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Rapid communication

Novel high-power laser Doppler anemometer using a diode-pumped fiber laser

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Abstract. We present for the first time the application of a diode-pumped double-clad fiber laser in laser Doppler anemometry. The use of fiber lasers with a fundamental transverse mode power of multiple Watts enables the realization of powerful laser Doppler anemometers with a high portability.

Powerful laser Doppler anemometers (LDA) usually have a complicated, bulky design. Due to a low efficiency about 0.1% of the conventionally employed Argon ion lasers, resulting in a high power consumption and high cooling efforts, the realized LDA systems have a low portability. Hence, the applications of such LDA systems is problematically in special potential measurement fields [1] e.g. at air plane flights. In order to enhance the applicability of the LDA technique, compact lasers with a high efficiency and reliability have to be employed. Although laser diodes meet the light source requirements for the realization of portable LDA systems [2], the currently available fundamental mode power of conventional single-stripe diodes in the range of only 100 mW is often not sufficient. A significant enhancement of the laser power can be achieved by laser diode arrays, having a not tolerable reduction of the laser beam quality. The recently developed MOPA (Master Oscillator Power Amplifier) laser diodes deliver a power of more than 1 W in the fundamental mode [3]. However, these systems are currently very expensive, have a low beam point stability and further power scaling is very difficult. Another well-known concept for the efficient generation of a high fundamental mode power is the diode-pumping of solid-state lasers. More than 60 W TEM_{00} optical power was already achieved by transversely pumped Nd:YAG lasers [4]. Longitudinally diode-pumped solid-state lasers, especially Nd:YAG miniature ring lasers [5], are able to fulfill the LDA demands on a high efficiency and a small size of the employed light source. The potential of these laser type was already demonstrated in a directional multicomponent LDA system, having a high portability and a flexible measuring head by incorporating fiber-optics [6]. Although this sophisticated LDA system opens several new LDA application areas, a further reduction of the technical effort of the LDA system is desirable.

In this communication we propose a diode-pumped double-clad fiber laser as low-cost and compact light source with an output power of multiple watts for the employment in the LDA technique. Fiber lasers [7] have a simple, compact and reliable design, they are light-weight and in contrast to Nd:YAG lasers they are not sensitive on thermal effects due to the intrinsic waveguide structure of the active fiber. Additionally, fiber lasers are directly compatible with fiber-optic components so that a fiber-optic LDA measuring head can easily be realized, especially without additional fiber launching. However, so far the output power of conventional single-clad monomode fiber lasers is limited to about 100 mW due to the incompatibility of the diameter of the doped fiber core with the large beam parameter product of high-power diode-laser arrays. In order to achieve a significant enhanced TEM_{00} output power, the double-clad concept [8,9] has been developed. In this concept, the pump radiation is not directly launched into the active monomode fiber core but into the surrounding multimode waveguide, with high numerical aperture and diameter, which allows an efficient launching of the diode-laser array radiation. The double-clad concept provides a simple and efficient conversion of the low beam quality multimode pump radiation into bright laser radiation with excellent beam quality. Recently, output powers of up to almost 10 W in single-transverse-mode operation have been reported [10,11]. Since emission linewidths of several nanometers occur, the LDA calibration factor has to show only a weak dependence on the light wavelength. This achromatic property can be achieved by employing a diffraction grating as beam splitter [12,13]. Based on the use of a double-clad neodymium-doped fiber laser in combination with a diffraction grating, an achromatic fiber laser Doppler anemometer (AFLDA) has been realized. The proposed AFLDA system has a high optical power, an excellent portability, a low technical effort and is easy to handle. Thus

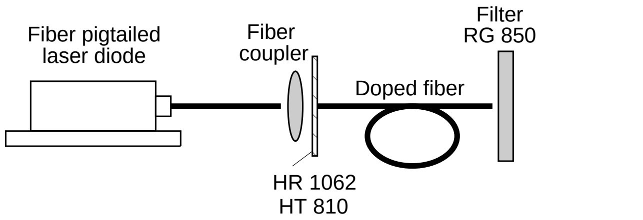

Fig. 1. Sketch of the diode-pumped neodymium-doped double-clad fiber laser

this low-cost AFLDA system has the potential for versatile sensor applications.

