Wolfgang Osten (Ed.)

# Fringe 2013

## 7th International Workshop on Advanced Optical Imaging and Metrology

Springer

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Editor

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ISBN 978-3-642-36358-0 ISBN 978-3-642-36359-7 (eBook)
DOI 10.1007/978-3-642-36359-7
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013943575

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# Preface

25 years ago it was a joint idea with Hans Rottenkolber to organize a workshop dedicated to the discussion of the latest results in the automatic processing of fringe patterns. This idea was promoted by the insight that automatic and high precision phase measurement techniques will play a key role in all future industrial and scientific applications of optical metrology. A couple of months later more than 50 specialists from East and West met in East Berlin, the capital of the former GDR, to spend 3 days with the discussion of new principles of fringe processing. In the stimulating atmosphere the idea was born to repeat the workshop and to organize the meeting in an Olympic schedule. And thus meanwhile 24 years have passed and we have now already the 7**th** Fringe workshop.

However, such a workshop is always embedded in a dynamic environment. Therefore the main topics of the previous events were always adapted to the most interesting subjects of the new period. In 1993 the workshop took place in Bremen and was dedicated to new principles of optical shape measurement, setup calibration, phase unwrapping and nondestructive testing, while in 1997 new approaches in multi-sensor metrology, active measurement strategies and hybrid processing technologies played a key role. 2001, the first meeting in the 21st century, was focused to optical methods for micro-measurements, hybrid measurement technologies and new sensor solutions for industrial inspection. In 2005 the fifth workshop was organized for the first time in Stuttgart, the capital of the state of Baden-Württemberg and the center of a region with a long and remarkable tradition in machine construction, vehicle manufacturing and optics. The topics in 2005 were extended to include resolution enhanced technologies and principles of wide-scale 4D optical metrology. For the Fringe 2009 we decided to stay in this region but to make a slight shift of the conference place from Stuttgart to Nürtingen. Nürtingen - a lovely medieval village – offers everything needed for a good conference: a nice conference hotel, attractive surroundings and a stimulating atmosphere. The topics have undergone a refreshment again: digital wavefront engineering and sensor fusion.

For the *FRINGE 2013* we meet again in Nürtingen. This brings back a moment of stability for the workshop. However, we extended the scope markedly by accentuating the bridge between optical imaging and metrology. While the previous workshops were dedicated to optical metrology, the scope of the Fringe 2013 was extended to include advanced technologies in both disciplines, optical imaging and optical metrology. On the one hand, optical imaging and optical metrology are self-standing topics with a long tradition. On the other hand, the current trends in both disciplines show increasing dynamics stimulated by many fascinating innovations such as high resolution microscopy, 3D imaging and nano-metrology. Consequently, both are getting even younger every day and are stimulating each other more and more. Thus, the main objective of the workshop was to bring experts from both fields together and to bridge between these strongly related and emerging fields. New topics are computational imaging, model-based reconstruction, compressed sensing, solutions to inverse problems, multimodality, in-line performance and remote technologies. This extended scope was honored again by a great response to our call for papers. Leading scientists from all around the world submitted more than 200 papers. This enormous response demanded a strong revision of the papers to select the best out of the overwhelming number of excellent papers. This hard job had to be done by the program committee since there is a strong limitation of the number of papers which can be presented and discussed during our workshop without having to deal with parallel sessions – a lasting feature of the Fringe workshops.

The papers presented in this workshop are summarized under 5 topics:

1. New methods and tools for the generation, acquisition, processing, and evaluation of data in optical imaging and metrology,
2. Application-driven technologies in optical imaging and metrology,
3. High dynamic range solutions in optical imaging and metrology,
4. Hybrid technologies in optical imaging and metrology, and
5. New optical sensors, imaging and measurement systems.

As in the former workshops, each topic is introduced by an acknowledged expert who gives an extensive overview of the topic and a report of the state of the art. The classification of all submitted papers into these topics was again a difficult job which often required compromises. We hope that our decisions will be accepted by the audience. On this occasion we would like to express our deep thanks to the international program committee for helping us to find a good solution in every situation.

The editor would like to express his thanks to all the authors who spent a lot of time and effort in the preparation of the papers. My appreciation also goes to Dr. Eva Hestermann-Beyerle and Birgit Kollmar from Springer Heidelberg for providing again excellent conditions for the publication of these proceedings. My deep thanks is directed to the members of the ITO staff. The continuous help given especially by Valeriano Ferreras Paz, Katharina Bosse-Mettler, Katja Costantino, Christina Hübl, Heiko Bieger, Erich Steinbeißer and Tobias Böttcher was the basis for making a successful *FRINGE 2013*. Finally, our special thanks and appreciation goes to all friends and colleagues for sharing with us again the spirit of the Fringe workshop.

Looking forward to *FRINGE 2017*.
Stuttgart, September 2013
Wolfgang Osten

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# Contents

Honorary Lecture and Key Note

**Holography Viewed from the Perspective of the Light Field Camera** ... 3
*Joseph W. Goodman*

**Invisibility, Perfect Imaging and More – Where Optics Meets Magic** ... 17
*Tomáš Tyc*

Topic 1: New Methods and Tools for the Generation, Acquisition, Processing, and Evaluation of Data in Optical Imaging and Metrology

**Fourier Modal Method and Its Applications to Inverse Diffraction, Near-Field Imaging, and Nonlinear Optics** ... 25
*Jari Turunen, Jani Tervo*

**The Road towards Accurate Optical Width Measurements at the Industrial Level** ... 35
*Bernd Bodermann, Rainer Köning, Detlef Bergmann, Wolfgang Häßler-Grohne, Jens Flügge, Harald Bosse*

**Lowering the Cross Correlation between Different Shape Parameters of the Inverse Grating Problem in Coherent Fourier Scatterometry** ... 43
*S. Roy, N. Kumar, S.F. Pereira, H.P. Urbach*

**Fast Geometric Characterization of Gold Nanorod Ensembles Based on Inverse Scattering Spectroscopy** ... 49
*Ninghan Xu, Benfeng Bai, Qiaofeng Tan, Guofan Jin*

**Engineering Harmonic Content in Diffractive Optical Elements** ... 57
*Ignacio Moreno, Jorge Albero, Jeffrey A. Davis, Don M. Cottrell*

**Linear Theory of Optical Surface Measuring Instruments** ............ 63
*Jeremy Coupland*

**Quasi Ellipse Method Enabling High Accuracy Phase Reconstruction with Random Phase Steps in Fizeau-Interferometers** ................ 71
*Michael F. Küchel*

**Measurement of Aspheres and Free-Form Surfaces with the Tilted-Wave-Interferometer** .......................................... 87
*Goran Bastian Baer, Johannes Schindler, Christof Pruss, Wolfgang Osten*

**Correction of Errors in Polarization Based Dynamic Phase Shifting Interferometers** .................................................. 97
*Bradley Kimbrough*

**Single Shot Shape Evaluation Using Dual-Wavelength Holographic Reconstructions and Regularization** .............................. 103
*Per Bergström, Davood Khodadad, Emil Hällstig, Mikael Sjödahl*

**Compressive Imaging and Spectroscopy – Beyond the Single Pixel Camera** .............................................................. 109
*Ting Sun, Yun Li, Lina Xu, Kevin F. Kelly*

**Wave-Optical Reconstruction of Plenoptic Camera Images** ........... 117
*André Junker, Tim Stenau, Karl-Heinz Brenner*

**Iterative Phase Retrieval and the Important Role Played by Initial Conditions** ........................................................ 123
*Lysann Megel, Damien P. Kelly, Thomas Meinecke, Stefan Sinzinger*

**High Precision Single Beam Phase Retrieval Techniques** ............. 129
*Konstantinos Falaggis, Tomasz Kozacki, Malgorzata Kujawińska, Michał Józwik, Arkadiusz Kuś*

**Comparison of Digital Holography and Transport of Intensity for Quantitative Phase Contrast Imaging** ........................... 137
*Chao Zuo, Qian Chen, Anand Asundi*

**Spatial Stationarity of Statistical Optical Fields for Correlation Holography** ....................................................... 143
*Mitsuo Takeda*

**Implementation of Image Inversion Microscopy by Using Digital Holography** ....................................................... 149
*Daniel Weigel, Andreas Stark, Holger Babovsky, Armin Kießling, Richard Kowarschik*

**Performance Evaluation of Phase Unwrapping Algorithms for Noisy Phase Measurements** . . . . . 155
*Samia Heshmat, Satoshi Tomioka, Shusuke Nishiyama*

**Fast Fourier Virtual Fields Method for Determination of Modulus Distributions from Full-Field Optical Strain Data** . . . . . 161
*Truong Tho Nguyen, Jonathan M. Huntley, Ian Ashcroft, Pablo D. Ruiz, Fabrice Pierron*

**Multi-wavelength Doppler Phase Shift Holography and Interferometry** . . . . . 167
*Toyohiko Yatagai*

**Characterization of the Sound Field Generated by an Ultrasonic Transducer in a Solid Medium by Rayleigh-Sommerfeld Back-Propagation of Bulk Acoustic Waves Measured with Double-Pulsed TV Holography** . . . . . 173
*Cristina Trillo, Ángel F. Doval, Lidia M. Fontán, José L. Fernández, Pablo Rodríguez-Gómez, J. Carlos López-Vázquez*

**Wavefront Reconstruction from Noisy Fringe Observations via Sparse Coding** . . . . . 179
*Vladimir Katkovnik, José Bioucas-Dias, Hongxing Hao*

**Fast Adaptive Processing of Low Quality Fringe Patterns by Automated Selective Reconstruction and Enhanced Fast Empirical Mode Decomposition** . . . . . 185
*Krzysztof Patorski, Maciej Trusiak, Maciej Wielgus*

**Use of Generalized N-dimensional Lissajous Figures for Phase Retrieval from Sequences of Interferometric Images with Unknown Phase Shifts** . . . . . 191
*Armando Albertazzi, Analucia V. Fantin, Allison F. Maia, Daniel P. Willemann, Mauro E. Benedet, Matias Viotti*

**Quantitative Analysis of Static and Vibratory Displacements by Holographic Processing of Projected Fringes** . . . . . 197
*Karl A. Stetson*

