Active stereovision systems for the 3D measurement of surfaces rely on the sequential projection of different fringe patterns onto the scene to robustly and accurately generate 3D surface data. This limits the temporal resolution to the time by which a sufficiently high number of patterns can be projected and recorded. By encoding patterns spectrally and recording them with a hyperspectral imager, it is possible to record several patterns in a single image, limiting the temporal resolution to only the duration of the illumination. A picosecond 3D surface measurement was demonstrated using a high pulse energy femtosecond Ti:Sa laser, spectrally broadened in a hollow core fiber, and two hyperspectral cameras recording the patterns generated by diffraction at an Echelle grating.
Figure 1: Signal intensity in the channels $\lambda_{1...9}$ of a hyperspectral camera for excitation with a modelocked Ti:Sa Laser. Measured by illuminating the camera with narrow sections of the laser spectrum, which is shown as the dashed line.

By color-coding the patterns with a single spectrally multiplexed pattern, the temporal resolution is limited only by the active time of the illumination. Hence, a temporal resolution on ultrafast timescales can be achieved by using a femtosecond laser as a light source.

For such an ultrafast spectrally multiplexed pattern generation, several key requirements must be met. To differentiate between spectrally multiplexed patterns, the spatial distribution as well as the spectral characteristics of the intensity patterns reflected from the scene have to be evaluated. Hyperspectral cameras offer this functionality. The working principle of these cameras is similar to a conventional RGB camera. In the case of RGB cameras, the color information is generated using spectral filters on the camera sensor arranged in a 2-by-2 Bayer matrix, from which a full scale color image is reconstructed [10,11]. This approach is enhanced for hyperspectral imaging by increasing the size of the filter matrix, e.g. to 25 sub-pixels with different spectral filters. By using Fabry-Perot interferometric filters, each color channel can be engineered to measure a narrow wavelength range [12]. The spectral sensitivity of a suitable hyperspectral camera that is illuminated with a Ti:Sa laser in the near infrared region is shown in Fig. 1. Hyperspectral cameras have found use in diverse research fields, for example medicine [13,14], archaeology [15], botany [16], as well as applications in defense [17], art conservation [18], and waste management [19]. As the different spectral channels are located on the same imaging sensor, no complex matching between the channels has to be done.

To utilize the ultrashort pulse duration of a femtosecond laser for 3D, the necessary measurement data has to be generated in a single laser pulse. This requires, depending on camera sensitivity and the size of the illuminated object, a pulse energy in the range of hundreds of microjoules.

The number of patterns that can be projected is limited by the spectral bandwidth of the light source. Modelocked Ti:Sa lasers provide ultrashort pulses with a conversely broad spectral bandwidth [20], both of which are desired in this application. Considering the spectral sensitivities of the different color channels in the hyperspectral camera, a bandwidth of at around 100 nm is required to illuminate $N = 10$ channels. This can be achieved by spectrally broadening the laser pulses, as in our case the initial bandwidth is insufficient. For this, self phase modulation (SPM) can be utilized. Confinement of the high intensity laser pulses in a hollow core fiber enhances this effect [21,22]. If a noble gas is used as the nonlinear medium, the ultrashort duration and high energy of the pulses is maintained. This method is well established in the generation of high energy few-fs laser pulses [23,24].

By combining the spectral resolution of the hyperspectral cameras with the broad spectrum and high energy of a nonlinearly broadened femtosecond laser, a single-shot 3D measurement with a temporal resolution below 100 ns was demonstrated. The quality of the projected fringes was evaluated based on the 3D reconstruction a surface moving at high subsonic speeds.
2 Methods

2.1 Spectrally broadened light source

A modelocked Ti:Sa oscillator, amplified using chirped pulse amplification, fulfills the requirements best, given the output of spectrally broad femtosecond pulses with energies in the range of millijoules in the near-infrared. In this case, a commercial chirped pulse amplification (CPA) system was used (Coherent Legend), generating 2 mJ sub-ps pulses with 60 nm bandwidth at 800 nm center wavelength.