1 Diode-pumped double-clad fiber laser

The principal arrangement of the realized diode-pumped neodymium-doped silica-based double-clad fiber laser is shown in Fig. 1. A high-power laser diode (model SDL 3450) with a multimode fiber pigtail of 600 μm diameter is used as a pump source. In order to achieve a high incoupling efficiency of the pump light accompanying with an emission of the fiber laser in a single-transverse mode, the double-clad concept [8,9,10] has been used (Fig. 2). This concept is based upon the application of a large diameter and high aperture pumping waveguide, in which a neodymium doped single-mode core is embedded. The multimode pump light core allows an efficient incoupling of the pump light into the inner fiber clad (pump core). The pump light is transfered from the multimode core into the active monomode core over the entire fiber length. Efficient pump light absorption requires the conversion of excited helical rays to meridional rays, which only cross the active fiber core. This can be achieved with fibers of D-shaped inner clad [11], which have been developed in cooperation with the Institut für Physikalische Hochtechnologie e.V., Jena, Germany. The D-shaped design of the pump core leads to a permanent rearrangement of the pump fiber modes, so that each ray in the pump core passes the doped core. Hence a high pump light absorption can be achieved.

The used double-clad fiber laser consists of an active monomode core of 5 μm diameter, doped with 1300 ppm neodymium, a D-shaped pure-silica inner clad with 125 μm maximum diameter, and an outer cladding, made of a highly transparent polymer with low index of refraction. The fiber resonator is formed by the monomode fiber of 20 m length, a dielectrical HR mirror butted to one fiber end and simply the Fresnel reflex of the other fiber surface. At 3.5 W of launched pump power, the fiber laser emits 1.3 W output power in the fundamental transverse mode with a center wavelength of 1062 nm and a linewidth of 10 nm (Fig. 3). The resulting efficiency of 37 % (optical to optical) demonstrates the merit of the double-clad fiber concept with D-shaped inner cladding.

2 Achromatic fiber laser Doppler anemometer (AFLDA)

Using the differential Doppler technique two laser beams are focused into the LDA measuring volume, forming a fringe system. Tracer particles in the fluid, passing the measuring

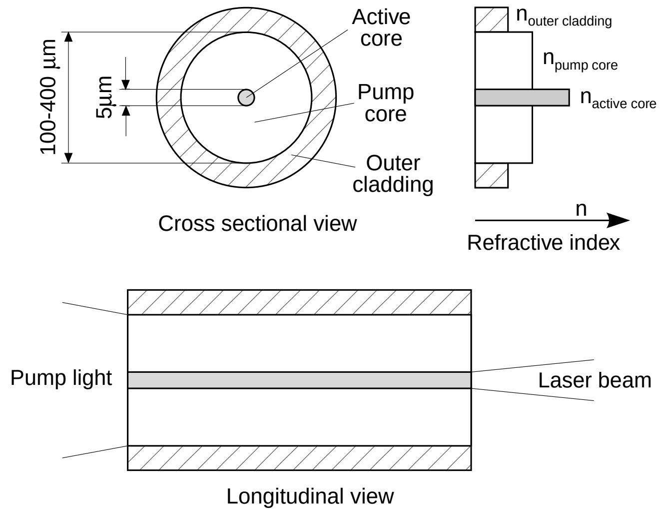

Fig. 2. Principle of the double-clad fiber laser concept

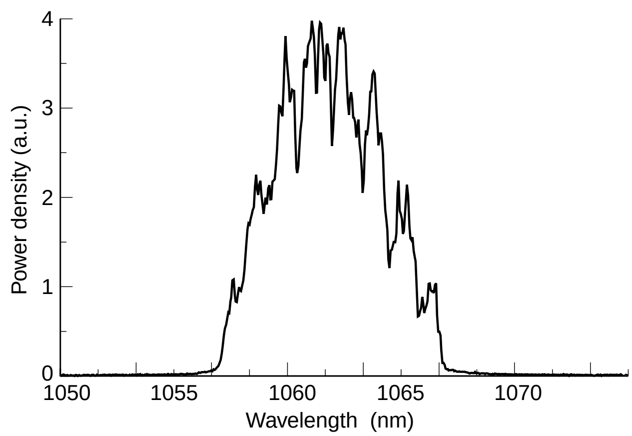

Fig. 3. Emission spectrum of the fiber laser

volume, generate Mie scattered light, which is detected by a photo diode. Conventionally, prism beam splitters are used for the generation of the two laser beams. The resulting fringe spacing d acts as LDA calibration constant and is given by

$$d = \lambda/(2 \sin \Theta) \quad (1)$$

[1], where λ denotes the light wavelength and 2Θ denotes the angle between the two laser beams.