**Experimental Analysis of n-Butanol Solubilization in Seawater by Pure-Phase Digital Holography** . . . . . 203
*Pierre Slangen, Laurent Aprin, Frédéric Heymes, Pascal Picart*

**Spatiotemporal Phase-Shifting Method for Robust Phase Analysis of Noisy Fringe Pattern** . . . . . 209
*Shien Ri, Hiroshi Tsuda*

**Axial Decorrelation of Paraxial Wavefields: Theory and Experiment** . . . 213
*Damien P. Kelly, Lysann Megel, Thomas Meinecke, Stefan Sinzinger*

**Phase Extraction by Spiral Phase Transform in Digital Shearography** . . . 217
*Jiancheng Xu, Jianxin Gao*

**Real-Time Fringe Evaluation for Displacement Measurement by Exploiting Multi-core Capabilities of Modern Computers** . . . 221
*Alexander Schöch, Sabine Linz-Dittrich, Carlo Bach, Andreas Ettemeyer*

**Comprehensive Fringe Pattern Processing Using Continuous Wavelet Transform** . . . 225
*Krzysztof Pokorski, Krzysztof Patorski*

**Comparison of Unwrapping Strategies for a 3D Measurement System Based on a Tailored Free-Form Mirror for Fringe Generation** . . . 229
*Christian Bräuer-Burchardt, Stefan Heist, Peter Kühmstedt, Gunther Notni*

**High Resolution Wavefront Measurement with Phase Retrieval Using a Diffractive Overlapping Micro Lens Array** . . . 233
*Xiyuan Liu, Karl-Heinz Brenner*

**Automated Defect Detection Algorithm Applied to Shearography in Composites** . . . 237
*Jean-François Vandenrijt, Marc Georges*

**Design of a Chromatic Fringe Projector for 3D Object Reconstruction** . . . 241
*Francoise Torner, Jörg Seewig, Thomas Fahlbusch, Günter Beichert, Thomas Böttner*

**Coherence Length Measurement for Ultra-short Laser Pulses Using Digital Holography and Statistical Fringe Analysis** . . . 247
*Esmerando Escoto, Joselito Muldera, Lean Dasallas, Elmer Estacio, Percival Almoro*

**A TVSOOPDE Model for Denoising Fringe Pattern in Electronic Speckle Pattern Interferometry** . . . 251
*Si Yan, Xinjun Zhu, Chen Tang, Haiqing Yan*

**Phase Profiling Using Single Shot Digital Holography** . . . 255
*P.T. Samsheerali, Kedar Khare, Joby Joseph*

**Digital Speckle Correlations in Coherent Surface Metrology and Imaging** . . . . . 257
*Ichirou Yamaguchi*

**A Robust Method for Full Chromatic Error Compensation in Digital Color Holography** . . . . . 263
*Mathieu Leclercq, Pascal Picart*

**High-Accuracy Characterisation of Spheres Using PTB's Sphere Interferometer with an Enhanced Stitching Procedure** . . . . . 267
*Guido Bartl, Michael Krystek, R. Arnold Nicolaus*

**Fiber Polarization Mode Excitation Applied to Confocal Microscopy** . . . 271
*Christoph Zeh, Thomas Härtling*

**Multi-level Spiral Phase Filtering in Speckle Interferometry Using Spatial Light Modulators** . . . . . 275
*Alberto Aguilar, Abundio Dávila, Enrique Landgrave*

**Fractional Vortex Dipole Spatial Filtering** . . . . . 279
*Manoj Kumar Sharma, Joby Joseph, Paramasivam Senthilkumaran*

**Measuring the Complex Amplitude of Wave Fields by Means of Phase Retrieval Using Partially Coherent Illumination** . . . . . 283
*Mostafa Agour, Khaled Elshaffey, Christoph von Kopylow,*
*Ralf B. Bergmann, Claas Falldorf*

**Some Characteristics of Doubly Scattered Speckle Fields** . . . . . 289
*Dayan Li, Damien P. Kelly, John T. Sheridan*

**Improving of Zero Order Fringe Detection in Full-Field Low Coherence Interferometry by Light Source Spectrum Shaping** . . . . . 293
*Anna Pakula, Leszek Salbut*

**Non Ripple-Effect Discrete Fourier Integration Method** . . . . . 297
*Juan Campos, Josep Nicolas, José Luis Martínez*

**Novel Analytical Method of Wavefront Tracing and Its Application in Ophthalmic Optics** . . . . . 301
*Stephan Trumm, Gregor Esser, Wolfgang Becken, Werner Müller*

**Imaging and Quantitative Microscopy in Turbid Microfluidic Channels by Digital Holography** . . . . . 305
*Vittorio Bianco, Melania Paturzo, Andrea Finizio,*
*Pasquale Memmolo, Pietro Ferraro*

**Phase and Polarization Measurement of a Spatially Varying Linear Polarization Distribution** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 309
*Sergej Rothau, Vanusch Nercissian, Andreas Berger, Irina Harder, Klaus Mantel, Norbert Lindlein*

**Dynamic Fringe Analysis in Spectral Interferometry and Optical Coherence Tomography Based on Recurrence Computational Algorithms** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 313
*Igor P. Gurov, Maxim Volynsky*

**Filtering ESPI Fringe Images with Non-local Means Algorithm** . . . . . . . 317
*Maciej Wielgus, Krzysztof Patorski*

**Computational Simulation of the Light Propagation Process through Nonlinear Media** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 321
*Sergey Nalegaev, Nikolay Petrov, Victor Bespalov*

**Measurement of All Orthogonal Components of the Displacement Field in the Volume of Scattering Materials Using Tilt Scanning Interferometry** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 325
*Pablo D. Ruiz, Jonathan M. Huntley, Bona S.H. Burlison*

**Positional Accuracy of Optical Vortex Metrology (OVM)** . . . . . . . . . . . . . 329
*Vivien Beyer, Wei Wang, Andrew J. Moore*

**Fringe Processing Methods for Adaptive Interferometry** . . . . . . . . . . . . . 333
*János Kornis*

**Optimized Phase Retrieval Algorithm with Multiple Illuminations** . . . . . 337
*Ni Chen, Jiwoon Yeom, Byoungho Lee*

**White-Light Interferometer–Micro-Profile Measurement Based on Higher Steps Phase-Shifting Algorithm** . . . . . . . . . . . . . . . . . . . . . . . . . . . 341
*Ming-Hsing Shen, Wei-Chung Wang, Chi-Hung Hwang*

**Increasing Scatterometric Sensitivity by Simulation Based Optimization of Structure Design** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 345
*Valeriano Ferreras Paz, Karsten Frenner, Wolfgang Osten*

**Estimating the Accuracy of Different Parametric Freeform Surface Descriptions** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 349
*Johannes Schindler, Goran Bastian Baer, Christof Pruß, Wolfgang Osten*

**An Inverse Measurement Strategy to Determine Phase Errors Introduced by Rigorous Effects in CGH** . . . . . . . . . . . . . . . . . . . . . . . . . . 355
*Sandy Peterhänsel, Christof Pruss, Wolfgang Osten*

**Rigorous Speckle Simulation Using Surface Integral Equations and Boundary Element Methods** . . . . . . . . 361
*Liwei Fu, Karsten Frenner, Wolfgang Osten*

**Programmable Microscopy** . . . . . . . . 365
*Malte Hasler, Tobias Haist, Wolfgang Osten*

**Phase Retrieval with Resolution Enhancement by Using Random-Phase Illumination** . . . . . . . . 369
*Peng Gao, Giancarlo Pedrini, Wolfgang Osten*

**Illumination Optics in Phase Space** . . . . . . . . 373
*Denise Rausch, Alois Herkommer*

**Holographic Imaging of a 3D Object Hidden behind a Diffuser or around a Corner** . . . . . . . . 377
*Alok Kumar Singh, Dinesh Narayana Naik, Giancarlo Pedrini, Mitsuo Takeda, Wolfgang Osten*

**Topic 2: Application-Driven Technologies in Optical Imaging and Metrology**

**Ultra High-Precision Wavefront Metrology Using EUV Low Brightness Source** . . . . . . . . 385
*Katsura Otaki, Naoki Kohara, Katsumi Sugisaki, Yoshinori Ichikawa, Yucong Zhu, Katsuhiko Murakami, Chidane Ouchi, Seima Kato, Masanobu Hasegawa, Tokuyuki Honda, Mitsuo Takeda*

**Interferometric Homogeneity Test Using Adaptive Frequency Comb Illumination** . . . . . . . . 393
*Klaus Mantel, Johannes Schwider*

**Wafer-Based Aberration Metrology for Lithographic Systems Using Overlay Measurements on Targets Imaged from Phase-Shift Gratings** . . . . . . . . 399
*Sven van Haver, Wim M.J. Coene*

**ISO Definition of Resolution for Surface Topography Measuring Instruments** . . . . . . . . 405
*Richard Leach, Claudiu Giusca, Andrew Henning, Ben Sherlock, Jeremy Coupland*

**Measurement Uncertainty of Optical Methods for the Measurement of the Geometrical Shape of Objects** . . . . . . . . 411
*Pavel Pavliček*

**Random Phase Shift Interferometer for the Measurement of Spherical Surfaces** ........ 417
*Hagen Broistedt, Rainer Tutsch*

**New Definition of the SI Unit Kilogram – Spherical Interferometry as the Limiting Factor** ........ 423
*R. Arnold Nicolaus*

**A Synchronized Stroboscopic Holography Setup for Traveling Wave Analysis on Biomechanical Structures** ........ 433
*Daniel De Greef, Joris J.J. Dirckx*

**Polarization State Detection by Using Multiplexing Digital Holography** ........ 439
*Caojin Yuan, Jun Ma, Shaotong Feng*

**Non Diffractive Beam Configurations for Optical Trapping** ........ 445
*Stephan Stürwald, Robert Schmitt*

**Biospeckle PIV and Applications** ........ 451
*Roberto Alves Braga, Graham William Horgan, Ellem Walleska N. da Fonseca, Rodrigo Reis Soares, Lucas Tiago Silva, Henrique Coelho Barbosa, Murilo Risso*

**The Connection between Rays and Waves** ........ 457
*Miguel A. Alonso*

**Object Depending Measurement Uncertainty of Confocal Sensors** ........ 465
*Florian Mauch, Wolfram Lyda, Wolfgang Osten*

