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Diffractive beam splitter for laser Doppler velocimetry

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A miniaturized sensor head for the optical measurement of velocities of fluids based on laser Doppler velocimetry is demonstrated. Holographic optical elements mounted on a glass substrate are used for beam splitting and deflection. Volume holograms in dichromated gelatin exhibit good optical efficiency (75% transmission of a cascade of two holographic optical elements). With diffractive devices one can achieve achromatic behavior that makes the sensor insensitive to wavelength drifts or mode hopping of a semiconductor laser.

Laser Doppler velocimetry (LDV) is a noncontact measurement method for the velocity of a fluid or gas flow.¹ The basic principle of this method is shown in Fig. 1: within the measurement volume two mutually coherent plane waves interfere. They form an interference pattern with sinusoidal intensity variations with period $\Lambda = \lambda/(2 \sin \vartheta)$, where λ denotes the wavelength and 2ϑ denotes the angle between the two beams. Within the flow, particles scatter the light in all directions. A particle traveling with the velocity v through the periodic intensity distribution causes a scattering signal periodic in time with period $T = \Lambda/v = \lambda/(2v \sin \vartheta)$. Hence, by counting the maxima of the scattered light or by Fourier analysis of the scattered light, one can determine the velocity of the flow.

Conventional LDV sensors consist of a number of conventional optical elements, such as a beam splitter and a lens, that have to be aligned with respect to each other and require a considerable volume. Miniaturization requires (i) a miniature light source, such as a semiconductor laser, and (ii) a miniaturized optical system. Diffractive optical elements are well suited for miniaturization since they have high functionality (beam splitting, deflection, and focusing are possible with the same element). They can be replicated by embossing in the case of surface-relief gratings or holographic copying in the case of volume gratings. Furthermore, they are compact and lightweight. Several elements can be fabricated on a common glass substrate in order to simplify alignment.²

Figure 2 shows schematically a diffractive component, which can be employed as an LDV sensor head. It consists of a beam splitter that splits the incoming beam into two beams of equal intensity. These beams propagate to deflectors, which direct them into the measurement volume with the desired angle ϑ .

Figure 3 shows some similar ideas according to the same geometry. If a large angle ϑ is required, the deflection angle in the beam splitter can be chosen

such that it exceeds the angle of total internal reflection within the substrate. The deflection elements used for coupling the light out of the substrate may then be located at a large distance from the beam splitter. Furthermore, all diffractive elements can be located on the same side of the substrate and be fabricated such that no further alignment is needed. Similar setups have been proposed for different purposes such as optical communications and optical interconnections.³⁻⁵

The described setups are symmetric, and in each case both arms have equal optical path lengths. Therefore, even if the semiconductor laser has low coherence length, the visibility of the fringes is still excellent.

Important issues are thermal drifts of the wavelength of the laser and mode hopping. If we assume thin gratings and a small deflection angle ϑ , the component in Fig. 2 is nearly wavelength independent. If p_1 and p_2 denote the grating periods of the beam splitter and the deflectors, respectively, and n is the refractive index of glass, then $\sin(\gamma) = \lambda/n p_1$ and $(1/n) \sin \vartheta - \sin(\gamma) = -(\lambda/n p_2)$; hence

$$\sin \vartheta = \lambda(1/p_1 - 1/p_2). \quad (1)$$

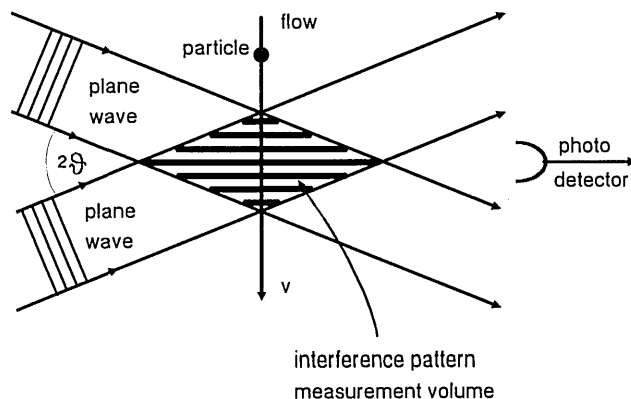


Fig. 1. Principle of LDV.