Since the fringe spacing is proportional to the light wavelength, precise LDA measurements conventionally require wavelength stabilized light sources with small emission linewidths. By generating of a wavelength independent fringe spacing in the LDA measuring volume, which fulfills the achromatic property of the LDA system, broadband emitting fiber lasers can be used for the LDA technique.

2.1 Demands on the AFLDA system

The wavelength independence of the achromatic fiber laser Doppler anemometer (AFLDA) can be achieved by using a diffraction grating as beam splitter. On a first step, a comparison between this AFLDA system and a conventional chro-

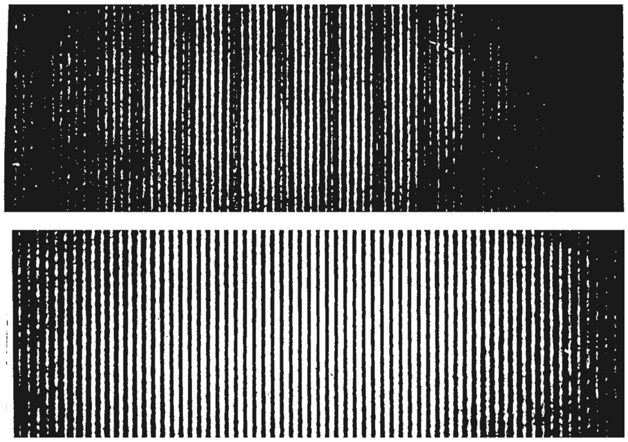

Fig. 4. Comparison between a conventional fringe system (*top*) and an achromatic fringe system (*bottom*), generated by two HeNe lasers of different wavelengths (544 nm, 633 nm)

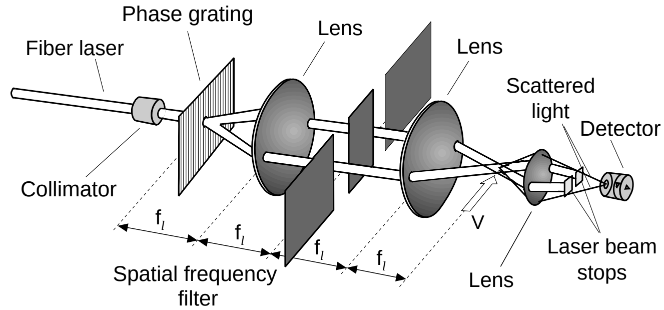

Fig. 5. Sketch of the achromatic fiber laser Doppler anemometer (AFLDA) f_1: lens focal length of 50 mm

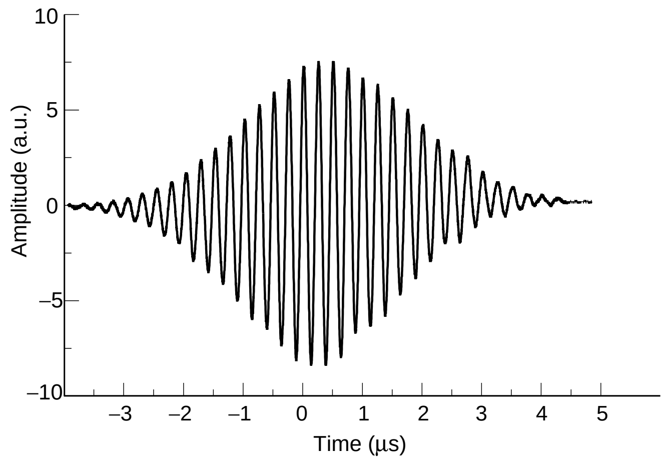

Fig. 6. Band pass filtered AFLDA burst signal

matic LDA system, incorporating a prism beam splitter will be done (Fig. 4). Both LDA systems are illuminated by two Helium-Neon lasers of different wavelengths. In the case of the conventional LDA system, the different wavelengths result in different fringe spacings, so that a not tolerable Moiré pattern occurs. In the case of the achromatic LDA system, the two fringe systems show the same spacing and are superimposed coincidently.

This achromatic property can be understood by means of the following fundamental relations [12,13,14]: (i) The diffiaction angle ϑ of the n-th diffraction order of the grating with a grating constant g is given by $\sin\vartheta = n\lambda/g$, assuming perpendicular laser beam incidence. (ii) The grating structure is imaged by an optical system into the LDA measuring volume with the lateral magnification $\beta = \sin\vartheta/\sin\Theta$, where 2ϑ is the beam splitting angle of the diffiaction grating and 2Θ is the beam crossing angle in the measuring volume.