**Survivability of MEMS Packages at High-g Loads** ........ 471
*Ryszard J. Pryputniewicz*

**Novel Industry Ready Sensors for Shape Measurement Based on Multi Wavelength Digital Holography** ........ 479
*Markus Fratz, Daniel Carl*

**Positioning Errors in Coherence Scanning Interferometers: Determination of Measurement Uncertainties with Novel Calibration Artifacts** ........ 485
*Sebastian Boedecker, Christian Rembe, Rolf Krüger-Sehm, André Felgner*

**Traceable Quasi-dynamic Stroboscopic Scanning White Light Interferometry** ........ 491
*Ville Vili Heikkinen, Anton Nolvi, Tor Paulin, Jeremias Seppä, Ivan Kassamakov, Antti Lassila, Edward Hæggström*

**Measurement of Temperature Profile around Heated Wire Using Digital Holography** .......... 497
*Varun Kumar, Manoj Kumar, Shobhna Sharma, Chandra Shakher*

**Experimental Study on the Absolute Measurement of Flats** .......... 503
*Wenchuan Zhao, Weihong Song, Gaofeng Wu, Yongqian Wu*

**Optical Measurements of Nonlinearity in the Middle Ear** .......... 507
*John Peacock, Rik Pintelon, Joris J.J. Dirckx*

**Efficient Optical Metrology for Industrial Inspection** .......... 511
*Yongkai Yin, Xiang Peng, Dong He, Meng Wang*

**Three-Dimensional Measuring of Immersed Objects in Transparent Media** .......... 515
*Ramon Rodriguez-Vera, Jesus E. Pinto, Daniel D. Aguayo, Juan A. Rayas, Fernando Mendoza-Santoyo*

**Fault Detection by Shearography and Fringes Projection Techniques** ... 519
*Angel Georgiev Baldjiev, Ventseslav Christov Sainov*

**Measurement of Temperature and Temperature Profile of Axi-symmetric Butane Torch Burner Flame Using Digital Speckle Pattern Interferometry (DSPI)** .......... 523
*Manoj Kumar, Varun Kumar, Gufran Sayeed Khan, Chandra Shakher*

**High Speed Fringe Pattern Topography for Detection of the Arterial Pulse Wave in Vivo** .......... 527
*Adriaan Campo, Joris J.J. Dirckx*

**6D-Measurement System for the Position Determination of a Robot End-Effector** .......... 531
*Alexej Janz, Christian Pape, Eduard Reithmeier*

**Interference Microscopy for Clean Air – How Optical Metrology Is Improving Quality Control of Fuel Injection Systems** .......... 535
*Robert Sachs, Frank Stanzel*

**Extending the Capabilities of PTB's Ultra-Precision Interferometer towards the Measurement of Piezoelectric Strain at High Temperatures** .......... 539
*Tatjana Quast, Guido Bartl, René Schödel*

**Spatial-Frequency Filtering of Images by Polymer-Dispersed Liquid Crystals** .......... 543
*Peter P. Maksimyak, Andrey Nehrych*

**Temperature Measurement of Diffusion and Pre-mixed Flames under the Influence of Magnetic Field Using Digital Holographic Interferometry** . . . 547
*Chandra Shakher, Shobhna Sharma, Manoj Kumar, Varun Kumar, Shilpi Agarwal*

**Interference Measurement of Surfaces Roughness** . . . 551
*Oleg V. Angelsky, Andrew P. Maksimyak, Peter P. Maksimyak*

**Holographic Three-Dimensional Tracking of Micro-objects Exploiting Their Morphological Properties** . . . 555
*Pasquale Memmolo, Andrea Finizio, Melania Paturzo, Lisa Miccio, Maria Iannone, Maurizio Ventre, Paolo Antonio Netti, Pietro Ferraro*

**Measurements of Three-Dimensional Freeform and Aspheric Geometries** . . . 559
*Denis Dontsov, Enrico Langlotz, Walter Schott*

**Comparison of Two Methods to Design Computer Generated Holograms of Discrete Points Objects** . . . 563
*Pablo Marín, Ángel Lizana, Alba Peinado, Miguel Mora-Gonzalez, Juan Campos*

**Wide-Field, Low-Cost Mapping of Power Ultrasound Fields in Water by Time-Average Moiré Deflectometry** . . . 567
*Lidia M. Fontán, José L. Fernández, Ángel F. Doval, José L. Meniño, Cristina Trillo, J. Carlos López-Vázquez*

**Model-Based Deflectometric Measurement of Transparent Objects** . . . 573
*Marc Fischer, Marcus Petz, Rainer Tutsch*

**Digital Holographic Setup for Measurement of Fast Developing Phenomenon in Wide Area** . . . 577
*Vít Lédl, Pavel Psota, Tomáš Vít, Roman Doleček*

**White Light Phase-Shifting Interference Microscopy for Quantitative Phase Imaging of Red Blood Cells** . . . 581
*Dalip Singh Mehta, Vishal Srivastava*

**Instantaneous Impact Measurements of an Anodised Aluminium Surface Using a Birefringent Phase Sensitive High Speed Camera** . . . 585
*Peter John Bryanston-Cross, Brenda H. Timmerman, Jo Nawsasra*

**Towards Grating Reconstruction in Coherent Fourier Scatterometry** . . . 591
*Nitish Kumar, Sarathi Roy, Omar El Gawhary, Silvania F. Pereira, Wim M.J. Coene, H. Paul Urbach*

**Contrast Enhancement in 3D Microscopic Imaging of Microorganisms Immersed in a Liquid Medium** .................................. 595
*Ahmad Faridian, Giancarlo Pedrini, Wolfgang Osten*

**3-Dimensional Quantification of Surface Shape and Acoustically-Induced Vibrations of TM by Digital Holography** ........ 599
*Morteza Khaleghi, Cosme Furlong, Jeffrey Tao Cheng, John J. Rosowski*

**Topic 3: High Dynamic Range Solutions in Optical Imaging and Metrology**

**Nanoscale Precision Measurements of Magnetic and Electric Fields by a Magneto-optical Sensor** ........................................ 605
*Jörg Wrachtrup, Bernhard Grotz*

**Transverse Polarization Structure of an Optical Vortex Beam around the Unfolding Point in a Birefringent Crystal** ........................................................ 611
*Maruthi Manoj Brundavanam, Yoko Miyamoto, Mitsuo Takeda, Ken'ichi Nakagawa*

**Ultra High Speed 3D Measurement with the Focus Variation Method** ........................................................ 617
*Franz Helmli, Reinhard Danzl, Manfred Prantl, Markus Grabner*

**Topography Measurements of High Gradient and Reflective Micro-structures by Digital Holography** ........................... 623
*Michał Józwik, Tomasz Kozacki, Kamil Liżewski, Maciej Barański, Christophe Gorecki*

**Interference Technique for Experimental Observation of the Spin Flow** ........................................................ 629
*Oleg V. Angelsky, Andrew P. Maksimyak, Peter P. Maksimyak, Claudia Yu Zenkova*

**High Dynamic Range Digital Holographic Method for Very Small Amplitude Measurement** ...................................... 635
*Pavel Psota, Vít Lédl, Roman Doleček*

**The Metrology of Optical Fields Using Nanomanipulation** ............ 641
*Claudia Yuriivna Zenkova, Iryna Soltys, Pavlo Angelsky*

**Interferometry with Stabilization of Wavelength within a Fixed Measuring Range** ........................................... 645
*Josef Lazar, Miroslava Holá, Jan Hrabina, Zdeněk Buchta, Ondřej Číp, Jindřich Oulehla*

**Speckle Noise Reduction in Michelson Digital Holography Using Known or Unknown Reference Linear Phases and Image Processing** ... 649
*Tomi Pitkäaho, Thomas J. Naughton*

**Generalized Phase Unwrapping for Multi-Wavelength Interferometry** ... 653
*Konstantinos Falaggis, David P. Towers, Catherine E. Towers*

**Acousto-mechanical Response of the Human TM Characterized by High-Speed Digital Holographic Methods** ... 657
*Ivo Dobrev, Cosme Furlong, Jeffrey Tao Cheng, John J. Rosowski*

**Topic 4: Hybrid Technologies in Optical Imaging and Metrology**

**Performance Limits for Computational Photography** ... 663
*Kaushik Mitra, Oliver Cossairt, Ashok Veeraraghavan*

**Problems and Solutions in Tomographic Analysis of Phase Biological Objects** ... 671
*Malgorzata Kujawinska, Björn Kemper, Arkadiusz Kus, Michal Dudek, Wojciech Krauze, Julianna Kostencka, Tomasz Kozacki*

**3D-Optical Interference Microscopy at the Lateral Resolution Limit** ... 677
*Peter Lehmann, Jan Niehues, Stanislav Tereschenko*

**Coherent Pattern Projection for Highspeed 3D Shape Measurements** ... 683
*Martin Schaffer, Marcus Große, Bastian Harendt, Richard Kowarschik*

**Multiwavelength Ptychography** ... 689
*Daniel Claus, John M. Rodenburg*

**Preliminary Comparison of DUV Scatterometry for CD and Edge Profile Metrology on EUV Masks** ... 695
*Johannes Endres, Bernd Bodermann, Gaoliang Dai, Matthias Wurm, Mark-Alexander Henn, Hermann Gross, Frank Scholze, Alexander Diener*

**Results of a Sensitivity Analysis for the Tilted-Wave Interferometer** .... 701
*Ines Fortmeier, Manuel Stavridis, Axel Wiegmann, Michael Schulz, Goran Bastian Baer, Christof Pruss, Wolfgang Osten, Clemens Elster*

**Application of Combined GI/DSPI Technique in Displacement Measurements of Cylindrical Objects** ... 707
*Dariusz Lukaszewski, Leszek Salbut*

**Automated Multi-sensor Inspection of 3D Objects** .................. 711
*Marc Gronle, Wolfram Lyda, Wolfgang Osten*

**Recording of 3D Spatial and Spectral Information of Self-luminous Objects Using a Mach-Zehnder Radial Shearing Interferometer** ....... 715
*Dinesh Narayana Naik, Giancarlo Pedrini, Mitsuo Takeda, Wolfgang Osten*

**Topic 5: New Optical Sensors, Imaging and Measurement Systems**

**Preservation of Cultural Heritage: The Bridge between Inspection and Conservation** ................................ 721
*Christoph Krekel, Niclas Hein, Heide Skowranek*

