Journal of Visualization, Vol. 2, Nos. 3/4 (2000) 281-292

Realization of High Performance LDA-systems using Optical Amplifiers, High Power Semiconductor Lasers and Optical Fiber Lasers

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Received 12 March 1999.
Revised 20 September 1999.

***Abstract*:** Advanced novel techniques for sophisticated LDA applications are presented in this paper. By applying laser sources with high output powers like MOPA-lasers (master oscillator power amplifier), fiber lasers and booster fiber amplifiers to increase the laser power in the measuring volume and by amplifying the scattered light power with optical fiber preamplifiers to increase the sensitivity of the receiving units, the signal-to-noise-ratio of laser Doppler signals is drastically improved and the overall performance of a laser Doppler anemometer is significantly enhanced.

***Keywords*:** novel LDA-techniques, semiconductor laser LDA, optical amplifiers, fibre amplifier LDA, fibre laser LDA.

1. Introduction

Scattered light of low intensities is produced by particles with small dimensions, particles in high speed flows and in LDA-systems with a large working distance. In these cases, powerful lasers and very high sensitive photodetectors are necessary to detect the velocity of the measured flow component with a high data rate and a low uncertainty. One possibility for increasing the laser power in the measuring volume is given by using one laser for each of the crossing laser beams. The laser power in the measuring volume is then doubled in comparision to conventional LDA systems. The authors have applied high power MOPA (master oscillator power amplifier) diode lasers to achieve about 2 W optical power in the measuring volume at a wavelength of 980 nm. An alternative method to obtain high laser power in the measuring volume can be achieved by using an optical fiber laser, where the fiber itself works as a multi-watt laser source, which will also be presented.

A very promising new concept at the receiving side to increase the sensitivity of the LDA system will be demonstrated. By using optical fiber amplifiers as preamplifier in front of the photodetector, the intensity of the scattered light is amplified and the SNR of the electrical burst signals delivered from the photodiode is drastically improved. This improvement is obtained by the optical gain and the low additional noise of the used fiber amplifiers. In addition, optical fiber amplifiers can also be used as booster amplifier to increase the output of pigtailed low power single frequency laser diodes. Both, the post and the preamplification process can be realized in small compact boxes and the system performance is much better than a conventional combination of water cooled Argon-ion laser with photomultipliers.

2. Overview about Realized LDA Performance Improving Techniques

A lot of work has been done during the past to improve the performance of LDA-technique by applying cross correlation and frequency domain processors for signal evaluation at low SNR. Fiber based transmitting and receiving optics have been used to separate the sensors from the basic unit and to obtain high light intensity in the probe volume. Comfortable processors and advanced miniaturized semiconductor LDAs are now commercially available by TSI (Bergner and Naqwi, 1998) and Dantec for example. However, LDA development has not yet been finished.

Some attempts to apply high output power of laser sources have been reported. Dopheide et al. (1990) realized a new technique to increase the light intensity of conventional cw-diode lasers by means of high frequency pulsating using nanosecond pulses at about 80 MHz. An increase of the laser output peak power by a factor 3-5 was achieved. Multicomponent velocity measurement by demultiplexing of several sequentially pulsed diodes using the so-called "coherent sampling" technique with a single signal processor was also realized. Further, the application of pigtailed laser sources together with fiber based pulse delay lines allowed to measure two velocity components simultaneously with one laser diode and one signal processor only, see Wang et al. (1994a), Wang et al. (1996).

The rapid development of semiconductor lasers enables now to buy high power singlemode cw-diode lasers, like MOPA diode lasers with output powers of 1 W, see Welch et al. (1992) and SDL (1993). These lasers can be used successfully for LDA applications which will be discussed by the authors.

The idea of doubling the laser power in the LDA probe volume and saving components for beam splitting and frequency shifting by applying two frequency stabilized monomode lasers for each of the crossing laser beams have already been described, and several systems for measurement of one or two velocity components have been realized, see Müller and Dopheide (1993) and Wang et al. (1994b).

As the optical frequency difference of monomode lasers is used as an auxiliary carrier frequency in the 100 MHz range, laser diodes with almost equal emission frequencies are required. Therefore it is necessary to select appropriate monomode laser diodes by measuring their spectral characteristics depending on the operating current and temperature. To avoid selection problems in finding appropriate monomode lasers with almost equal emission frequencies and overlapping tuning ranges without mode hopping, DBR laser diodes (distributed Bragg reflector) have been applied successfully. Due to the Bragg reflector resonator structure these DBR laser diodes have well defined emission wavelengths and mode hopping free tunable ranges in the nm-range, so that they are very well suited for LDA concepts using one laser source for each beam, see Wang et al. (1994b) and Müller et al. (1996a).

