Proceedings of the
Second Annual Meeting of the
Smart Optics Systems Programme

Preface

The Smart Optics Systems (SOS) program started under the sponsorship by the Dutch National Science Foundation STW in 2008. It aims at making the use of optical components, such as deformable mirrors, wavefront sensors, etc. acceptable on a wide industrial scale. The program aims at achieving this goal in two ways. First, it aims at developing technology for a dramatic improvement in the quality of optical instruments. Second, it will result in a new and optimized integrated design that will allow for true integration of smart optics into the next generation of imaging equipment.

In such integrated design approach, taking into consideration from the onset of the design of the imaging equipment the capabilities of e.g. feedback control has the potential of revolutionizing the overall design. Such integrated approach may lead to similar breakthroughs as was manifested in the last century by the development of operational amplifier. Here feedback control enabled the production of high performance components from low quality and low cost physical open-loop components.

In addition to the methodological improvement anticipated by the program, the goal of integration and stimulating multidisciplinary research is pursued by two organizational manners. First there is the definition of six multi-disciplinary research projects where researchers with a different technological expertise work intensively together on a common imaging demonstrator. A second way to disseminate the knowledge and the experience between the researchers actively involved in the program on one hand and between these researchers and external experts on the other hand is enabled by the organization of program meetings on an annual basis.

These proceedings presents the activity report of the second annual meeting of the Smart Optics Systems STW perspective Program. In the proceedings the progress on the following six projects is reported:

1. Integrated High-resolution Observing through Turbulence
2. Smart Microscopy of Biological Tissues
3. Integrated Smart Microscopy
4. Waveguide-based External Cavity Semiconductor Laser
5. Smart Multilayer Interactive Optics for Lithography at Extreme UV wavelengths
6. Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems

For the second annual meeting we are proud to announce that Dr. Samuel Bucourt âĂŞ CFO of Imagine Optics will give a keynote presentation on *"Imagine Optic: story and success; Adaptive optics in France: overview"*.

For this second annual meeting we have foreseen a full exposure of all running projects. Since most of these projects are in their second year, interesting and innovative results will be presented. This means that also the temporary researchers have reached a degree of maturity so that we can expect interesting discussion that will stimulate interaction and cross-fertilization.

The program as a whole has been presented at different location. One was the recent Workshop on Adaptive Optics in Industry and Medicine in Murcia, Spain, June 2011. A copy of that keynote presentation is enclosed in the appendix.

The second annual meeting is held in Delft on September 12th, 2011.

On behalf of the organization committee, I can indicate that we look forward towards an interesting day of discussion, exchange of ideas and stimulation towards future new and bright ideas.

Prof. Michel Verhaegen
Program Leader SOS

Contents

Program

Morning sessions

Time:	Project:	Speaker:
8.30	Welcome with coffee/thee	
9.00	Opening of the day	Prof. Michel Verhaegen
	Keynote lecture	
9.05	Imagine Optic: story and success;	Dr. Samuel Bucourt
	Adaptive optics in France: overview	CEO Imagine Optic
Project:	Integrated Smart Microscopy	
10.00	All-in-focus wide field microscopy using time-avarage	Darko Simonovic
	shaping of point spread function	
10.30	Correction of Coverslip Mismatch via Image Quality Measures	Hans Yoo
11.00	Coffee/Tea break	
Project:	Smart Microscopy Biological Tissues	
11.15	Smart microscopy — Phase-shifting interferometric	Tim van Werkhoven
	wavefront sensing	
11.45	Data driven identification and aberration correction	Jacopo Antonello
	for model based sensorless adaptive optics	
12.15	Lunch	