Given the spectral sensitivity of the cameras shown in Fig. 1, approximately seven channels are illuminated using this laser. By spectrally broadening the ultrashort pulses, a larger number of channels can be illuminated to increase the accuracy and robustness of the surface measurement.

Spectral broadening of high energy ultrashort pulses has been demonstrated in noble gas filled hollow core fibers, like the one shown in Fig. 2a. The pulses are confined in the core of the fiber by Fresnel reflection off the inner core wall at grazing incidence, resulting in Bessel like modes. The absorption coefficient $\alpha$ for propagation in the hollow core depends on the radius of the core $a$ and the ratio between the refractive indices of cladding and core $\nu$:

$$\alpha = \left(\frac{2.405}{2\pi}\right)^2 \frac{\lambda^2}{a^2} \frac{1}{2} \frac{\nu^2 + 1}{\sqrt{\nu^2 - 1}}$$

As the pulses are not propagating in glass, high powers can be guided without destroying the fiber. In case of the fiber setup used for this application, the pulse evolution is mainly governed by SPM stemming from the nonlinear Kerr index of the noble gas.

The nonlinear effect of SPM on the spectrum of an ultrashort pulse is well described by the nonlinear Schrödinger equation. The nonlinear phase acquired during propagation of a pulse introduces a change in the instantaneous frequency, thus spectrally broadening the pulse. For this application, the pulse energy and duration is not affected significantly. This spectral broadening is limited by, among other effects, parasitic self-focusing during propagation stemming from the SPM, as well as the ionization of the nonlinear medium. Quantitatively, these two limitations manifest in a maximal pressure of the nonlinear medium and a minimal radius of the fiber core respectively. The maximum pressure $p_{\text{max}}$

$$p_{\text{max}} = 0.15 \frac{\lambda_0^2}{\nu_2 P_0}$$

depends on the center wavelength $\lambda_0$ and peak power $P_0$ of the pulses, as well as the pressure dependent nonlinear Kerr index $\nu_2$. As the nonlinear Kerr index increases with gas pressure, higher pressures lead to stronger spectral broadening. Numerical models for the ionization caused by ultrashort electrical fields provide an upper limit on the gas pressure based on the duration $T_0$ and energy $E_0$ of the pulse. The effect of the gaseous nonlinear medium is expressed in the constant $A_{\text{gas}}$. The exponents $\beta, \gamma$ are fitted to 0.51 and 0.45 respectively, so that the minimal radius $a_{\text{min}}$ of the fiber core can be determined by

$$a_{\text{min}} = A_{\text{gas}} T_0^{-\gamma} E_0^{\beta}.$$ 

This is illustrated in Fig. 3 for varying pulse duration and typical energies. A smaller radius leads to a reduced effective mode area and a stronger field confinement and thus to increased broadening. These two parameters have to be balanced to achieve an optimal and stable broadening.

2.2 Fringe pattern generation

For the generation of sufficiently variant and dense stripe patterns in each of the spectral channels of a hyperspectral camera an Echelle grating was chosen. These low groove density blazed gratings can be engineered to exhibit a higher efficiency for high number diffraction orders. They are commonly used in high resolution spectrometers. The high order diffraction maxima are spectrally dependent and thus generate a hyperspectral fringe pattern.

To project the interference fringes onto a scene, a 2f-setup consisting of a cylindrical lens is used for the horizontal direction along the diffraction. By using a perpendicular cylindrical lens, the pattern is stretched vertically to cover a larger measurement area. In Fig. 3 this is illustrated for three diffraction maxima and two wavelengths.

2.3 Active stereovision 3D surface measurement

In general, a 3D measurement setup aims to generate depth values $z$ as a function of the position $(x, y)$, which can be expressed as a matrix $z_{ij} = (x_i, y_j)$ that represents the measured surface in 3D space. Furthermore, if each point
(a) Typical layout and size of a hollow core fiber. The light is guided in the air filled core in the center of the fiber.

Figure 2: Structure and characteristics of the hollow core fiber used for the spectral broadening of ultrashort pulses with high energy.

