e. at scattering particles with a size smaller than the laser wavelength. Since the Rayleigh scattering coefficient goes with the light wavelength^{-4}, the efficiency of the photo-detector and the optical losses of the fibre in the green spectral range do not dominate the LDV system performance. By the realisation of different fibre delay lengths, multiple-component directional velocity measurement can be accomplished. This scheme was already realised in the telecommunication wavelength range (Czarske et al. 1997) and can be transferred to the presented chirp heterodyne LDV technique, using a green solid-state laser. As described by Fig. 1 the measurement of multiple velocities from different measuring volumes were accomplished. Using different adjustments of the fibre-coupled measuring head (Schäfter&Kirchhoff, Hamburg) different orientations of the measuring volumes are achieved.

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References:

Agrawal, G. (1989) Nonlinear fiber optics, Academic Press, Boston, 1989, pp. 265.

Bode, M., Freitag, I., Tünnermann, A., Welling, H. (1997) Frequency-tunable 500mW continuous-wave all-solid-state single-frequency source in the blue spectral region, Opt. Lett. 22, 16, pp.1220-1222, 1997.

Czarske, J., Müller, H. (1996) Two-dimensional directional fiber-optic laser Doppler anemometer based on heterodyning by means of a chirp frequency modulated Nd:YAG miniature ring laser, Optics Communications, 1996, Vol.132, pp.421-426

Czarske, J., Dölle, O., Freitag, I., Welling, H., Müller, H. (1997) Optimized two-component directional laser Doppler velocimeter using a chirp frequency modulated powerful Nd:YAG miniature ring laser, Proc. 7th International Conference Laser Anemometry - Advances and Applications, Karlsruhe, Germany, 8-12. September 1997, pp.73-80.

Czarske, J., Dölle, O. (1998) Quadrature demodulation technique used in laser Doppler anemometry, Electronics Letters, 43 (6), 19th March 1998, pp.547-549.

Freitag, I., Tünnermann, A., Welling, H (1997) Intensity Stabilised Nd:YAG Ring Laser with 1.5W Single-Frequency Output Power at 1.357m m. Electron. Lett. 33 (1997), pp. 777-778.

Grosche, G., Müller, H., Strunck, V., Dopheide, D. (1998) Erste in-flight Messungen mit einem 2-Watt-LDA, 6. Fachtagung zu Lasermethoden in der Strömungsmeßtechnik, Essen, Germany, 1998, paper 2 (in German).

Hänsch, T. W., Couillaud, B.: Laser Frequency Stabilization by Polarization Spectroscopy of a Reflecting Reference Cavity, Opt. Comm. 35 (1980), pp.441-445.

Jones, J. D. C., Jackson, D., Corke, M., Kersey, A. D. (1984) Solid state and fibre optic laser Doppler velocimeters, Optics and Lasers in Engineering, 5, pp.127-139, 1984

Plamann, K., Zellmer, H., Czarske J. and Tünnermann, A. (1998) 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.

Mini-Circuits: Product catalogue of Mini-Circuits Inc USA

New Focus: Product catalogue of New Focus Inc., 2630 Walsh Avenue, Santa Clara, CA 95051, USA, pp. 25

Reich, M.; Korte, F.; Fallnich, C.; Welling, H.; Tünnermann, A.: Electrode geometries for periodical poling of ferroelectric materials. Optics Letters 23, pp.1817-1819, 1998.

Schneider, K., Schiller, S., Mlynek, J., Bode, M., Freitag, I. (1996) 1.1 W Single-Frequency 532 nm Radiation by Second Harmonic Generation of a Miniature Nd:YAG Ring Laser, Opt. Lett. 21, 1996, pp.1999-2001.

Tropea C (1995) Laser Doppler anemometry: recent developments and future challenges, Meas. Sci & Tech. 6 (1995) pp.605-619.

D. Wandt, M. Laschek, F. v. Alvensleben, A. Tünnermann, H. Welling (1998) Continuously tunable 0.5 W single-frequency diode laser source, Opt. Commun. 148 (1998), pp.261-264.