Assuming the use of the +1. and -1. diffraction orders and taking into account (1) and the relations (i) and (ii), the resulting fringe spacing in the measuring volume is given by $d = g\beta/2$, i.e. the achromatic property is fulfilled. The achromatic fringe spacing can directly be seen by recognizing that the fringe system in the measuring volume is an image of the diffraction grating [15,16,17]. Therefore the fringe spacing is wavelength independent.

Besides the achromatic property, further conditions have to be fulfilled for an accurate AFLDA system: 1) Two-beam interferometry. In order to ensure the sinusoidal intensity distribution in the measuring volume, only two LDA laser beams have to be used. Otherwise Talbot fringes occur, which exhibit different fringe spacings [15]. The two-beam interference can be reforced by inserting a spatial frequency filter in the AFLDA arrangement. 2) Symmetry of the diffraction orders. The coincidence of the fringe systems, corresponding to the different light wavelengths, requires a constant orientation of the fringe system. Hence, the bisector of the two LDA beams has to be independent on the wavelength. This requires two grating diffraction orders of the same amount and the opposite sign, e.g. the $-1./+1.$ diffraction orders. 3) Telecentric property. A conventional optical imaging has a central image projection, which results in a changing magnification along the optical system axis. In order to achieve a constant magnification and hence a constant fringe spacing in the measuring volume, a parallel projection with a telecentric imaging system is necessary. 4) Corrected imaging aberrations. Especially the achromatic aberrations and the astigmatism of the imaging system have to be corrected.

2.2 Experimental arrangement and results of the AFLDA system

The realized achromatic fiber laser Doppler anemometer (AFLDA) is shown in Fig. 5. The single-mode emission of the fiber laser is collimated onto a holographic diffraction grating, having a sinusoidal phase modulation. In the $+1./-1.$ diffraction orders more than 60 % of the incident optical power is contained, so that about 800 mW power are available in the measuring volume. The other diffraction orders of the phase grating are stopped by a spatial frequency filter, in order to ensure the two-beam interference (see Conds. 1 and 2 in Sect. 2.1). It should be noted that a significant enhancement of the diffraction efficiency up to over 90 % is possible with an optimized triangular phase modulation function of the diffraction grating structure. The grating is imaged into the measuring volume by using a Kepler telescope, so that the telecentric property is fulfilled (see Cond. 3). It should be remarked, that a significant reduction of the geometrical length of the AFLDA system is possible by realizing the imaging system with mirrors in a folded arrangement. Finally, the Cond. 4 is fulfilled by the use of achromatic lenses for the realization of the telescope.

As a preliminary experiment, a pin-hole disk, rotating through the measuring volume with a constant velocity, is used as scattering object. The scattered light is detected by a photo diode behind the pin-hole. The generated burst measuring signal is shown in Fig. 6. The signal frequency f_D determines the scattering object velocity v according to $v = f_D d$. The Gaussian shape demonstrates the fiber laser emission in the fundamental transverse mode. The sinusoidal fringe modulation with constant period is a result of the two-beam interference and the achromatic property, giving a constant fringe spacing d in the measuring volume.

The imaging of the diffraction grating results in a negligible path length difference of the two laser beams, since the path lengths of each imaging beam are constant. Therefore the fringe systems, corresponding to different wavelengths, have the same phase and in consequence, they are superimposed coincidently. This is the reason for the good visibility of the fringe system, despite of the low coherence length of the used light source. A further advantage of the imaging of the grating into the measuring volume is the alignment insensitivity of the setup, especially compared to conventional LDA systems with prism beam splitters.

3 Conclusions

This contribution describes for the first time the application of a diode-pumped fiber laser in the laser Doppler anemometry. Based on the use of a diffraction grating as beam splitter, an achromatic LDA system was realized, which enables the use of powerful fiber lasers with a great emission line width in accurate laser Doppler anemometry measurements. It can be pointed out that the realized achromatic fiber laser Doppler anemometer (AFLDA) offers significant advantages compared to conventional LDA systems: (i) high powers in the measuring volume (ii) reliable operation due to the use of diode-laser pumping and fiber-optic technology, (iii) high portability, resulting from the low power consumption and the robust design, (iv) high potential for miniaturization, especially by employing integrated optic elements [18,19] and (v) low-cost potential [20] by using of mass production components.

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