(b) Lower limit of the core radius given by ionization effects for different pulse duration $T_0$ and energies $E_0$ in an Argon filled fiber.

![Echelle Grating](image)

Figure 3: Fringe pattern generation by high order diffraction from an Echelle grating.

on the surface has a scalar value $f$ associated to it, one can define a point cloud $P_i = (x_i, y_i, z_i, f_i)$, where $f$ can for example represent the measured intensity or the surface reflectance at the $i$th surface point [1]. This can be extended to vectorial quantities $\mathbf{v}_i = (\lambda_1^i, \lambda_2^i, \lambda_3^i, ..., \lambda_n^i)$ of dimension $n$, e.g. if the spectral characteristics are measured for $n$ different wavelengths $\lambda$ [2].

The approach of active stereovision aims to generate the $z$ values by triangulation. A scene is recorded by two cameras with known separation, pointing and imaging behavior. For the triangulation, the position of the corresponding image points of each object point have to be known, commonly referred in literature as the correspondence problem in computer vision [32]. It can be solved by finding the maximum of the cross correlation of the two images [5]. By artificially generating an intensity distribution in the scene by projecting a fringe pattern, the solution of the correspondence is aided by giving each object point a unique brightness sequence. This is in our case a unique spectral distribution [1]. With this spectral multiplexing a large number of patterns can be projected onto the scene at the same time, so that for each given wavelength region, a different pattern is projected.

The two camera images are rectified by rotation and translation of the coordinate system [33] to reduce the dimensionality of the correspondence problem. The cameras are modeled by the geometric imaging of pinhole cameras, which requires calibration. A detailed description of the reconstruction algorithm can be found in [2].

To evaluate the suitability of the fringe patterns measured in the different spectral channels, the 3D reconstruction was calculated for objects with known geometry, i.e. a diffusely reflective plane. The temporal resolution was tested by measuring the plane object moving at high speed. A suitable parameter for this is the standard deviation of the measured position from the expected plane, as well as the percentage of measurement values that can be attributed to reconstruction artifacts or outliers. The expected plane is fitted using a linear regression. Reconstruction artifacts are defined as measurement points with a distance from the fitted plane that is larger than 5 mm, to exclude measurement values that are within the uncertainty of the measured plane.
3 Experimental Work

3.1 Light source

The output of the commercial CPA system was coupled into a hollow core fiber of 50 cm length with an inner core radius of 220 µm, which is in the vicinity of the critical radius defined by equation 3. To fill the fiber core with the nonlinear medium, it was placed in a vacuum chamber with two Brewster windows for entry and exit ports. By repeatedly evacuating the chamber and filling it with gas, a high purity of the nonlinear medium was ensured. For the experiment, Argon was chosen as the nonlinear medium. It provides a sufficiently high nonlinear Kerr index, reasonable maximum pressure of 835 mbar, and is readily available. For the given fiber parameters a transmission over 90% in the linear regime is possible, based on equation 1.

The output of the hollow core fiber was evaluated using a spectrometer (OceanOptics USB2000+), a camera and a autocorrelation setup (APE PulseCheck). The transmission of the broadening setup was measured with a thermal powermeter as approximately 50%. In Fig. 4 the measurement of the spectrum and the pulse duration is shown. The spectral width is increased to nearly 150 nm of usable spectrum, while the output temporal profile only shows a marginally increased pulse duration. It has to be noted that the input pulse is intentionally stretched, which was used to balance the spectral broadening with the parasitic effect of self-focusing reducing transmission. Pulse duration before and after the fiber broadening is below 1 ps.

(a) Optimized spectrum with a usable spectrum spanning from 700 nm to nearly 850 nm.

(b) Temporal Pulse Profile before and after spectral broadening, measured using autocorrelation.

Figure 4: Output of the fiber broadening

3.2 Pattern generation

An Echelle grating (Thorlabs GE2550-0363) with a groove density of 31.6 m^{-1} and a blaze angle of 63° is used in perpendicular incidence of the laser beam. The so-generated high order diffraction fringes are projected as described above onto a plane and diffusely reflecting surface and were recorded with the hyperspectral cameras (Ximea MQ022HG) with a 2048-by-1088 subpixel resolution. The complete setup of the diffractive pattern generation is shown in Fig. 6. The Echelle grating is visible as a gray rectangle in the middle of the image. In Fig. 5 the four spectral channels with the overall highest intensity are shown as measured by both cameras.