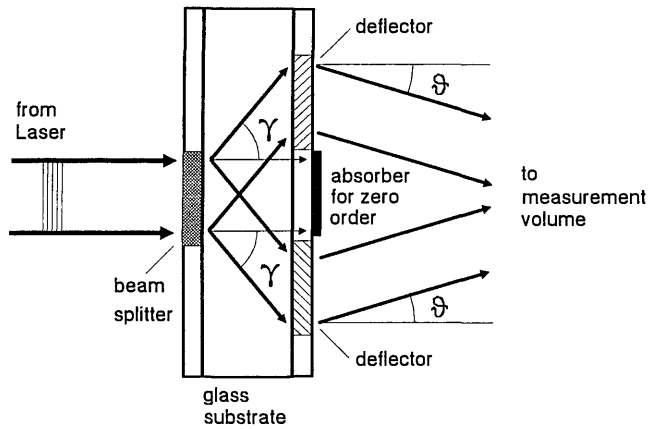


Fig. 2. Compact diffractive element for beam splitting and deflection on a common substrate.

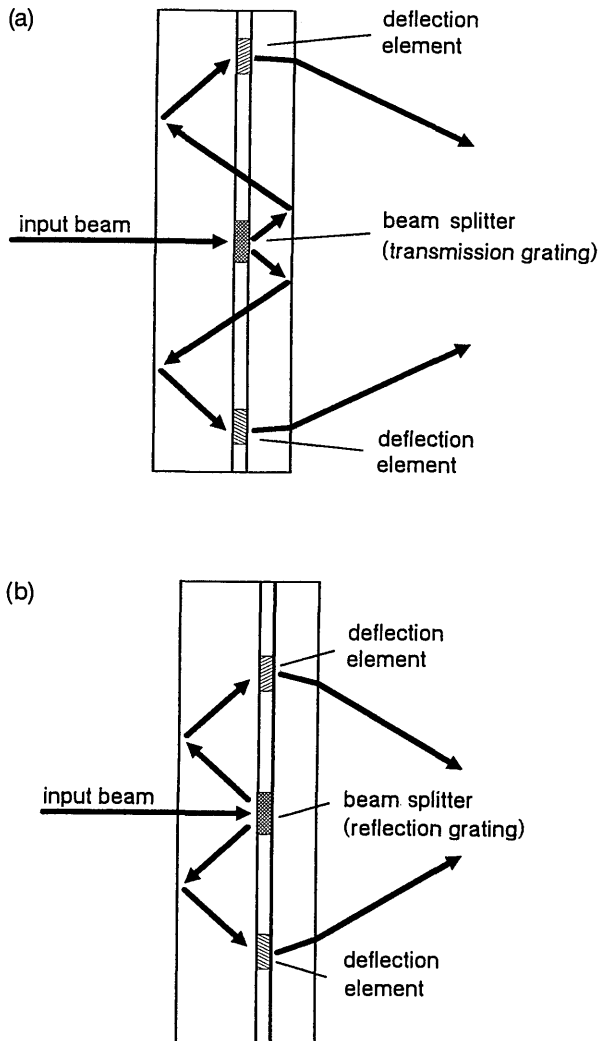


Fig. 3. Alternative geometries. In both cases all gratings are situated in one plane³: (a) increased base length by using total internal reflection, (b) mixture of reflection holograms and transmission holograms.

The period of the interference pattern Λ is $\Lambda = \lambda / (2 \sin \vartheta)$. Therefore we obtain

$$1/\Lambda = 2(1/p_1 - 1/p_2), \quad (2)$$

which is independent of the wavelength λ . This

achromatic behavior of the diffractive device is a clear advantage compared with conventional (refractive, reflective) optics, where $\Lambda = \lambda / (2 \sin \vartheta)$ and therefore $\Delta\Lambda/\Lambda \approx \Delta\lambda/\lambda$. The achromatic behavior of diffractive elements has been studied in detail by Leith and Swanson.⁶

For the experimental demonstration diffractive elements realized as volume holograms in dichromated gelatin were chosen. Dichromated gelatin is a phase material that permits high diffraction efficiencies and exhibits low scattering. Highly efficient deflection elements as well as beam splitters have been reported previously.^{3-5,7} The beam splitter was fabricated as a multiplex hologram⁷ with deflection angles of $+26$ and -26 deg within the glass substrate. The deflection elements are plane gratings with diffraction angles of $+26$ and -26 deg. The exit angle has been chosen to be 0 deg, and an additional lens is used to bring the beams to intersection at their waists in the measurement volume. Figure 4 shows quantitatively the diffraction effi-