**Precise Optical Metrology Using Computational Shear Interferometry and an LCD Monitor as Light Source** ........................ 729
*Claas Falldorf, Aleksandar Simic, Gerd Ehret, Michael Schulz, Christoph von Kopylow, Ralf B. Bergmann*

**Potentials of Endoscopic Fringe Projection – A Differentiation of Measuring Video-, Fiber- and Borescopy** ........................ 735
*Christoph Ohrt, Andreas Pösch, Markus Kästner, Eduard Reithmeier*

**Digital Holographic Imaging Based on Shearing Interferometry** ....... 741
*Pascal Picart, Mokrane Malek*

**High-NA Interferometrical Stylus for Free Form Surface Measurement in Optical and Automotive Industry** ................ 747
*Matthias Fleischer, Gerald Franz, Pawel Drabarek*

**The Value of Fringes: How Interferometry Made Money** ............ 753
*Chris L. Koliopoulos*

**Mid-infrared Interferometer Operating at 4.41 μm: Design, Fabrication and Application** .................................. 761
*Qun Yuan, Zhishan Gao, Rihong Zhu, Jun Ma*

**Dynamic Measurements by Interferometry Based on High-Speed Camera and Photodetector** .................................. 767
*Yu Fu, Min Guo, Huan Liu, Keyu Yan, Yingjun Xu*

**Shape Measurements of Fast Rotating Objects with Enhanced Speckle Correlation Coefficient** ................................ 773
*Jürgen W. Czarske, Robert Kuschmierz, Philipp Günther*

**A Traceable Nanometre Sensor Based on FP Feedback Cavity** ........ 779
*Zhaoli Zeng, Shulian Zhang*

**Revelations in the Art of Fringe Counting: The State of the Art in Distance Measuring Interferometry** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 785
*Peter J. de Groot, Vivek G. Badami*

**Novel Parabolic Mirror Microscope Illuminated with Cylindrical Vector Beams for Confocal and Tip Enhanced Super Resolution Imaging** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 791
*Kai Braun, Dai Zhang, Xiao Wang, Josip Mihaljevic, Alfred J. Meixner*

**Longitudinal-Differential Interferometry: Axial Phase Study of Light for Micro- and Nano-optical Problems** . . . . . . . . . . . . . . . . . . . . . . . . . . . . 797
*Myun-Sik Kim, Toralf Scharf, Hans Peter Herzig, Reinhard Voelkel*

**Digital Holographic Recording of a Diffusely Reflecting Object without Speckle Noise** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 803
*You Seok Kim, Taegeun Kim, Sung-soo Woo, Hoonjong Kang, Ting-Chung Poon, Changhe Zhou*

**Handheld 3D Scanning with Automatic Multi-view Registration Based on Optical and Inertial Pose Estimation** . . . . . . . . . . . . . . . . . . . . . . . 809
*Christoph Munkelt, Bernhard Kleiner, Torfi Torhallsson, Peter Kühmstedt, Gunther Notni*

**Heterodyne Common-Path Interference Microscope with a Wavelength-Tunable Diode Source** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 815
*Shunpei Yukita, Yukihiro Ishii, Kosuke Kiyohara, Jun Chen, Eiji Tokunaga*

**Automatic 3D Imaging and Modelling System with Color Information for Cultural Heritage Digitization** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 821
*Xiaoli Liu, Xiang Peng, Dong He, Xingming Liu, Ameng Li, Yongkai Yin, Jiwang Ye, Yabin Ding*

**Fabrication of Square-Lattice Crossed Gratings Based on Diffraction of a Reference Grating** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 827
*Lijiang Zeng, Lifeng Li*

**Using LED Illumination in Fringe Projection Profilometry with a Sinusoidal Phase Grating** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 831
*Elena Stoykova, Hoonjong Kang, Natalia Berberova, Branimir Ivanov, Sung-soo Woo*

**High-Speed 3D Shape Measurement Using an Array Projector** . . . . . . . . 835
*Stefan Heist, Marcel Sieler, Peter Kühmstedt, Gunther Notni*

**Spectral Properties of Saturation Pressure Filled Iodine Absorption Cells** . . . . . 839
*Jan Hrabina, Miroslava Holá, Josef Lazar, Martin Sarbort, Ondřej Číp*

**Spectroscopic Traceability Route for Variable Synthetic Wavelength Absolute Distance Interferometry** . . . . . 843
*Günther Prellinger, Karl Meiners-Hagen, Florian Pollinger*

**System and Method for Cylindrical Error Measurement with Interferometry** . . . . . 847
*Dongbao Ge, Junzheng Peng, Yingjie Yu, Mingyi Chen, Asundi Anand*

**Comparison of System Properties for Wave-Front Holographic Printers** . . . . . 851
*Hoonjong Kang, Elena Stoykova, Hiroshi Yoshikawa, Sunghee Hong, Youngmin Kim*

**Multidimensional Mueller Matrices Microscopy of Biological Crystal Networks Structure** . . . . . 855
*Yuriy A. Ushenko, Alexander V. Dubolazov, Artem O. Karachevtsev, Mikhail Yu. Sakhnovskiy, Liliya I. Bizer, Olena B. Bodnar*

**Double-Ended Interferometer for Measuring Gauge Blocks without Wringing** . . . . . 859
*Katharina Rau, René Schödel*

**The New Sphere Interferometer for Diameter Determination of the Si-Spheres for a Redefinition of the Kilogram** . . . . . 863
*Torsten Mai, Guido Bartl, R. Arnold Nicolaus, Andreas Peter*

**Thickness Measurement with Multi-wavelength THz Interferometry** . . . 867
*Thi-Dinh Nguyen, J.D. Valera, Andrew J. Moore*

**An Innovative Multi-headed Camera Network: A Displacement-Relay Videometrics Method in Unstable Areas** . . . . . 871
*Yang Shang, Qifeng Yu, Yong Xu, Guangwen Jiang, Xiaolin Liu, Sihua Fu, Xianwei Zhu, Xiaochun Liu*

**Stereophotogrammetric Image Field Holography** . . . . . 875
*Holger Babovsky, Markus Hanemann, Marcus Große, Armin Kießling, Richard Kowarschik*

**Broad Area Laser Diode Coherence Measurement and Modeling** . . . . . . 879
*Henri Simo Partanen, Sandy Claudia Peterhänsel, Christof Pruss, Wolfgang Osten, Jani Tervo, Jari Turunen*

**SLM-Based Fringe Projection Profilometry Under Coherent Illumination** . . . . . . . . . . 883
*Natalia Berberova, Elena Stoykova, Hoonjong Kang, Joo-Sup Park, Branimir Ivanov*

**New Sensor for Small Angle Deflectometry with Lateral Resolution in the Sub-millimetre Range** . . . . . . . . . . 887
*Gerd Ehret, Susanne Quabis, Michael Schulz, Birk Andreas, Ralf D. Geckeler*

**Displacement Interferometry within a Passive Fabry-Perot Cavity** . . . . . 893
*Miroslava Holá, Jan Hrabina, Antonín Fejfar, Jan Kočka, Jiří Stuchlík, Ondřej Číp, Jindřich Oulehla, Josef Lazar*

**Flying Triangulation – Towards the 3D Movie Camera** . . . . . . . . . . 895
*Florian Willomitzer, Svenja Ettl, Christian Faber, Gerd Häusler*

**3D Scanning System for In-Vivo Imaging of Human Body** . . . . . . . . . . 899
*Miguel Ares, Santiago Royo, Jordi Vidal, Laia Campderrós, David Panyella, Frederic Pérez, Sergio Vera, Miguel A. González Ballester*

**A Novel Form Measurement System for Precision Components Using Interferometric Sub-aperture Stitching** . . . . . . . . . . 903
*Sören Laubach, Gerd Ehret, Holger Knell, Peter Kühnhold, Peter Lehmann*

**Quantitative Deflectometry Challenges Interferometry** . . . . . . . . . . 907
*Evelyn Olesch, Christian Faber, Roman Krobot, Ralf Zuber, Gerd Häusler*

**Looking beyond Smoke and Flames by Lensless Infrared Digital Holography** . . . . . . . . . . 911
*Vittorio Bianco, Melania Paturzo, Massimiliano Locatelli, Eugenio Pugliese, Andrea Finizio, Anna Pelagotti, Pasquale Poggi, Lisa Miccio, Riccardo Meucci, Pietro Ferraro*

**Simultaneous Temperature and Deformations Measurements Using Long-Wave Infrared Speckle Interferometry: A Novel Hybrid Technique for Industrial Nondestructive Testing** . . . . . . . . . . 917
*Marc Georges, Jean-François Vandenrijt, Cédric Thizy, Igor Alexeenko, Giancarlo Pedrini, Jonathan Rochet, Birgit Vollheim, Iagoba Jorge, Pablo Venegas, Ion Lopez, Wolfgang Osten*

**Digital Holographic Interferometry in the Long-Wave Infrared for the Testing of Large Aspheric Space Reflectors** . . . . . . . . . . 921
*Jean-François Vandenrijt, Cédric Thizy, Yvan Stockman, Patrick Queeckers, Frank Dubois, Dominic Doyle, Marc Georges*

**VIS-NIR Full-Field Low Coherence Interferometer for Surface Layers Non-destructive Testing and Defects Detection** ............... 925
*Leszek Salbut, Slawomir Tomczewski, Anna Pakula*

**Fringe Projection Based Real-Time Three-Dimensional Measurement System** .............................................. 929
*Cong Liu, Zhenning Chen, Xiaoyuan He*

**In-Vivo Skin Roughness Measurement by Laser Speckle** ............. 933
*Tim K. Lee, Lioudmila Tchvialeva, Harvey Lui, Haishan Zeng, David I. McLean*

**Surface Reaction under Climate Impact: A Direct Holographic Visualisation of Assumed Processes** ............................... 937
*Vivi Tornari*

**Technology, Business, and Ethics in the Age of Open Access** ................................................. 943
*Nadya Reingand, Yan Hankin*

**Design of a Hybrid Miniaturized Zoom Imaging System** ............. 947
*Simon Thiele, Marc Blattmann, Hans Zappe, Andreas Seifert, Alois Herkommer*