Due to the non-uniform spectral and spatial profile of the laser pulse, the fringes show an intensity variance in each channel, as well as between the channels. The spectral dependence of the hyperspectral camera, given by the different transmission of the Fabry-Perot etalons and the varying efficiency of a silicon based sensor in the near-infrared spectral region, also contributes to this.

3.3 3D reconstruction

The temporal resolution of the surface measurement can be tested by measuring the surface of a rapidly spinning rotor. A flat, 20 cm long piece of aluminium is mounted on a drone motor and rotated at more than 25000 rpm. Based on an estimation of the motion blur, a temporal resolution of the measurement system in the range of 100 ns would be required, a value far below the temporal resolution of state of the art measurement setups. An image of a static and a moving rotor is shown in Fig. 7a and 7b respectively, which were recorded with a continuous illumination at 1 ms exposure time of the hyperspectral cameras. It is evident that the movement of the rotor cannot be resolved at this time resolution. Compared to this, Fig. 8a and 8b show the ultrafast patterns projected onto the stopped and the moving rotor. The image of the moving rotor shows no recognizable motion blur. The exposure time of 1 ms ensures, that
only one laser pulse is measured, due to the repetition rate of the laser amplifier of 1 kHz. A common trigger signal for both cameras ensures that the same pulse is measured.

Based on a measurement of the moving rotor, the surface data is reconstructed. The resulting point cloud is shown in Fig. 9a. As the cameras are not placed perpendicular to the rotor, a small gradient in the depth value is visible. Laterally, the size of the measurement volume is approximately 4 cm by 6 cm, which is the area where fringes are projected. Object space pixel resolution is approx. 50 µm for individual subpixels. The 5-by-5 pixel thus has an object space resolution of 250 µm. An interpolation is done to generate full resolution images for each color channel. In z-direction the measurement volume is limited by the depth of focus of the camera objectives.

A plane surface is fitted through the measured point cloud, and the resulting difference to the reference plane is plotted in Fig. 9. This histogram contains 200 bins in an interval of size 2.5 cm on each side of the reference plane and is plotted logarithmically. Over four of these measurements, a mean standard deviation from the plane of 2.5 mm and a mean percentage of reconstruction artifacts of 1.95% is measured.

Due to the lack of motion blur, a temporal resolution of less than 100 ns can be demonstrated, which is a lower limit to the temporal resolution, as no measurements that require higher temporal resolution could be done for safety reasons. The estimated temporal resolution of the measurement setup is expected to be in the range of single picoseconds.
estimate is given by the output pulse duration, as seen in Fig. 4. The dispersive effects of the diffractive pattern generation and the refractive projection is negligible for an input pulse with pulse duration 1 ps.

These snapshot measurements with high temporal resolution can be done at the frame rate of the camera, which is given by the manufacturer as up to 340 Hz, while the light source supports a 1 kHz frame rate, given by the repetition rate of the laser amplifier.

To investigate the measurement accuracy for more complex three dimensional structures, a static reference sphere with 40 mm diameter was measured with the setup. For a homogeneous reflective behaviour, the sphere was coated with an opaque and diffusely reflecting paint. Based on the generated depth information for the illuminated spherical section, the surface was reconstructed with a Delaunay triangulation. The result is visible in Fig. 10. The difference of the measured depth values to an ideal sphere is calculated using a spherical fit through the data. Analogously to the plane measurement, this difference is plotted as a logarithmic histogram in Fig. 10b. The measurement performance is comparable to the plane measurement.

Figure 7: Motion Blur for CW illumination with an exposure time less than 1 ms.

Figure 8: Motion Blur for ultrashort illumination with averaged intensity over all channels.