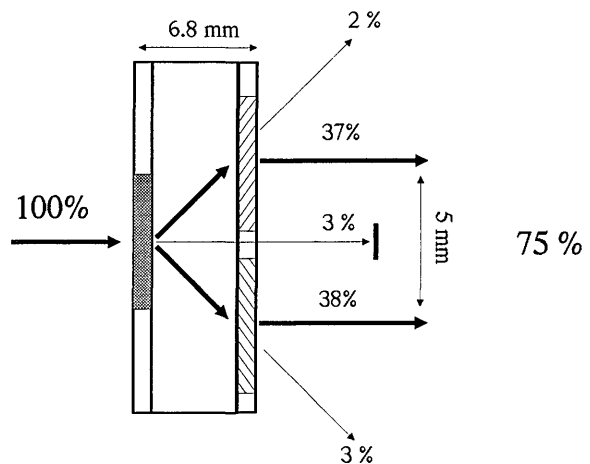


Fig. 4. Principle of the demonstration element.

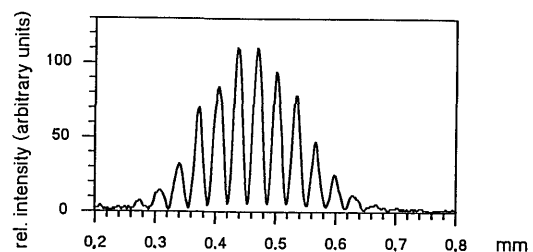


Fig. 5. Photography of the interference fringes in the focal plane and the intensity scan.

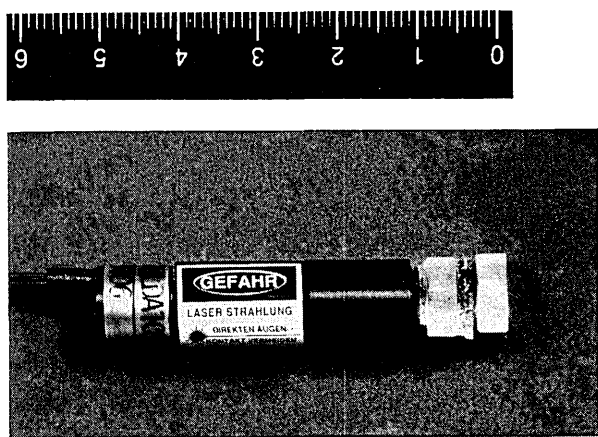


Fig. 6. Components of the optical sensor head for LDV outside the mount.

ciencies of the element (all beams are labeled with their intensities in terms of the incoming intensity). Note that the zero diffraction orders are fairly low and most of the incoming light (75%) is diffracted into the desired beams. Note also that the zero-order light is either absorbed or travels in a completely different direction, thus it will not disturb the measurement process. The glass surfaces are not antireflection coated and therefore have 4% reflection each under normal incidence. The measured overall efficiency of 75% for the component is therefore quite good, indicating efficiencies well above 90% for each individual volume grating. The volume gratings were individually recorded and mounted onto a 4-mm-thick glass substrate with UV-hardening epoxy (Norland optical adhesive 61). With this procedure the parallelism of the output beams can be adjusted accurately *in situ* before the

cement is hardened. A parallelism of better than 1 arcmin was measured. A lens was used to bring the parallel beams into focus and to cause them to intersect in the measurement volume. Figure 5 shows the interference fringes in the focal plane, which are straight throughout the measurement volume. This means that the component is practically free from wavelength aberration. As expected from the analysis of the diffraction efficiencies, the contrast of the fringes is excellent.

Figure 6 is a photograph of the parts of the miniaturized LDV head, a diode laser with a 670-nm wavelength, the diffractive element, and a lens. The overall length is 5 cm and can be reduced further.

In summary, it can be stated that diffractive beam splitters for laser Doppler velocimetry offer two distinct advantages: (i) the potential for miniaturization of the sensor head and (ii) insensitivity of the signal against wavelength drift and mode hopping of the laser diode.

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