**Optical Methods for the Assessment of Transport and Age Induced Defects of Artwork** ........................................ 951
*Michael Morawitz, Niclas Hein, Igor Alexeenko, Marc Wilke, Giancarlo Pedrini, Christoph Krekel, Wolfgang Osten*

***itom* – An Open Source Measurement, Automation and Evaluation Software Suite** .......................................... 957
*Marc Gronle, Christian Kohler, Marc Wilke, Wolfram Lyda, Heiko Bieger, Wolfgang Osten*

**Appendix** ............................................. 965

**Author Index** .......................................... 971

# Honorary Lecture

## Holography Viewed from the Perspective of the Light Field Camera

Given by:

**Joseph W. Goodman**
Stanford
**(USA)**

# Key Note

## Invisibility, Perfect Imaging and More – Where Optics Meets Magic

Given by

**Tomáš Tyc**
Brno
**(Czech Republic)**

# Comparison of Digital Holography and Transport of Intensity for Quantitative Phase Contrast Imaging

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## 1 Introduction

Extracting quantitative phase information has received increased interest in many fields where either phase imaging or structure retrieval is an issue, such as optical testing, bio-medical imaging and materials science. In the past couple of decades, digital holography (DH) has emerged as a front-runner for phase imaging by providing quantitative phase measurements of the wave field with high accuracy and in near real-time [1]. However, DH systems need a highly coherent light source, suffer phase aberration, ambiguity and unwrapping problems, and cannot offer the highest spatial resolution. Recently, however, direct phase retrieval from intensity measurements using the Transport-of-Intensity Equation (TIE) [2, 3] has gained increasing attention. A minimum of two measurements of the spatial intensity of the optical wave in closely spaced planes perpendicular to the direction of propagation are needed to reconstruct the spatial phase of the wave by solving a second-order differential equation, i.e., with a non-iterative deterministic algorithm. In this paper, these two quantitative phase imaging methods: DH and TIE are introduced and compared. Two samples: a regular array of micro-bumps fabricated on Si substrate based on laser induced non-ablative texturing and a refractive quartz microlens array from SUSS MicroOptics were tested by DH and TIE. The results were compared and the merits and limitations of each method are discussed.

## 2 Basic Principles

There are different configurations in DH, including off-axis Fresnel, Fourier, image plane, in-line, Gabor, and phase-shifting DH. In this work, we only discuss the off-axis DH since it simultaneously provides an amplitude and a phase-contrast image on the basis of a single hologram. In both transmission and

W. Osten (ed.), *Fringe 2013*,

DOI: 10.1007/978-3-642-36359-7_17, © Springer-Verlag Berlin Heidelberg 2014

reflective setups for DH, a coherent laser beam is split into two parts – the reference beam illuminates the CCD directly. The object beam either passes through or reflects off the sample and interferes with the reference beam at the CCD plane with a small angle to generate the off-axis hologram. The intensity distribution recorded by the camera can be written as

$$I_H(x,y) = |O|^2 + |R|^2 + RO^* + R^*O \tag{1}$$

$R(x,y)$ and $O(x,y)$ are the reference and object waves respectively, *denotes the complex conjugate. The hologram is sampled by the CCD array and then transferred into a computer as an array of numbers. Filtering the hologram's two-dimensional Fourier spectrum can eliminate the virtual image and the zero-order term. The diffracted field, including amplitude and phase distribution at the image plane is then numerically propagated from the hologram plane using Fresnel transform, convolution, or angular spectrum methods.

The TIE uses only object field intensities at multiple axially displaced planes without any interference with a separate reference beam. The experimental setup for TIE typically involves a 4*f* imaging system. By translating the camera or the object, multiple intensity images at different image distance can be obtained. Due to its non-interferometric nature, the illumination can be quasi-monochromatic and partially-coherent. TIE determines the object-plane phase from the first derivative of intensity in the near Fresnel region [3]

$$-k\frac{\partial I(x,y)}{\partial z} = \nabla \cdot \left[ I(x,y)\nabla\varphi(x,y) \right] \tag{2}$$

Where $k$ is the wave number. $\nabla$ is the gradient operator over $(x,y)$. $z$ denotes position along the optics axis perpendicular to the $x$-$y$ plane. If $I(x,y) > 0$ and $\varphi(x,y)$ is continuous in a region with smooth boundaries, the solution to TIE is unique. That is, the phase can be uniquely determined by solving TIE with $I(x,y)$ and $\partial I(x,y)/\partial z$. Experimentally, the intensity is easy to obtain and the intensity derivative is estimated by finite differences between two close separated images. Then the phase can be obtained by solving the TIE by treating it as a modified Poisson equation or expanding it into a complete set of Zernike polynomials.

## 3 Results Analysis and Comparison

Two samples: a regular array of micro-bumps fabricated on Si substrate based on laser induced non-ablative texturing and a refractive quartz microlens array from SUSS MicroOptics were tested by DH and TIE (using ordinary bright field microscope). The results are shown in Fig. 1. For both transmission and reflection samples, the focus stacks used for TIE (a, f), off-axis holograms (b, g), the phases recovered by TIE (c, h) and DH (d, i) are shown. For better quantitative analysis, the plot along a typical line across the samples (e, j) was shown as well. Good overall agreement is seen at the first glance. It should be note that the phase recovered by TIE is continuous, without $2\pi$ jumps [2], and the phase displayed is digitally rewrapped for better comparison. No need for unwrapping is an advantageous feature of TIE, but remember that it does not mean TIE could eliminate the $2\pi$ ambiguous problem since it inherently assumes the phase is continuous. A small tilt in background can be observed in Fig. 1(d) because of the off-axis carrier is not completely removed during the spectrum centering process. A low spatial frequency non-uniformity is also noticed in TIE results, even with regularization and boundary treatments. Bearing in mind that a brutal application of the TIE algorithm without caring about problems in the solution of the TIE, the influence of noise, and boundary conditions may lead to an unusable result, which is most likely the ones shown in Fig. 2. Another difference visible is the TIE seems to generate a smoother and less noisy result than DH. One important reason for this is TIE uses partially coherent light while DH uses laser so suffers from the laser speckle noise. From the technique itself, some factors may also affect the phase resolution and noise, e.g. in DH, using smaller filtering window can improve the smoothness while reduce phase resolution. In TIE, similar smoothing effects also exist implicitly but the contributing factors are much more complex.

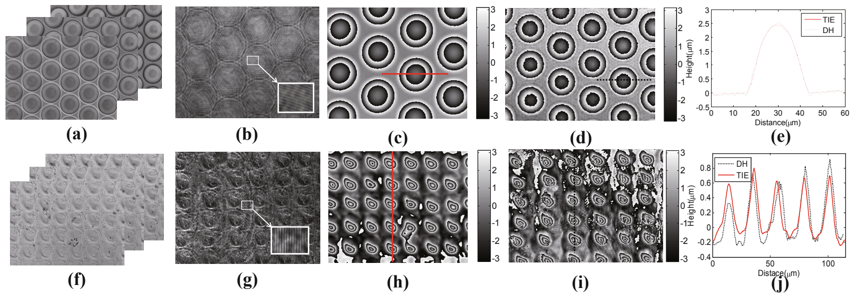

**Fig. 1** Experimental comparison of TIE and DH

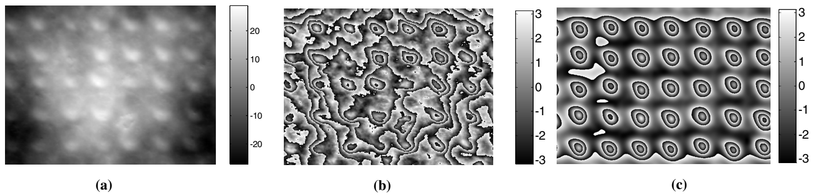

**Fig. 2** Experimental results as examples when TIE is not properly used

## 4 Advantages, Limitations and Improvements

The real strength of the off-axis DH is that it can obtain the phase map from single exposure, so the camera itself only limits the acquisition rate. Besides, if the camera quantization effect is the only quantity that limits phase measurement, the phase measurement resolution is less than $\pi/100$. However, this theoretical axial resolution cannot be achieved since there are many other factors that may cause errors between the original object wavefront and the reconstructed object wavefront [4]. In off-axis DH, a carrier frequency is introduced and spatial filtering is required, which of course has adverse effect on the phase spatial resolution. Theoretically, if an objective is used and the magnification is chosen in such a way that the smallest imaged structures pass the Abbe criterion and are adequately represented by the image-recording device, this problem can be avoid. However, practically it is quite difficult to achieve such high phase resolution because of the speckle produced by the impurities on the optics and parasitic reflections from the various surface in the system. The coherent noise is a major impediment to achieve a high-quality quantitative phase map. The only two ways to alleviate the problem of coherent noise is 1) using minimum optical elements and keep them pristine. 2) decreasing the coherence length of the illumination source (e.g. the compact digital holoscope shown in Fig. 3(a) contains only single beam splitter and uses low-coherent laser diode). Another notorious error source in DH is phase aberration, i.e. the difference in the curvatures between the experimental reference beam and the idealized numerical reconstruction beam. The phase aberration can be physically compensated by introducing a curvature-matching objective lens or a position-adjustable lens, though a precise alignment of all the involved optical elements are required [5]. Alternatively, numerical phase aberration compensation needs to be applied during the holographic reconstruction procedure [6]. Finally, another important factor for studying dynamic phenomena using DH is the temporal stability. Since DH is based on two-beam interference, air fluctuations, mechanical vibrations of optical components may affect the stability and reproducibility of the DH system. Using a common path configuration [7] can compensate effectively the optical path difference (OPD) due to mechanical vibrations and the phase curvature aberration can be automatically cancelled (Fig. 3(b)).