Figure 9: 3D reconstruction of moving rotor

Figure 10: A static reference sphere with 40 mm diameter was measured with the setup. The surface was reconstructed with a Delaunay triangulation. The difference of the measured depth values to an ideal sphere is calculated using a spherical fit through the data. Analogously to the plane measurement, this difference is plotted as a logarithmic histogram.
4 Conclusion and outlook

The demonstrated approach enables the first 3D measurement of surfaces on ultrafast time scales. This is achieved by combining the well-known fringe pattern projection method for surface measurement with the spectral-spatial resolution of hyperspectral cameras as well as the high energy and ultrashort pulse duration of a femtosecond laser system, specifically enhanced by spectral broadening in a hollow core fiber. A system was realized, consisting of two synchronized hyperspectral cameras on CMOS basis with 25 spectral channels, fringe pattern generation utilizing high order diffraction and an amplified Ti:Sapphire laser, offering 1 mJ pulses with over 100 nm bandwidth and a sub-ps pulse duration.

By measuring a rotor at near sonic speeds a lower bound for the temporal resolution of the measurement system was established in the range of 100 ns. Despite the high speed of the measured object, no degradation due to motion blur was measured. The estimation for the maximum temporal resolution is given by the pulse duration of the broadened laser pulses, which is in the range of single picoseconds. The depth resolution was evaluated by the standard deviation of the measurement data to a fitted reference plane and was determined as 2.5 mm. These measurements can be done at the frame rate of the hyperspectral cameras.

Due to the extremely high temporal resolution, but comparatively low frame rate, the measurement system is well suited for measurements of reproducible processes, for example in conjunction with an optical delay stage. Possible areas of interest include laser induced plasma or surface deformation due to sound propagation in solid media.

This initial demonstration of the measurement principle opens up several possible avenues for optimization. With an increased spectral broadening during the fiber propagation, a more robust and accurate 3D reconstruction is expected due to the increased number of patterns. Similarly, complex diffractive elements can be engineered for the pattern generation, offering more design space in regards to the fringe pattern parameters, as well as the homogeneity of the illumination. Further optimization is possible in the hyperspectral camera technology, where a reduction in crosstalk as well as an increase in spectral channels could be achieved by using more sophisticated spectral filters.

Funding

Bundesministerium für Bildung und Forschung (13XP5053A, 03ZZ0475, 13N15429)
Carl Zeiss Stiftung (Jena Alliance Life in Focus)

Acknowledgments

The authors thank S. Börner of the Institute of Applied Physics for assistance with the vacuum setup and electronics. FE acknowledges support by the Zwanzig20 Research Alliance 3Dsensation.

Disclosures

The authors declare no conflicts of interests.
Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document

Hyperspectral imaging

Hyperspectral cameras can differentiate between a large number of spectral regions due to a Fabry-Perot filter matrix placed on the imaging sensor. Each Fabry-Perot etalon consists of two parallel reflective surfaces with separation $h$ and reflectances $r_1$, $r_2$. The intensity transmittance is thus given by

$$ T = \frac{T_{\text{max}}}{1 + \left(\frac{2F}{\pi}\right)^2 \sin^2 \phi}, $$

where $T_{\text{max}}$ is

$$ T_{\text{max}} = \frac{(1 - |r_1|^2)(1 - |r_2|^2)}{(1 - |r_1r_2|)^2} $$

and with the finesse $F$ defined as

$$ F = \frac{\pi \sqrt{|r_1r_2|}}{1 - |r_1r_2|}, $$

as well as the phase $\phi$ given by the separation $h$, the refractive index $n$ between the interfaces, the angle of incidence

$$ \phi = \frac{2\pi nh \cos \theta}{\lambda}, \quad n \sin \theta = \sin \theta_0. $$

Thus, the center wavelength of the transmission of a Fabry-Perot etalon is determined by the separation between the two surfaces. Notably, due to the width of the transmission spectra of the individual filters, a certain amount of overlap is present between the spectral channels. In Fig. 11 the spectral sensitivity of the camera is shown. This effect is also called crosstalk and is generally undesirable, as light from a different spectral region is attributed to the channel it is measured in. Other effects, like an imperfect placement of the filter matrix on the imaging sensor or leakage between adjacent pixels can also contribute to crosstalk. For the application in a spectrally multiplexed fringe projection system, this also leads to a reduce in contrast in the fringe patterns, and negatively affects the uniqueness of the individual patterns.