3. Directional 2 W MOPA LDA System and Experimental Results

The MOPA diode lasers mentioned before are delivering output powers of about 1 W in the diffraction limited mode. The device consists of a single transverse and a single longitudinal mode laser oscillator which is coupled monolithically to a flared optical power amplifier, see Fig. 1. The output power of the single frequency laser oscillator is about 50 mW. The subsequent semiconductor amplifier amplifies the single frequency beam up to 1 W and emits from a 0.2 mm wide output facet. Beam shaping optical lens systems allows to obtain a low astigmatism for LDA-use. As the design of the MOPA laser consists of a DBR master oscillator defined by second-order gratings coupled to a flared amplifier, the wavelength tuning properties are similar to that of conventional DBR lasers with wide mode hopping free tuning ranges.

Figure 2 presents the wavelength dependence of the two MOPA lasers as a function of the oscillator current I_{osc} and the temperature of the device as parameter while the amplifier current I_{amp} is kept at 500 mA. It can be clearly seen, that both MOPA lasers can be tuned in such a way that they emit nearly at the same frequency or wavelength if the oscillator current and the temperatures of the devices are properly adjusted. According to the wavelength-current-temperature results presented in Fig. 2, it is possible to operate e.g. the lasers at a wavelength of about 981.52 nm at a temperature of 20°C at moderate oscillator currents I_{osc} and high output power.

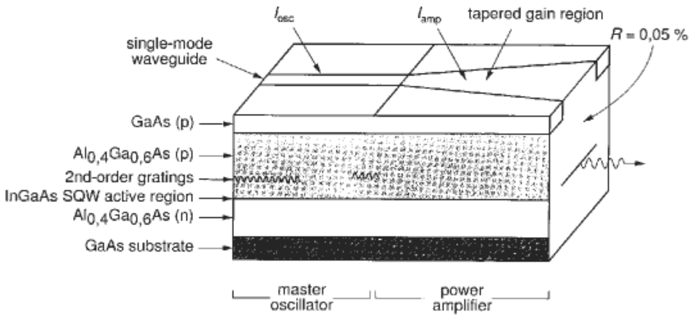

Fig. 1. Schematic diagram of a monolithic master oscillator power amplifier laser, MOPA-laser, see Welch et al. (1992) and SDL (1993).

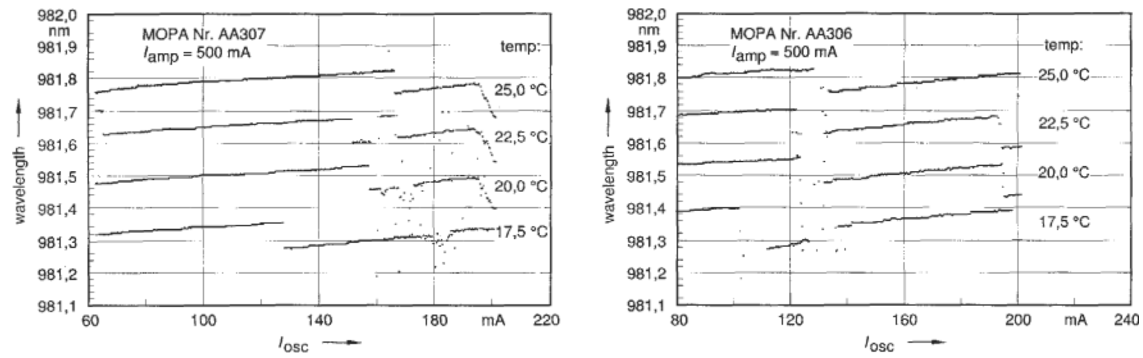

Fig. 2. Wavelength dependence of the selected tunable MOPA lasers for LDA experiments. The wavelengths of a pair of selected diodes is shown as a function of oscillator current at constant amplifier current and different operating temperatures as parameters.

The wavelength tuning behavior of the MOPA lasers allows to use the optical frequency difference of the selected MOPA laser pair as a shift frequency in a directional LDA system when the beat signal of the lasers, see Fig. 3, is used as a reference signal as presented in the block diagram of Fig. 4. It shows the optical set-up of the directional frequency shift LDA-system based upon the application of two stabilized MOPA lasers of the SDL-5762 type, which is presented in more detail in Müller et al. (1997). The shift frequency is given by the beat signal of the two MOPA lasers and is exclusively used as auxiliary carrier for the generation of a sine-cosine signal pair in the base band. In this context the beat signal is called also as reference signal.