Afternoon sessions

Time:	Project:	Speaker:
Project:	Integrated High-Res. Observation through Turbulence	
13.15	Joint optimization of phase-diversity and adaptive optics: demonstration of potential	Visa Korkiakoski
13.45	Bilinear phase diversity for extended objects	Raluca Andrei
Project:	Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems	
14.15	Deterministic Reticle Clamping	Geert-Jan Naaijkens
14.45	Mode shape excitation measurement with sub-nanometer precision	Johan Vogel
15.15	Distributed control of wafer deformations in photolithography systems	Ruxandra Mustata
15.45	Coffee/Tea break	
Project:	Smart Multilayer Interactive Optics for Lithography at Extreme UV wavelengths	
16.00	Reflectance Tuning at Extreme Ultraviolet Wavelengths with Active Multilayer Mirrors	Muharrem Bayraktar
Project:	Waveguide-based External Cavity Semiconductor Laser arrays	
16.30	Waveguide-based External Cavity Semiconductor Lasers	Ruud Oldenbeuving
17.00	Model-based wavelength estimation with tunable color filter and single photodiode	Michel Verhaegen
17.30	Announcements	
17.45	Drinks	

Keynote lecture

Samuel Bucourt
Imagine Optic: story and success — Adaptive optics in France: overview

Dr. Samuel Bucourt
President and CEO
Imagine Optic
18 rue Charles de Gaulle
Orsay France 91400
+33 (0)1 64 86 15 60
sbucourt@imagine-optic.com
http://www.imagine-optic.com

Soon after his first experience as an engineer at Le Conoscope, **Samuel Bucourt** became an entrepreneur, co-founding Imagine Optic in association with Xavier Levecq in 1996. In the five short years following the debut of their endeavor, their company had already become an international leader as a provider of optical wavefront sensors. Samuel brings solid expertise in corporate management to Imagine Eyes including sales-force organization, finance, strategic and business development, and growth management.

Imagine Optic is one of the world's leading providers of Shack-Hartmann wavefront sensing hardware and software, adaptive optics technologies and professional services in applied optics. Imagine Optic works with scientists and industrials in domains including pure science, industrial quality control, space and defense, semiconductors and many others. Since 1996, Imagine Optic has been supplying industry leaders around the world with the high-quality products and services that they need to perform.

From X-EUV, through the visible light spectrum and on to NIR (near infra-red), Imagine Optic develops, manufactures, distributes and supports the largest range of wavefront measurement and correction technologies available.

Integrated Smart Microscopy

Applicants:	Prof. Paddy French (TU Delft) (project leader) Dr. Gleb Vdovin (TU Delft / Flexible Optical BV) Prof. Michel Verhaegen (TU Delft) Prof. Lina Sarro (TU Delft) Dr. Georg Schitter (TU Delft) Prof. Wiro Niessen (TU Delft / Erasmus MC, Rotterdam) Dr. Erik Meijering (Erasmus MC, Rotterdam) Dr. Adriaan Houtsmuller (Erasmus MC, Rotterdam) Dr. Gert van Cappellen (Erasmus MC, Rotterdam)
Researchers:	Dr. Martin van Royen (Erasmus MC, Rotterdam) Dr. Ihor Smal (Erasmus MC, Rotterdam) Hans Yoo (TU Delft)
Budget:	1000k€

Project outline

Optical microscopy and fluorescent labeling technologies have gone through impressive progress in the past decades and have provided powerful instruments for biomedical research. Especially the availability of a large variety of fluorescent proteins, including photoactivatable and -switchable mutants, has revolutionized live cell imaging. Quantitative investigation of the molecular mechanisms responsible for normal biological function of living cells and organisms, but also aberrant processes in diseases such as cancer, Alzheimer's, and Parkinson's, requires very precise localization of active factors inside subcellular organelles, as well as the structure and dynamics of active chromatin sites inside the cell nucleus. For such studies, the resolution of commercially available optical (confocal) microscopy systems is a very limiting factor. In a practical setting, the loss of performance compared to theoretical values is largely due to the mismatch between the refractive index of the specimen. Especially in a confocal setup, this mismatch increases with increasing depth of penetration into the specimen. Microscope systems available today are generally based on fixed optical setups, and are unable to correct for dynamic, higher-order wavefront aberrations due to distortions in the optical path, or manufacturing inaccuracies. Smart optics and control systems have a high potential to serve as enabling technologies to address this problem. Therefore, the aim of this multidisciplinary project is to develop and evaluate an integrated smart confocal microscoppe for live cell imaging, which combines adaptive optics in the imaging path with adaptive postprocessing of the resulting 3D image data. This requires optical systems research (design and integration of adaptive optics components), control systems research (real-time control for improved scanning, active compensation, and adaptive optics), image processing research (adaptive filtering, deconvolution, detection, and tracking), and biomedical research (evaluation of the new system by application to biomedically relevant problems).