Figure 11: Quantum efficiency of the 25 different color channels generated by the 5-by-5 filter matrix of a hyperspectral camera (XIMEA MQ NIR). The grey area shows the transmittance of a bandpass filter for use of the camera in the red and near infrared region.
References

[1] Jason Geng. “Structured-light 3D surface imaging: a tutorial”. In: Advances in Optics and Photonics 3.2 (2011), p. 128. DOI: 10.1364/AOP.3.000128.

[2] Stefan Heist et al. “3D hyperspectral imaging: fast and accurate measurement of surface shape and spectral characteristics using structured light”. In: Optics express 26.18 (2018), pp. 23366–23379. DOI: 10.1364/OE.26.023366.

[3] Thomas Luhmann. “Close range photogrammetry for industrial applications”. In: ISPRS Journal of Photogrammetry and Remote Sensing 65.6 (2010), pp. 558–569. ISSN: 0924-2716. DOI: 10.1016/j.isprsjprs.2010.06.003.

[4] Zeev Zalevsky et al. Method and System for Object Reconstruction. Patent WO2007043036 (A1). PRIME SENSE LTD et al., 2007.

[5] E. Z. Psarakis and G. D. Evangelidis. “An enhanced correlation-based method for stereo correspondence with subpixel accuracy”. In: Tenth IEEE International Conference on Computer Vision. Los Alamitos, Calif: IEEE Computer Society, 2005. ISBN: 076952334X. DOI: 10.1109/ICCV.2005.33.

[6] Peter Lutzke et al. “Experimental comparison of phase-shifting fringe projection and statistical pattern projection for active triangulation systems”. In: Optical Measurement Systems for Industrial Inspection VIII. Ed. by Peter H. Lehmann, Wolfgang Osten, and Armando Albertazzi. SPIE Proceedings. SPIE, 2013, p. 878813. DOI: 10.1117/12.2020910.

[7] Stefan Heist et al. “High-speed three-dimensional shape measurement using GOBO projection”. In: Optics and Lasers in Engineering 87 (2016), pp. 90–96. ISSN: 01438166. DOI: 10.1016/j.optlaseng.2016.02.017.

[8] Jae-Sang Hyun, George T-C Chiu, and Song Zhang. “High-speed and high-accuracy 3D surface measurement using a mechanical projector”. In: Optics express 26.2 (2018), pp. 1474–1487. DOI: 10.1364/OE.26.001474.

[9] Haihua Zhang et al. “High Speed 3D Shape Measurement with Temporal Fourier Transform Profilometry”. In: Applied Sciences 9.19 (2019), p. 4123. DOI: 10.3390/app9194123.

[10] Bryce E. Bayer. Color imaging array. Patent US3971065 (A). EASTMAN KODAK CO, 1976.

[11] L. Pjotr Stoevelaar et al. “Nanostructure-modulated planar high spectral resolution spectro-polarimeter”. In: Optics express 28.14 (2020), pp. 19818–19836. DOI: 10.1364/OE.392536.

[12] Nicolaas Tack, Andy Lambrechts, and Luc Haspeslagh. Integrated circuit for spectral imaging system. Patent US2019285474 (A1), IMEC, 2019.

[13] Yating Zhang and Naiqian Zhang. “Imaging technologies for plant high-throughput phenotyping: a review”. In: Frontiers of Agricultural Science and Engineering (2018). ISSN: 2095-7505. DOI: 10.15302/J-FASE-2018242.

[14] Tong Chen et al. “Detection of Psychological Stress Using a Hyperspectral Imaging Technique”. In: IEEE Transactions on Affective Computing 5.4 (2014), pp. 391–405. ISSN: 1949-3045. DOI: 10.1109/taffc.2014.2362513.