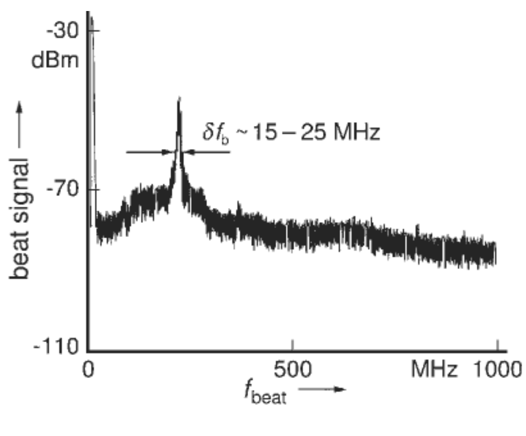

Fig. 3. Beat signal of the selected MOPA laser pair, which is used as a reference signal in the directional LDA according to Fig. 4.

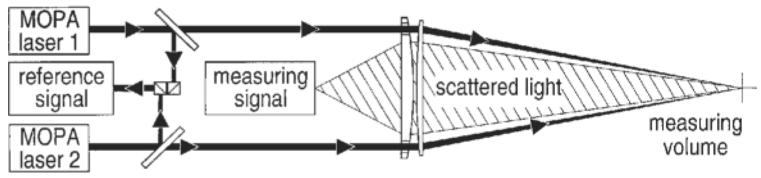

Fig. 4. Experimental set-up of the directional 2W MOPA LDA system which was realized for the first time.

The measuring signal, which is the Doppler signal from the photodetector, will be correlated with the reference signal pair generated with the phase shifter by means of the two mixer units and subsequent integrators (low-pass filters), as shown in the block diagram of Fig. 5. The idea of this back-mixing technique was already described in a Special Issue of FMI about optical techniques for fluid flow measurement by the authors, see Müller et al. (1996b) and will be summarized here therefore only briefly. The resulting quadrature signal pair at the output of the mixer unit is completely free of any frequency shift influences and any frequency fluctuations of the laser diodes and permits the magnitude and sign of velocities to be determined precisely. Figure 6 shows a typical quadrature signal pair containing only a few Doppler cycles resulting from a tracer particle which was passing only a few fringes of the measuring volume.

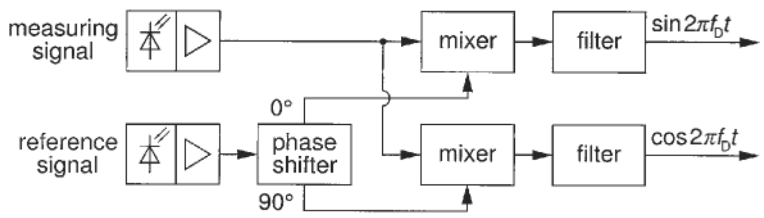

Fig. 5. Block diagram for correlating the measuring signal of the LDA unit with the reference signal to obtain the measuring information from the resulting quadrature signal pair in the base band, see e.g. Müller et al. (1996a).

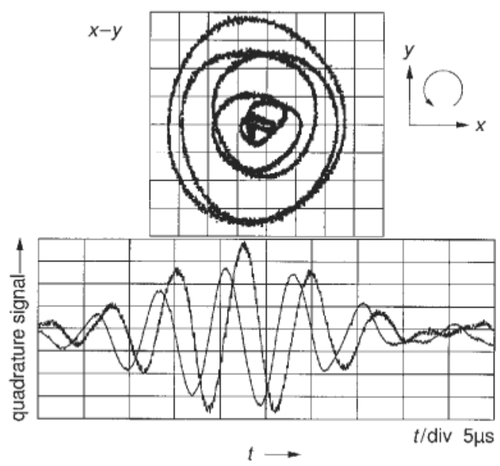

Fig. 6. LDA quadrature signal pair measured with the experimental set-up according to Figs. 4 and 5.

Using the advantages of quadrature signal evaluation, the presented directional 2W LDA system is indeed a powerful velocity sensor with enhanced measuring possibilities at any situation where strong laser power in a complex flow situation is required.

In combination with the very flexible transient recorder technique any flow velocity from 'zero' up to 500 m/s can be measured with the same signal processing unit. It is actually possible to measure the velocity 'zero,' that means that the position of a tracer particle inside the measuring volume can be identified by using this technique, see e.g. Müller et al. (1995). It should be mentioned that the local velocity (frequency) inside the probe volume can be determined precisely as it was shown recently by Strunck et al. (1998).

Such a 2-Watt MOPA LDA as shown in Fig. 4 was designed for in-flight measurements to measure air speed at high altitudes. Particles with submicron diameter could be detected at a data rate up to 10 Hz with this system as described by Grosche et al. (1998).

As mentioned before in the introduction, the attainable SNRs can be further improved by means of a novel concept for the receiving photodetector unit using optical fiber amplifiers. This concept will be explained in the next chapter.