The greatest strength of TIE is its non-interferometric nature, which makes phase reconstruction possible with partially coherent beam from ordinary microscopes. Benefiting from the Köhler illumination and the aberration-optimized optics in a commercial microscope, the diffraction limited intensity images with spatial uniformity can be easily obtained. Besides, it is inherently common path, which ensures stability. However, the TIE method is not trouble free. Quite different from the DH, wherein the phase is encoded in sinusoidal fringes (therefore the relation between captured intensity and phase is linear to a certain degree), in TIE, the phase is determined solely by the intensity distribution and longitudinal intensity derivative (estimated by finite difference). Actually, considering the object with a uniform amplitude distribution for simplicity, the phase is directly related to the defocused intensity, wherein the phase contrast increases quadratically with the phase spatial frequency [8]. Because of the lower amplification of low-frequency phase structure in the free-space propagation, the TIE is very sensitive to errors in the low-frequency components of the intensity data, especially when the defocus distance is chosen too small (see examples shown in Figs. 2(a-b)). Experimentally, using a larger defocus distance can increase the low spatial frequency signal over the noise in the intensity difference, and thus helpful to reduce the cloud-like low frequency artifacts. Nevertheless, the breakdown of the linear approximation in the derivative estimation induces nonlinear errors and reduces the phase resolution (see Fig. 2(c)) [9]. To obtain a compromise between nonlinearity error and the low-frequency noise, there exists an optimal defocus distance which is dependent on both the maximum physically significant frequency of the object and the noise level. Nevertheless, the knowledge of these two aspects is not known in advance. The contradiction can be solved by using more intensities captured at different defocus distances [10], but extra intensity measurements prolong the acquisition time. Another issue in TIE is it must be solved with appropriate boundary conditions. The FFT-based Poisson method provide simple and fast numerical solution, but it implies periodic boundary conditions for the object, which is often in contradiction to the experiment, leading to the artifacts at the image boundaries. Finally, to acquire the images with slight defocus, either the camera or the object has to be manually or mechanically translated, which inevitably slows down the acquisition speed and thereby limits its applicability to static objects. To address this difficulty, we presented two novel experimental setup for TIE based on a tunable lens or SLM, which can yield high-speed, real-time TIE phase imaging without any manual or mechanical operation (Figs. 3(c) and (d)).

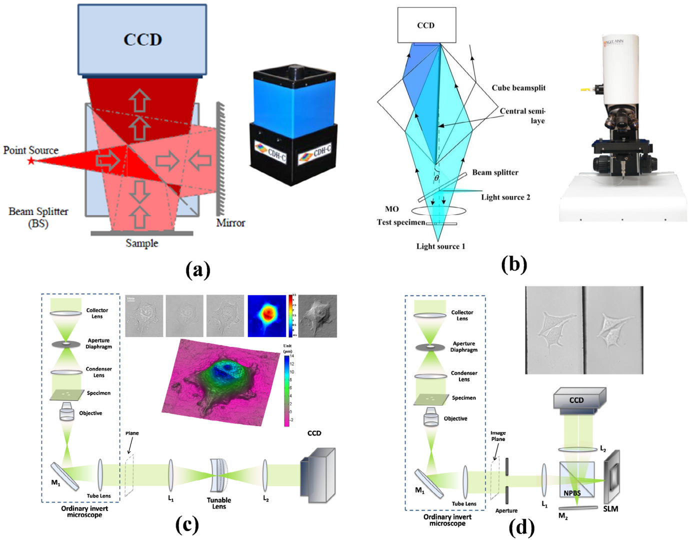

**Fig. 3** (a) Compact digital holoscope. (b) Common-path digital holoscope. (c) Tunable lens TIE system. (d) Single-shot TIE system based on SLM.

## 5 Conclusions and Discussions

Partially coherent imaging is more difficult to analyze since its transfer function is actually four-dimensional. However, by imposing some assumptions on the illumination and for small propagation distance, it can then be simplified to two-dimension. Of course, TIE also works under coherent illumination, as a deterministic phase retrieval method. By introducing TIE to DH, the continuous phase map can be directly obtained by using intensity images reconstructed from DH. Meanwhile, the tilt and quadratic phase aberration can be effectively eliminated.

Despite a relatively short history, DH has demonstrate its effectiveness and gained exponentially increased applications not only in optical physics and engineering, but also in diverse areas such as microbiology, medicine, particle analysis, MEMS and microsystem metrology. Phase imaging using the TIE has also gained increasing attention recently. Admittedly, limitations of the TIE technique (in particular, the high sensitivity to low frequency noise, the effect of coherence and defocus distance, proper treatment of boundary conditions) remain challenging problems. Nevertheless, TIE still shows its unique advantages and demonstrates it is really a competing and alternative method to DH rather than just being a complementary technique for phase retrieval where DH cannot be employed.

This project was supported by the Research Fund for the Doctoral Program of Ministry of Education of China (No. 20123219110016). Chao Zuo gratefully acknowledges the financial support from China Scholarship Council.

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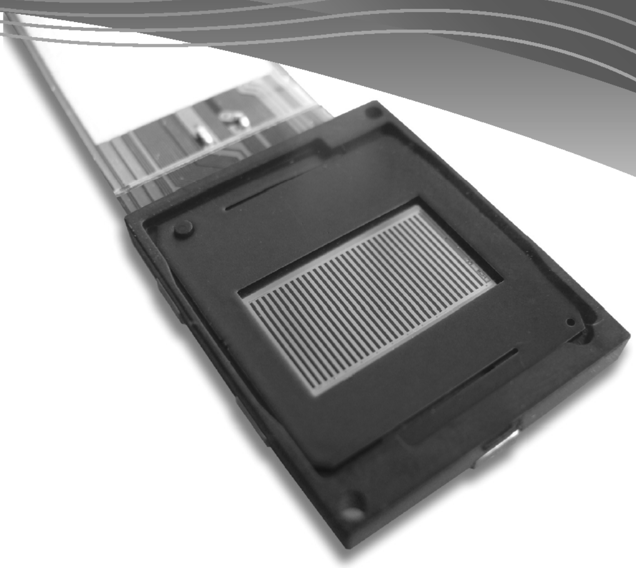
# Appendix

## New Products



HOLOEYE
LCOS Microdisplays for Fringe-Projection Systems

The application of high resolution cameras require high resolution fringe projection systems. HOLOEYE offers a wide range of microdisplays with resolutions up to 1920x1080 (HDTV) pixel. Panel sizes range from 1.8“ down to 0.177”. Even microdisplays with high frame rates up to 180 Hz are available.
Besides exact pixel addressing HOLOEYE´s microdisplay panel solutions can provide high contrast and high brightness due to the reflective surface of LCOS microdisplays and a precise grayscale resolution and gama correction for sinusoidal projections with exact defined slope are possible.

HOLOEYE Pioneers in Photonic Technology

HOLOEYE Photonics AG / Albert-Einstein-Str. 14 / 12489 Berlin / Germany
Phone +49 (0)30 63 92 36 60 / Fax +49 (0)30 63 92 36 62 / contact@holoeye.com / www.holoeye.com

HOLOEYE
Spatial Light Modulators

HOLOEYE's offers the greatest variety of Spatial Light Modulators (SLM) for phase and amplitude modulation. These SLM devices are based on translucent or reflective liquid crystal microdisplays. The optical function or information to be displayed can be taken directly from the optic design software or an image source and can be transferred by a computer interface.

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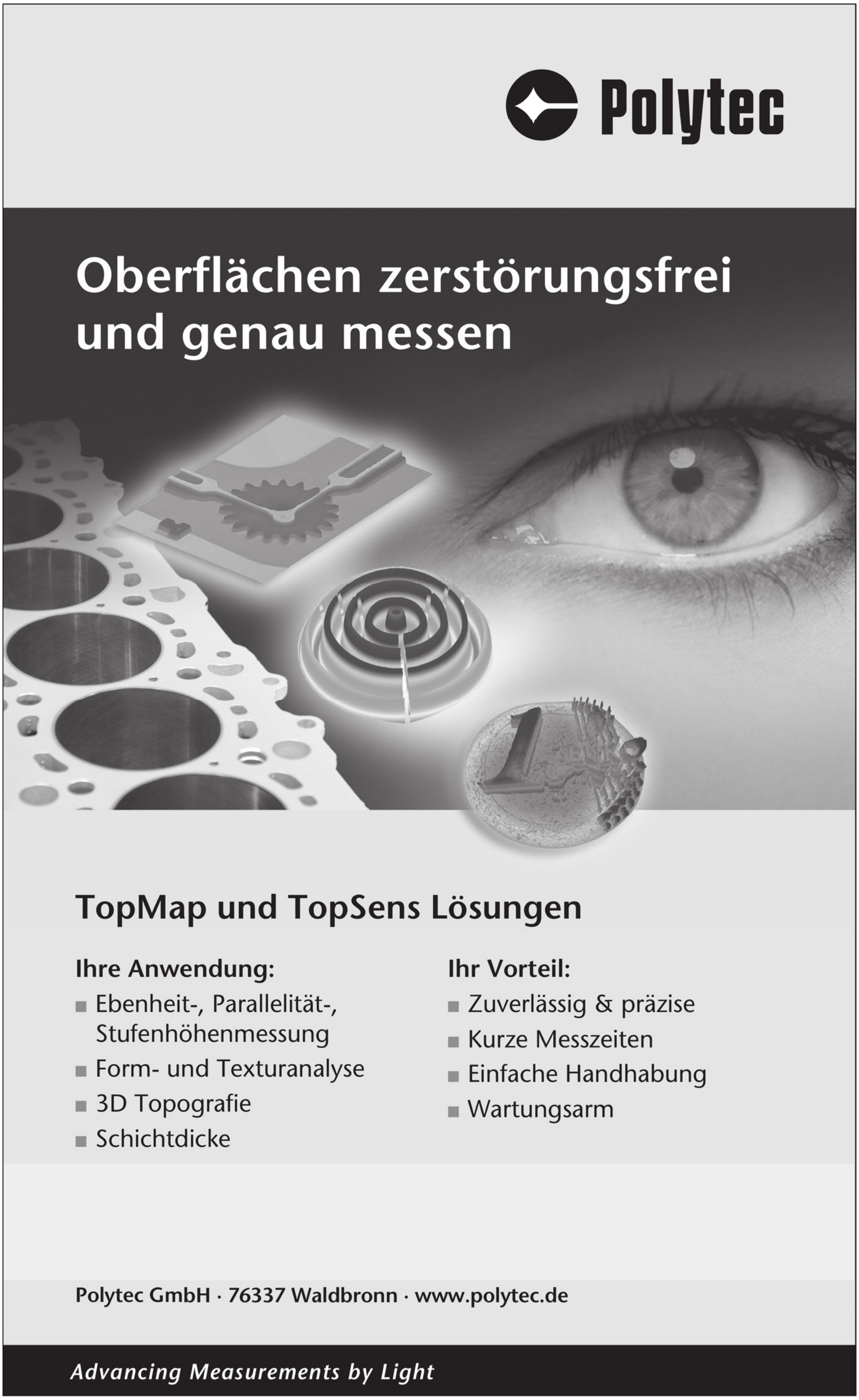