All-in-focus wide field microscopy using time-avarage

Darko Simonovic
Delft University of Technology
Electronic Instrumentation
Mekelweg 4, 2628 CD, Delft, The Netherlands
d.simonovic@tudelft.nl

Abstract

Depth of focus in fluorescence and bright field imaging is extended by designing point spread function (PSF) to be independent on z position. Its advantage over z-stacking based methods is that single image is sufficient to reconstruct all-in-focus image. It is similar to method used in wavefront coding, but without limitations imposed by using complex phase masks [1].

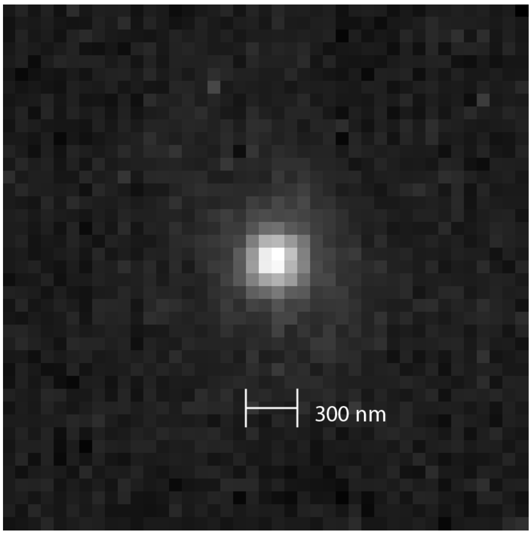
Method is based on averaging PSF/image over z-range of interest. In this work averaging/integrating is performed by scanning z-stage during single frame acquisition.

Average image intensity distribution is processed by deconvolution with corresponding 2D PSF. Measured 2D PSF is reconstructed from fluorescence beads image. In this way aberration in the optical system are corrected for, as well as some of the immersion/coverglass/sample aberrations. For theoretical 2D PSF, Fourier transform does not have zeros, which means that no information is lost.

Deconvolution is done in Fourier domain using Wiener filter with adjustable noise variance. Deconvolution can be performed in real time for 1 Megapixel images and computational time scales same as with Fast Fourier Transform. For high signal to noise ratio, sub-diffraction resolution image is reconstructed.

Additional benefit of this method is that simultaneously moving x-stage and z-stage creates apparent rotation of the sample. "Rotated" 2D PSF will differ for each angle, and can be reconstructed from 3D PSF (real or theoretical).

Method is best suited for transparent samples. Also it can be applied for imaging opaque objects and surfaces, at the price of losing exactness (c.f. Fig. 1).



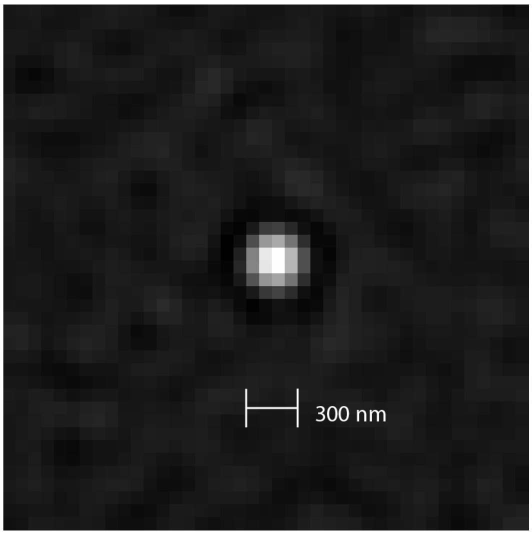


Figure 1: Wide field raw image of fluorescent bead (left) and image after reconstruction (right).