4. Introduction to Fiber Amplifiers in LDA Systems

An advantageous way to improve SNRs of fiber-based LDA systems is the optical amplification with fiber amplifiers. Detailed descriptions about the fiber amplifier technique are presented in books like France (1991), Digonnet (1993), Bjarklev (1993), Desurvire (1994) and Sudo (1997). Up to now the amplification of optical signals typically is performed in an electronic stage or in a photodiode with internal gain like an avalanche photodiode. In front of and behind the electronic stage an optical to electrical conversion with photodiodes and an electrical to optical conversion with a laser diode is necessary. A roundabout way like this doesn't occur by using fiber amplifiers which are now standard tools in the telecommunication technique and which are also qualified for the improvement of the performance of LDA systems.

Due to very low scattered light intensities of submicron particles as used in high speed turbulent flows, the MOPA-concept as explained in the previous chapter to generate probe volumes with 2W optical power is very useful. Some authors have applied diode pumped solid state Nd:YAG-lasers for such LDA systems. Unfortunately the emission wavelengths of the Nd:YAG and of the Argon ion lasers are aside of the maxima of responsivity of commonly used conventional photodiodes as explained later in detail, see also Fig. 9. Therefore the output power of these lasers can not be completely utilized for the LDA-system. For example, Arndt et al. (1996) have demonstrated that twice of the laser power of a 830 nm diode laser LDA must be applied in a 1064 nm Nd:YAG LDA to obtain the same sensitivity for the whole system for particles sizes smaller than 1 μm. A drastical increase of the sensitivity can be obtained by optical preamplification with fiber amplifiers placed in front of photodetectors (Desurvire, 1994).

A further interesting application of fiber amplifiers is the optical post amplification of laser radiation produced by laser sources with small emission linewidths but low output powers like longitudinal singlemode laser diodes as DBR- or DFB- (distributed feedback) diodes as discussed in the previous chapters. The most significant advantage of the post or booster amplification using fiber amplifiers is the increase of the signal source output power without changing the spectral characteristics by pumping with a pump source with low requirements on its spectral characteristics.

Fiber amplifiers can also be used in already existing fiber optical LDA-systems, i.e. multicomponent LDAs where fibers are used to couple the LDA sources with the measuring head. In this case, it is easy to amplify the laser radiation by simply inserting fiber amplifiers.

4.1 Fundamentals of Fiber Amplifiers

The basic functional principle of a fiber amplifier which is placed between standard fibers is shown in Fig. 7. A fiber amplifier consists essentially of a pump laser diode, a fiber coupler and a short fiber doped with rare earth ions like the well known Neodymium. The pump power of the pump laser diode supplies the amplifier with energy. The doped fiber core creates the active medium and its dopant is excited to higher energy levels by the pump power. Amplification occurs if the excited energy level of an ion is depleted by an incident photon which induces, or stimulates, the emission of a second photon, as shown in Fig. 8. Because the emitted new photon has the same frequency, phase and polarization as the stimulating photon, an avalanche process starts. The radiation remains coherent and the spectral emission characteristic does not change. A fiber coupler combines the pump and the signal radiation in the doped fiber. The coupler can be placed in front of or behind the active fiber for backward or forward pumping.

The greatest efforts in developing optical amplification with fiber amplifiers have been done in the optical telecommunication technique for realizing long distance transmission systems with transmission rates of Gbit/s at a wavelength of 1.55 μm. The most developed fiber amplifier is the EDFA (Erbium doped fiber amplifier). The EDFA, which can be pumped by 980 nm or 1480 nm broadband emitting multimode laser diodes, amplifies laser radiation in the wavelength range between 1520 nm and 1560 nm.

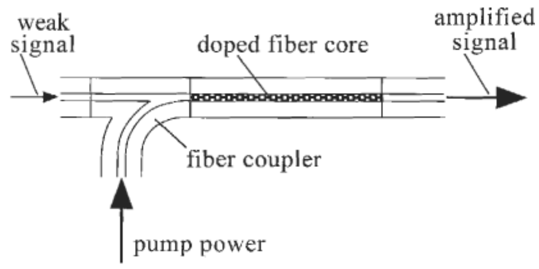

Fig. 7. Basic functional principle of a fiber amplifier.

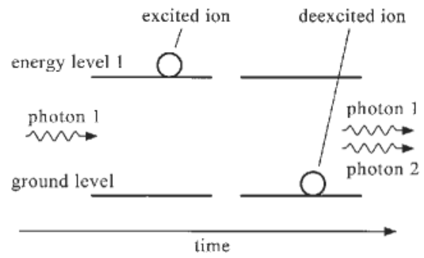

Fig. 8. Principle of stimulated emission in an optical fiber amplifier as shown in Fig. 7.