Polytec

Oberflächen zerstörungsfrei und genau messen

**TopMap und TopSens Lösungen**

**Ihre Anwendung:**
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- 3D Topografie
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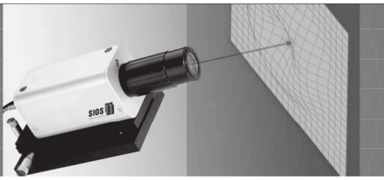
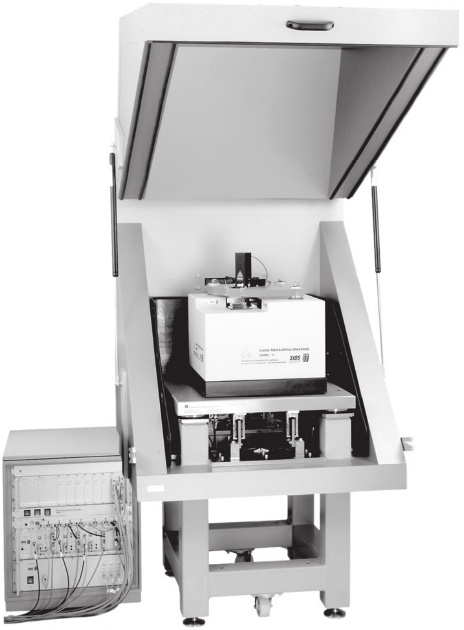
*Advancing Measurements by Light*

SIOS



Precision in
Measurements

NANOPOSITIONING AND NANOMEASURING MACHINE
NMM-1



The Nanopositioning and Nanomeasuring Machine NMM-1 allows the positioning, manipulation, processing and measurement of objects in the fields of micromechanics, microelectronics, optics, molecular biology genetics and microsystems engineering with a resolution of

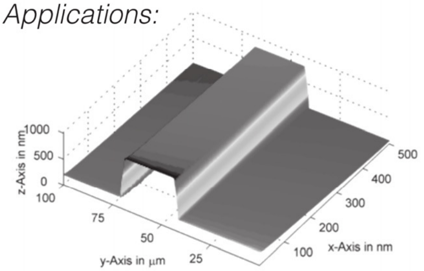
0,1 nm

in a measuring range of

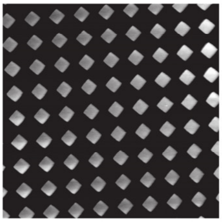
25 mm x 25 mm x 5 mm

Various probe systems can be implemented, e.g. Scanning Probe Microscopes, Atomic Force Microscopes, Autofocus and Fixfocus Systems, White Light Interferometers, capacitive and inductive 3D probe systems.

Applications:



Step height calibration



Pitch calibration

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# Author Index

Agarwal, Shilpi 547
Agour, Mostafa 283
Aguayo, Daniel D. 515
Aguilar, Alberto 275
Albero, Jorge 57
Albertazzi, Armando 191
Alexeenko, Igor 917, 951
Almoro, Percival 247
Alonso, Miguel A. 457
Anand, Asundi 847
Andreas, Birk 887
Angelsky, Oleg V. 551, 629
Angelsky, Pavlo 641
Aprin, Laurent 203
Ares, Miguel 899
Ashcroft, Ian 161
Asundi, Anand 137

Babovsky, Holger 149, 875
Bach, Carlo 221
Badami, Vivek G. 785
Baer, Goran Bastian 87, 349, 701
Bai, Benfeng 49
Baldjiev, Angel Georgiev 519
Barański, Maciej 623
Barbosa, Henrique Coelho 451
Bartl, Guido 267, 539, 863
Becken, Wolfgang 301
Beichert, Günter 241
Benedet Mauro E. 191
Berberova, Natalia 831, 883
Berger, Andreas 309
Bergmann, Detlef 35
Bergmann, Ralf B. 283, 729
Bergström, Per 103
Bespalov, Victor 321
Beyer, Vivien 329
Bianco, Vittorio 305, 911
Bieger, Heiko 957
Bioucas-Dias, José 179
Bizer, Liliya I. 855
Blattmann, Marc 947
Bodermann, Bernd 35, 695
Bodnar, Olena B. 855
Boedecker, Sebastian 485
Bosse, Harald 35
Böttner, Thomas 241
Braga, Roberto Alves 451
Bräuer-Burchardt, Christian 229
Braun, Kai 791
Brenner, Karl-Heinz 117, 233
Broistedt, Hagen 417
Brundavanam, Maruthi Manoj 611
Bryanston-Cross, Peter John 585
Buchta, Zdeněk 645
Burlison, Bona S.H. 325

Campderrós, Laia 899
Campo, Adriaan 527
Campos, Juan 297, 563
Carl, Daniel 479
Chen, Jun 815
Chen, Mingyi 847
Chen, Ni 337
Chen, Qian 137
Chen, Zhenning 929
Cheng, Jeffrey Tao 599, 657
Číp, Ondřej 645, 839, 891

Claus, Daniel 689
Coene, Wim M.J. 399, 591
Cossairt, Oliver 663
Cottrell, Don M. 57
Coupland, Jeremy 63, 405
Czarske, Jürgen W. 773

da Fonseca, Ellem Walleska N. 451
Dai, Gaoliang 695
Danzl, Reinhard 617
Dasallas, Lean 247
Dávila, Abundio 275
Davis, Jeffrey A. 57
De Greef, Daniel 433
de Groot, Peter J. 785
Diener, Alexander 695
Ding, Yabin 821
Dirckx, Joris J.J. 433, 507, 527
Dobrev, Ivo 657
Doleček, Roman 577, 635
Dontsov, Denis 559
Doval, Ángel F. 173, 567
Doyle, Dominic 921
Drabarek, Pawel 747
Dubois, Frank 921
Dubolazov, Alexander V. 855
Dudek, Michal 671

Ehret, Gerd 729, 887, 903
El Gawhary, Omar 591
Elshaffey, Khaled 283
Elster, Clemens 701
Endres, Johannes 695
Escoto, Esmerando 247
Esser, Gregor 301
Estacio, Elmer 247
Ettemeyer, Andreas 221
Ettl, Svenja 895

Faber, Christian 895, 907
Fahlbusch, Thomas 241
Falaggis, Konstantinos 129, 653
Falldorf, Claas 283, 729
Fantin, Analucia V. 191
Faridian, Ahmad 595
Fejfar, Antonín 891
Felgner, André 485
Feng, Shaotong 439
Fernández, José L. 173, 567
Ferraro, Pietro 305, 555, 911
Ferreras Paz, Valeriano 345
Finizio, Andrea 305, 555, 911
Fischer, Marc 573
Fleischer, Matthias 747
Flügge, Jens 35
Fontán, Lidia M. 173, 567
Fortmeier, Ines 701
Franz, Gerald 747
Fratz, Markus 479
Frenner, Karsten 345, 361
Fu, Liwei 361
Fu, Sihua 871
Fu, Yu 767
Furlong, Cosme 599, 657

Gao, Jianxin 217
Gao, Peng 369
Gao, Zhishan 761
Ge, Dongbao 847
Geckeler, Ralf D. 887
Georges, Marc 237, 917, 921
Giusca, Claudiu 405
González Ballester, Miguel A. 899
Goodman, Joseph W. 3
Gorecki, Christophe 623
Grabner, Markus 617
Gronle, Marc 711, 957
Gross, Hermann 695
Große, Marcus 683, 875
Grotz, Bernhard 605
Günther, Philipp 773
Guo, Min 767
Gurov, Igor P. 313

Hæggström, Edward 491
Haist, Tobias 365
Hällstig, Emil 103
Hanemann, Markus 875
Hankin, Yan 943
Hao, Hongxing 179
Harder, Irina 309
Harendt, Bastian 683
Härtling, Thomas 271
Hasegawa, Masanobu 385
Hasler, Malte 365
Häßler-Grohne, Wolfgang 35
Häusler, Gerd 895, 907
He, Dong 511, 821
He, Xiaoyuan 929

Heikkinen, Ville Vili 491
Hein, Niclas 721, 951
Heist, Stefan 229, 835
Helmli, Franz 617
Henn, Mark-Alexander 695
Henning, Andrew 405
Herkommer, Alois 373, 947
Herzig, Hans Peter 797
Heshmat, Samia 155
Heymes, Frédéric 203
Holá, Miroslava 645, 839, 891
Honda, Tokuyuki 385
Hong, Sunghee 851
Horgan, Graham William 451
Hrabina, Jan 645, 839, 891
Huntley, Jonathan M. 161, 325
Hwang, Chi-Hung 341

Iannone, Maria 555
Ichikawa, Yoshinori 385
Ishii, Yukihiro 815
Ivanov, Branimir 831, 883

Janz, Alexej 531
Jiang, Guangwen 871
Jin, Guofan 49
Jorge, Iagoba 917
Joseph, Joby 255, 279
Józwik, Michał 129, 623
Junker, André 117

Kang, Hoonjong 803, 831, 851, 883
Karachevtsev, Artem O. 855
Kassamakov, Ivan 491
Kästner, Markus 735
Katkovnik, Vladimir 179
Kato, Seima 385
Kelly, Damien P. 123, 213, 289
Kelly, Kevin F. 109
Kemper, Björn 671
Khaleghi, Morteza 599
Khan, Gufran Sayeed 523
Khare, Kedar 255
Khodadad, Davood 103
Kießling, Armin 149, 875
Kim, Myun-Sik 797
Kim, Taegeun 803
Kim, Youngmin 851
Kim, You Seok 803
Kimbrough, Bradley 97
Kiyohara, Kosuke 815
Kleiner, Bernhard 809
Knell, Holger 903
Kohara, Naoki 385
Kohler, Christian 957
Koliopoulos, Chris L. 753
Kočka, Jan 891
Köning, Rainer 35
Kornis, János 333
Kostencka, Julianna 671
Kowarschik, Richard 149, 683, 875
Kozacki, Tomasz 129, 623, 671
Krauze, Wojciech 671
Krekel, Christoph 721, 951
Krobot, Roman 907
Krüger-Sehm, Rolf 485
Krystek, Michael 267
Küchel, Michael F. 71
Kühmstedt, Peter 229, 809, 835
Kühnhold, Peter 903
Kujawińska, Malgorzata 129
Kujawinska, Malgorzata 671
Kumar, Manoj 497, 523, 547
Kumar, N. 43
Kumar, Nitish 591
Kumar, Varun 497, 523, 547
Kuś, Arkadiusz 129
Kus, Arkadiusz 671
Kuschmierz, Robert 773