[15] Costanza Cucci, John K. Delaney, and Marcello Picollo. “Reflectance Hyperspectral Imaging for Investigation of Works of Art: Old Master Paintings and Illuminated Manuscripts”. In: Accounts of chemical research 49.10 (2016), pp. 2070–2079. DOI: 10.1021/acs.accounts.6b00048.

[16] Giuseppe Bonifazi and Silvia Serranti. “Quality control by HyperSpectral Imaging (HSI) in solid waste recycling: logistics, algorithms and procedures”. In: International Society for Optics and Photonics, 2014, 90240T. DOI: 10.1117/12.2038374.

[17] A. Stingl et al. “Sub-10-fs mirror-dispersion-controlled Ti:sapphire laser”. In: Optics letters 20.6 (1995), pp. 602–604. ISSN: 0146-9592. DOI: 10.1364/OL.20.000602.

[18] Jan Rothhardt et al. “1 MHz repetition rate hollow fiber pulse compression to sub-100-fs duration at 100 W average power”. In: Optics Letters 36.23 (2011), pp. 4605–4607. ISSN: 1539-4794. DOI: 10.1364/OL.36.004605.

[19] Steffen Hädrich. “Peak Power Enhancement of Ultrashort Fiber Lasers for High Harmonic Generation”. Dissertation. Friedrich-Schiller-University, 2012.
[23] Frederik Böhle et al. “Compression of CEP-stable multi-mJ laser pulses down to 4 fs in long hollow fibers”. In: Laser Physics Letters 11.9 (2014), p. 095401. ISSN: 1612-2011. DOI: 10.1088/1612-2011/11/9/095401

[24] Hermance Jacqmin et al. “Passive coherent combining of CEP-stable few-cycle pulses from a temporally divided hollow fiber compressor”. In: Optics Letters 40.5 (2015), pp. 709–712. ISSN: 1539-4794. DOI: 10.1364/OL.40.000709

[25] E. A. J. Marcatili and R. A. Schmeltzer. “Hollow Metallic and Dielectric Waveguides for Long Distance Optical Transmission and Lasers”. In: Bell System Technical Journal 43.4 (1964), pp. 1783–1809. ISSN: 00058580. DOI: 10.1002/j.1538-7305.1964.tb04108.x

[26] Govind P. Agrawal. Nonlinear fiber optics. 5th ed. Optics and Photonics. Burlington: Elsevier Science, 2013. ISBN: 9780123970237.

[27] C. Vozzi et al. “Optimal spectral broadening in hollow-fiber compressor systems”. In: Applied Physics B 80.3 (2005), pp. 285–289. ISSN: 1432-0649. DOI: 10.1007/s00340-004-1721-1

[28] M. V. Ammosov et al. “Tunneling ionization of atoms and atomic ions in an intense laser field with a nonhomogeneous space–time distribution”. In: Journal of the Optical Society of America B 9.8 (1992), p. 1225. ISSN: 0740-3224. DOI: 10.1364/JOSAB.9.001225

[29] Frank L. Pedrotti et al. Optik für Ingenieure: Grundlagen. 4., bearb. Aufl. Berlin: Springer, 2008. ISBN: 9783540734710.

[30] Peter N. Keliher and Charles C. Wohlers. “Echelle Grating Spectrometers in Analytical Spectrometry”. In: Analytical Chemistry 48.3 (1976), 333A–340A. ISSN: 0003-2700. DOI: 10.1021/ac60367a782

[31] Thomas W. Barnard et al. “Design and evaluation of an echelle grating optical system for ICP-OES”. In: Analytical Chemistry 65.9 (1993), pp. 1225–1230. ISSN: 0003-2700. DOI: 10.1021/ac000587a020

[32] Worthy N. Martin and J. K. Aggarwal, eds. Motion Understanding: Robot and Human Vision. Vol. 44. The Kluwer international series in engineering and computer science. SECS Robotics, vision, manipulation and sensors. Boston: Kluwer, 1988. ISBN: 978-0-89838-258-7.

[33] Richard Hartley and Andrew Zisserman. Multiple View Geometry in Computer Vision. Cambridge University Press, 2003. ISBN: 9780521540513.