A record amplification value of 54 dB (factor: 250,000) was achieved with an EDFA for small signal amplification (input power in nW-range) reported by Laming et al. (1992). Further well developed fiber amplifiers have been realized for the wavelength range around 1.3 μm with Neodymium or Praseodymium doped fibers. The experiences gathered from these fiber amplifiers, specially from the EDFA, can be transferred to other fiber amplifier set-ups to realize amplification at preferred wavelengths.

4.2 Characteristics of Fiber Amplifiers

Fiber amplifiers placed behind a laser source with low output power (mW or sub-mW range) can be used as booster (post) amplifier. They work in the saturated regime and convert pump power delivered from broadband sources into signal power of high precision lasers. With an EDFA as booster amplifier, a pump-to-signal power conversion efficiency of 59% was realized by Laming et al. (1991). Behind fiber coupled lasers, booster amplifiers give the chance to use high quality spectral sources like DFB- or DBR-laser diodes with low output power and low price. Specially to realize fiber optical multicomponent LDA-systems utilizing the optical frequency difference of separate fiber coupled laser sources for each LDA beam, booster amplifiers simply inserted as "black boxes" can be used to increase the laser power in the measuring volume.

As preamplifiers in front of photo detectors fiber amplifiers can be used to increase the signal-to-noise ratio (SNR). Specially, aside of the maxima of responsivity at 900 nm in Si-detectors and at 1.55 μm in InGaAs- or Ge-detectors, for example at 1064 nm or 532 nm (see Fig. 9) which are emission wavelengths of powerful Nd:YAG solid state lasers, the minimum detectable signal level can be drastically reduced by broadband optical preamplification.

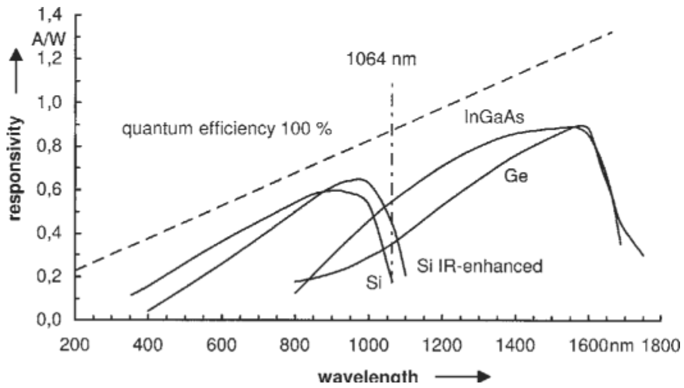

Fig. 9. Spectral responsivity of commonly used conventional photodiodes.

SNR calculations made by Desurvire (1994) have shown that the SNR of the electrical current delivered from a PIN photodiode can be drastically increased by optical preamplification with an EDFA. The calculations have demonstrated that:

– The electrical SNR of signal detection with a PIN photodiode can be increased by about 36 dB (factor: 4000) in combination with optical preamplification in an EDFA for typical values used for the amplification of 1.55 μm signals.

–If a SNR of 20 dB (factor: 100) should be required for the detection unit, an enhancement of minimum detectable power of 25 dB (factor: 316) can be achieved by using optical preamplification.
–In comparison with an APD photodiode the PIN photodiode with optical preamplification delivers the best results.

Thus, the conclusion is that optical preamplification technique is a very valuable tool in laser Doppler anemometry.

5. Concept of a LDA-system with Fiber Amplifiers

Figure 10 shows the concept of using fiber amplifiers in a well known LDA-setup. A typical application of post amplification with a fiber amplifier is shown at the transmitting side of the LDA-system. A fiber amplifier placed behind the LDA source amplifies the laser output power P_{laser} up to higher power levels $P_{laser,\ ampl.}$ and increases the power in the measuring volume. Therefore, DBR laser diodes (DBR-LD) with low output powers could be inserted as LDA sources.

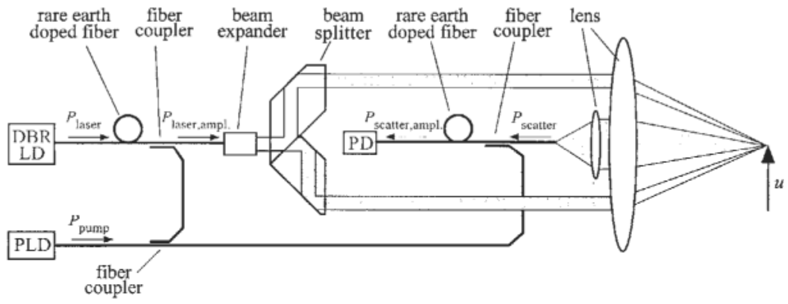

Fig. 10. Concept of a well known LDA set-up improved with fiber amplifiers for increasing the light intensity in the probe volume and enhancing the detector sensitivity by means of an optical fiber-based preamplifier in front of the photodiode.