Landgrave, Enrique 275
Langlotz, Enrico 559
Lassila, Antti 491
Laubach, Sören 903
Lazar, Josef 645, 839, 891
Leach, Richard 405
Leclercq, Mathieu 263
Lédl, Vít 577, 635
Lee, Byoungho 337
Lee, Tim K. 933
Lehmann, Peter 677, 903
Li, Ameng 821
Li, Dayan 289
Li, Lifeng 827
Li, Yun 109
Lindlein, Norbert 309
Linz-Dittrich, Sabine 221
Liu, Cong 929
Liu, Huan 767

Liu, Xiaochun 871
Liu, Xiaoli 821
Liu, Xiaolin 871
Liu, Xingming 821
Liu, Xiyuan 233
Lizana, Ángel 563
Liżewski, Kamil 623
Locatelli, Massimiliano 911
Lopez, Ion 917
López-Vázquez, J. Carlos 173, 567
Lui, Harvey 933
Lukaszewski, Dariusz 707
Lyda, Wolfram 465, 711, 957

Ma, Jun 439, 761
Mai, Torsten 863
Maia, Allison F. 191
Maksimyak, Andrew P. 551, 629
Maksimyak, Peter P. 543, 551, 629
Malek, Mokrane 741
Mantel, Klaus 309, 393
Marín, Pablo 563
Martínez, José Luis 297
Mauch, Florian 465
McLean, David I. 933
Megel, Lysann 123, 213
Mehta, Dalip Singh 581
Meinecke, Thomas 123, 213
Meiners-Hagen, Karl 843
Meixner, Alfred J. 791
Memmolo, Pasquale 305, 555
Mendoza-Santoyo, Fernando 515
Meniño, José L. 567
Meucci, Riccardo 911
Miccio, Lisa 555, 911
Mihaljevic, Josip 791
Mitra, Kaushik 663
Miyamoto, Yoko 611
Moore, Andrew J. 329, 867
Mora-Gonzalez, Miguel 563
Morawitz, M. 951
Moreno, Ignacio 57
Muldera, Joselito 247
Müller, Werner 301
Munkelt, Christoph 809
Murakami, Katsuhiko 385

Naik, Dinesh Narayana 377, 715
Nakagawa, Ken'ichi 611
Nalegaev, Sergey 321
Naughton, Thomas J. 649
Nawsasra, Jo 585
Nehrych, Andrey 543
Nercissian, Vanusch 309
Netti, Paolo Antonio 555
Nguyen, Thi-Dinh 867
Nguyen, Truong Tho 161
Nicolas, Josep 297
Nicolaus, R. Arnold 267, 423, 863
Niehues, Jan 677
Nishiyama, Shusuke 155
Nolvi, Anton 491
Notni, Gunther 229, 809, 835

Ohrt, Christoph 735
Olesch, Evelyn 907
Osten, Wolfgang 87, 345, 349, 355, 361, 365, 369, 377, 465, 595, 701, 711, 715, 879, 917, 951, 957
Otaki, Katsura 385
Ouchi, Chidane 385
Oulehla, Jindřich 645, 891

Pakula, Anna 293, 925
Panyella, David 899
Pape, Christian 531
Park, Joo-Sup 883
Partanen, Henri Simo 879
Patorski, Krzysztof 185, 225, 317
Paturzo, Melania 305, 555, 911
Paulin, Tor 491
Pavliček, Pavel 411
Peacock, John 507
Pedrini, Giancarlo 369, 377, 595, 715, 917, 951
Peinado, Alba 563
Pelagotti, Anna 911
Peng, Junzheng 847
Peng, Xiang 511, 821
Pereira, S.F. 43
Pereira, Silvania F. 591
Pérez, Frederic 899
Peter, Andreas 863
Peterhänsel, Sandy 355, 879
Petrov, Nikolay 321
Petz, Marcus 573
Picart, Pascal 203, 263, 741
Pierron, Fabrice 161
Pintelon, Rik 507

Pinto, Jesus E. 515
Pitkäaho, Tomi 649
Poggi, Pasquale 911
Pokorski, Krzysztof 225
Pollinger, Florian 843
Poon, Ting-Chung 803
Pösch, Andreas 735
Prantl, Manfred 617
Prellinger, Günther 843
Pruss, Christof 87, 355, 701, 879
Pruß, Christof 349
Pryputniewicz, Ryszard J. 471
Psota, Pavel 577, 635
Pugliese, Eugenio 911

Quabis, Susanne 887
Quast, Tatjana 539
Queeckers, Patrick 921

Rau, Katharina 859
Rausch, Denise 373
Rayas, Juan A. 515
Reingand, Nadya 943
Reithmeier, Eduard 531, 735
Rembe, Christian 485
Ri, Shien 209
Risso, Murilo 451
Rochet, Jonathan 917
Rodenburg, John M. 689
Rodríguez-Gómez, Pablo 173
Rodriguez-Vera, Ramon 515
Rosowski, John J. 599, 657
Rothau, Sergej 309
Roy, S. 43
Roy, Sarathi 591
Royo, Santiago 899
Ruiz, Pablo D. 161, 325

Sachs, Robert 535
Sainov, Ventseslav Christov 519
Sakhnovskiy, Mikhail Yu. 855
Salbut, Leszek 293, 707, 925
Samsheerali, P.T. 255
Sarbort, Martin 839
Schaffer, Martin 683
Scharf, Toralf 797
Schindler, Johannes 87, 349
Schmitt, Robert 445
Schöch, Alexander 221
Schödel, René 539, 859
Scholze, Frank 695
Schott, Walter 559
Schulz, Michael 701, 729, 887
Schwider, Johannes 393
Seewig, Jörg 241
Seifert, Andreas 947
Senthilkumaran, Paramasivam 279
Seppä, Jeremias 491
Shakher, Chandra 497, 523, 547
Shang, Yang 871
Sharma, Manoj Kumar 279
Sharma, Shobhna 497, 547
Shen, Ming-Hsing 341
Sheridan, John T. 289
Sherlock, Ben 405
Sieler, Marcel 835
Silva, Lucas Tiago 451
Simic, Aleksandar 729
Singh, Alok Kumar 377
Sinzinger, Stefan 123, 213
Sjödahl, Mikael 103
Skowranek, Heide 721
Slangen, Pierre 203
Soares, Rodrigo Reis 451
Soltys, Iryna 641
Song, Wenchuan 503
Srivastava, Vishal 581
Stanzel, Frank 535
Stark, Andreas 149
Stavridis, Manuel 701
Stenau, Tim 117
Stetson, Karl A. 197
Stockman, Yvan 921
Stoykova, Elena 831, 851, 883
Stuchlík, Jiří 891
Stürwald, Stephan 445
Sugisaki, Katsumi 385
Sun, Ting 109

Takeda, Mitsuo 143, 377, 385, 611, 715
Tan, Qiaofeng 49
Tang, Chen 251
Tchvialeva, Lioudmila 933
Tereschenko, Stanislav 677
Tervo, Jani 25, 879
Thiele, Simon 947
Thizy, Cédric 917, 921
Timmerman, Brenda H. 585
Tokunaga, Eiji 815

Tomczewski, Slawomir 925
Tomioka, Satoshi 155
Torhallsson, Torfi 809
Tornari, Vivi 937
Torner, Francoise 241
Towers, Catherine E. 653
Towers, David P. 653
Trillo, Cristina 173, 567
Trumm, Stephan 301
Trusiak, Maciej 185
Tsuda, Hiroshi 209
Turunen, Jari 25, 879
Tutsch, Rainer 417, 573
Tyc, Tomáš 17

Urbach, H.P. 43
Urbach, H. Paul 591
Ushenko, Yuriy A. 855

Valera, J.D. 867
Vandenrijt, Jean-François 237, 917, 921
van Haver, Sven 399
Veeraraghavan, Ashok 663
Venegas, Pablo 917
Ventre, Maurizio 555
Vera, Sergio 899
Vidal, Jordi 899
Viotti, Matias 191
Vít, Tomáš 577
Voelkel, Reinhard 797
Vollheim, Birgit 917
Volynsky, Maxim 313
von Kopylow, Christoph 283, 729

Wang, Meng 511
Wang, Wei 329
Wang, Wei-Chung 341
Wang, Xiao 791
Weigel, Daniel 149
Wiegmann, Axel 701
Wielgus, Maciej 185, 317
Wilke, Marc 951, 957
Willemann, Daniel P. 191
Willomitzer, Florian 895
Woo, Sung-soo 803, 831
Wrachtrup, Jörg 605
Wu, Gaofeng 503
Wu, Yongqian 503
Wurm, Matthias 695

Xu, Jiancheng 217
Xu, Lina 109
Xu, Ninghan 49
Xu, Yingjun 767
Xu, Yong 871

Yamaguchi, Ichirou 257
Yan, Haiqing 251
Yan, Keyu 767
Yan, Si 251
Yatagai, Toyohiko 167
Ye, Jiwang 821
Yeom, Jiwoon 337
Yin, Yongkai 511, 821
Yoshikawa, Hiroshi 851
Yu, Qifeng 871
Yu, Yingjie 847
Yuan, Caojin 439
Yuan, Qun 761
Yukita, Shunpei 815

Zappe, Hans 947
Zeh, Christoph 271
Zeng, Haishan 933
Zeng, Lijiang 827
Zeng, Zhaoli 779
Zenkova, Claudia Yu 629
Zenkova, Claudia Yuriivna 641
Zhang, Dai 791
Zhang, Shulian 779
Zhao, Wenchuan 503
Zhou, Changhe 803
Zhu, Rihong 761
Zhu, Xianwei 871
Zhu, Xinjun 251
Zhu, Yucong 385
Zuber, Ralf 907
Zuo, Chao 137