The second application is shown at the receiving side of the LDA system. The scattered light of tracer particles $P_{scatter}$ is focused into the fiber core of a fiber amplifier which is used as preamplifier in front of the thermal limited photodiode (PD). The optical gain of the preamplifier amplifies the launched scattered light to higher power levels $P_{scatter,\ ampl.}$ with a minimum of additional noise and enhances therefore the SNR of the electrical current delivered by the photodiode. Both, the preamplifier and the post amplifier are supported with pump power P_{pump} by a powerful multimode emitting pump laser diode (PLD). To keep away disturbing radiation, e.g. pump radiation, from the DBR laser diode and the receiving photodiode optical filters or optical isolators can be placed in front of these devices.

Többen et al. (1998) have recently shown the drastic improvement of sensitivity and SNR by using this optical preamplification technique in front of photodetectors. The corresponding block diagram is presented in Fig. 11, which is a detail of the receiving side in Fig. 10.

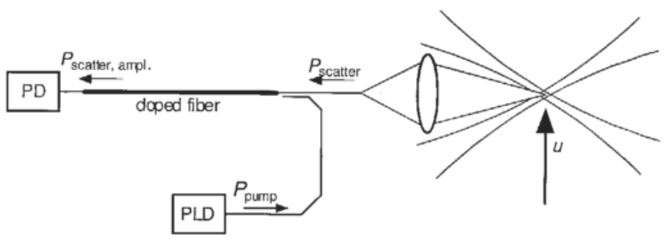

Fig. 11. Schematic diagram of a fiber amplifier receiver module for preamplification of scattered light.

In this experiment the scattered light of a particle is transmitted to a photodector without and with optical preamplification. With a conventional LDA setup and a 1064 nm Nd:YAG laser as LDA source a measuring volume with a diameter of 170 µm and a fringe distance of 2 µm was created. A short rotating piece of a fiber acts as scatterer. A high sensitive avalanche photodiode detects the burst signals that travel through the fiber amplifier receiving module. The electrical unfiltered photo currents have been plotted on a digital ocsilloscope. For the demonstration: Figure 12 shows a LDA burst with very weak amplitude and extremely small SNR whilst Figure 13 presents the same signal after optical preamplification. An enormous improvement of amplitude and SNR can be recognized easily.

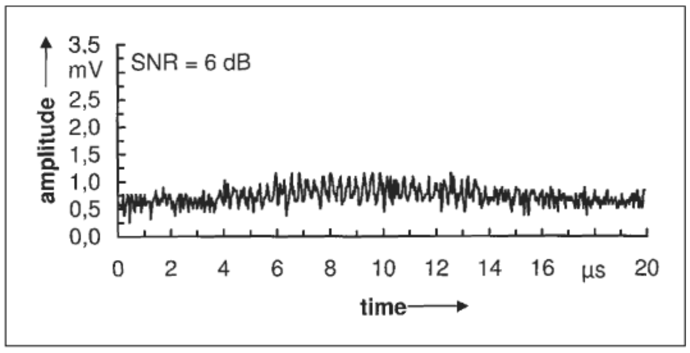

Fig. 12. Burst signals generated without optical preamplification.

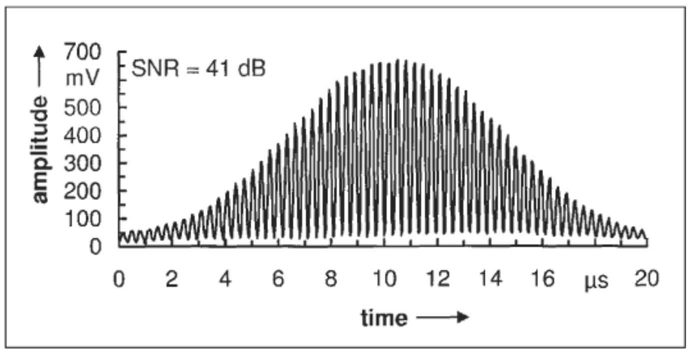

Fig. 13. Burst signals generated with optical preamplification.

The detected LDA burst in Fig. 12 reaches with only a small part the detection limit of photodiode and exhibits a weak amplitude with only few periods. At the center of the burst signal a SNR of 6 dB was measured. If the launched burst signals are amplified by the fiber amplifier before the optical-electrical conversion is done in the photodiode, very good signals as presented in Fig. 13 are obtained. A pronounced increase in amplitude and in number of periods of the LDA burst as well as a strong noise reduction is shown in Fig. 13. The SNR is increased now up to 41 dB. Figs. 12 and 13 exhibit that the optical preamplification process allows to push the signal intensities over the detection limit of the photodetector and to improve simultaneously the signal-to-noise ratio of LDA signals.

In comparison to the direct detection with a solitary photodiode the concept of optical preamplification of LDA radiation with low power levels is attractive if the incoupling losses of scattered light into the fiber amplifier are much lower (in percent or dB) than the optical gain produced by the fiber amplifier. First calculations and examinations shows an optimistic way to realize this aim.

6. Concept of a Fiber Optical Shift-LDA with Fiber Amplifiers

The concept of a fiber optical shift-LDA-system which combines the post and pre amplification of optical radiation with fiber amplifiers, which was presented for the first time by Többen et al. (1998a) is shown in Fig. 14. Two laser diodes (LD1 and LD2) with an emission frequency difference and emission linewidths in the MHz range produce the LDA radiation (P_{LD1} and P_{LD2}). Booster fiber amplifiers behind each source increase the laser power

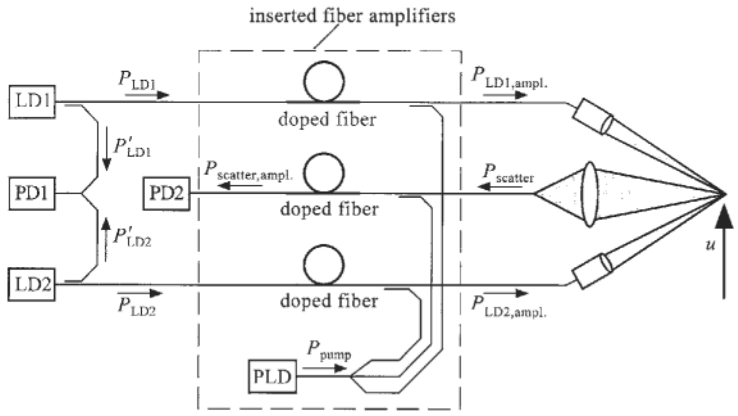

Fig. 14. Schematical set-up of a fiber optical shift-LDA system with fiber amplifiers for post and pre-amplification.

levels ($P_{LD1, ampl.}$ and $P_{LD2, ampl.}$). Therefore, low power laser diodes i.e. conventional pigtailed well tunable DFB laser diodes can be used as LDA sources. A fiber coupler combines small parts of the laser radiation (P'_{LD1} and P'_{LD2}) to produce a beat signal in the photodiode 1 (PD1) as reference signal for the signal evaluation unit. Miniaturized focusing optics with fiber pigtails focus the amplified laser radiation into the measuring volume.

The scattered light of tracer particles in the flow is focused into the fiber core of a third fiber amplifier in front of the photodiode 2 (PD2) which is used as preamplifier. For enhancing the SNR of the measuring signal the preamplifier amplifies the launched scattered light ($P_{scatter}$) to higher power levels ($P_{scatter, ampl.}$). A fiber coupler splits up the output power (P_{pump}) of the pump laser (PLD) into three parts, which are coupled into the doped fibers by WDM (wavelength division multiplexer) fiber couplers. A powerful multimode laser diode can be used as pump source.

By mixing the measuring signal, delivered from PD2, with the simultaneously detected reference signal, delivered from PD1, and employing heterodyne and quadrature signal processing techniques (see Fig. 5), the shift frequency f_{sh} with all its fluctuations and bandwidth influences are eliminated, the directional information is retained and the Doppler frequency f_D is obtained in the base band.

7. Fiber Lasers for LDA Applications

A really interesting new laser source for LDA systems are fiber lasers which are in principle fiber amplifiers with an optical feedback mechanism. The simplest way to create a fiber laser is to attach a mirror to each end of the laser active fiber to produce a Fabry-Perot resonator with an incorporated amplifying medium. Because fiber lasers are optically pumped by powerful laser sources, the dielectric stack mirror at the pump side is fabricated with a suitably high transmission at the pump wavelength and a high reflection at the lasing wavelength. At the output side the mirror reflectivities are changed nearly inversely. Producing high fiber laser output powers, high power laser diodes like laser bars or arrays with great emitting areas and laser active double-cladding fibers have to be used.

The pump radiation of this sources can be launched over an inner waveguiding cladding with a large diameter and a high numerical aperture into the monomode laser active core of the double-clad fiber. Figure 15 shows the principle set-up of a double-clad fiber laser. The diameter of this inner cladding is typically 125 - 400 μm. The inner monomode laser core has a diameter between 5 μm and 10 μm depending on the wavelength of the generated TEM_{00}-radiation. Output powers of up to 32 W with excellent beam quality have been realized with a 1060 nm fiber laser (Zellmer et al., 1997).

Fiber lasers have several advantages. They have a high efficiency, a simple, compact and reliable design, they are light-weight and in contrast to Nd:YAG lasers, they are insensitive to thermal effects due to intrinsic waveguide structure of the active fiber core. Additionally, fiber laser emits typically in the TEM_{00}-gound mode with best focusing and collimating properties. Therefore, they are directly compatible with fiber optical components, so that fiber optical LDA measuring heads can be realized without additional launching components.

Because the emission spectrum of high power fiber lasers with a bandwidth up to 10 nm is really broad,conventional prism beam splitters produce a measuring volume with a bad visibility in the fringe system due to the chromatic aberration. By using a diffraction grating as beam splitter the illuminating laser beams - these are the ±1 diffraction orders - have the same optical path length and the fringe systems, corresponding to the different wavelengths, have the same phase and superimpose coincidentally. An achromatic fringe spacing can be achieved and high power fiber laser LDA systems are realizable as shown by Czarske et al. (1997). The realized achromatic fiber laser Doppler anemometer is shown in Fig. 16. At PTB a 3 Watt fiber laser at 1060 nm was designed and tested.

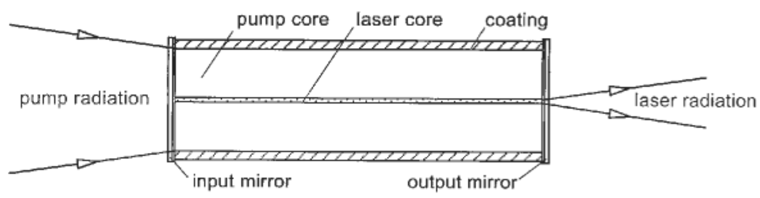

Fig. 15. Schematic representation of a fiber laser with a Fabry-Perot resonator structure and a double-clad fiber as active medium; a fiber laser with an output power of 3 W and an emission wavelength around 1060 nm was realized at PTB.

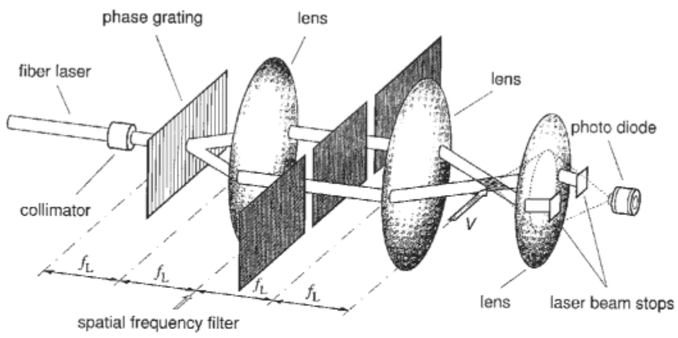

Fig. 16. Schematic diagram of an achromatic fiber laser Doppler anemometer as realized by Czarske et al. (1997).

8. Conclusions and Outlook

The paper describes novel concepts for future improvement of LDA-systems to obtain high light intensities in the probe volume and improved sensitivity by means of tunable MOPA laser diodes, fiber lasers and optical fiber amplifiers in front of photodiodes. The advantageous use of two laser diodes for each of the LDA laser beams can only be used in combination with carrier frequency techniques and signal quadrature demodulation. A 2 Watt system has been very successfully applied for in-flight measurements using a DO128 two propeller research aircraft.

Fiber amplifiers as booster amplifiers, offer the possibility to increase the output power at DFB- or DBR-laser sources with low cost broadband emitting pump lasers with high conversion efficiencies.

As preamplifier in front of a PIN-photodiode fiber amplifiers enhance the SNR of the detected signals and allow to detect extremely weak burst signals. An enhancement of 35 dB (factor: 3162) was realized at PTB with a Neodymium-doped fiber amplifier set-up. Such a fiber amplifier can improve the sensitivity of LDA-receivers dramatically and allows to set novel impetus to diode pumped solid state lasers and photodiode receivers. The possibility to dope the active fiber with different rare earth ions, nearly every laser wavelength can be amplified by fiber amplifiers. Especially for Nd:YAG LDA systems at 1064 nm where photodiodes show a gap in the sensitivity an optical preamplification is very useful.

In addition, the doped fiber itself can be used as the laser source and not only as a amplifier. The concept of such a fiber laser has been described and it was shown that in combination with diffractive optics very powerful LDA system can be designed.

Acknowledgments

The authors would like to thank the Deutsche Forschungsgemeinschaft for supporting this work.

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