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[1] E. R. Dowski, Jr., W. T. Cathey, Extended depth of field through wave-front coding, *Applied Optics*, Vol. 34, No. 11, 1995.

Correction of Coverslip Mismatch via Image Quality Measures

Han Woong Yoo and Michel Verhaegen

Delft University of Technology, Delft Center for Systems and Control, Mekelweg 2

2628 CD, Delft, The Netherlands, `h.w.yoo@tudelft.nl` and `m.verhaegen@tudelft.nl`

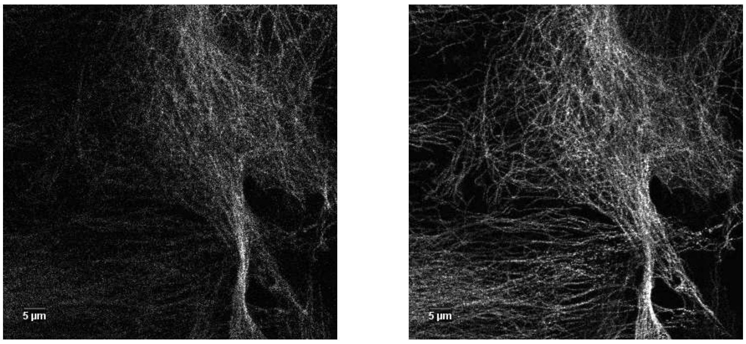
Georg Schitter

Vienna University of Technology, Automation and Control Institute

Gusshausstr. 27-29,1040 Vienna, Austria, `schitter@acin.tuwien.ac.at`

Abstract

Coverslip, also called coverglass, is a thin transparent plate to fix a specimen to microscope slides and protect the specimen from damages caused by exposure of specimen such as dehydration and collision with other materials. For water immersion objectives with high numerical aperture, the thickness variation of coverslip is one of the major sources of spherical aberration and can degrade microscope images as Figure 2. To cope with this aberrations induced by coverslip, microscope manufacturers provide a coverslip correction ring in objective. It is, however, not easy and convenient for users to coincide the optimal correction because of imprecise manual manipulation and subjective correction quality measures depending on users.



(a) about $15\mu m$ mismatch from optimal

(b) After correction

Figure 2: Confocal microscopy images of green fluorescent protein dyed microtubules, which have 25 nm diameter cylindrical structures. The left image is taken with approximately 15 μm coverslip thickness mismatch and the right image is the corrected image by the coverslip correction ring. Specimen is provided by Martin E. van Royen, Erasmus MC, and measured by Leica SP5, $\times$40 1.1NA water immersion objective.

In this presentation, a model based coverslip mismatch correction is proposed based on image quality measures. The model of the coverslip reflection is derived for the image quality calculation in ideal case. Using the image quality measures of ideal and measured axial images, the current mismatch between actual coverslip thickness and correction ring position are estimated in nonlinear least square manner and applied as an actuation signal. The simulation results based on experiment data illustrate the fast convergence of the proposed algorithm.

Smart Microscopy of Biological Tissues

Applicants:	Prof. Hans Gerritsen (Utrecht University) (project leader) Prof. Christoph Keller (Utrecht University) Prof. Michel Verhaegen (TU Delft)
Researchers:	Tim van Werkhoven Jacopo Antonello H.H. Truong
Budget:	916k€

Project outline

Microscopy has become increasingly more important in biological and biomedical work. This is to a great extent due to the development of advanced imaging methods such as confocal microscopy and multi-photon excitation microscopy that provide 3-D imaging in (optically thick) specimens. At present, multi-photon excitation microscopy is the technique of choice for high-resolution in-vivo imaging. Unfortunately, the use of these techniques is seriously hampered by specimen-induced aberrations that result in reduced depth penetration, loss of spatial resolution, and increased phototoxicity.

Current implementations of adaptive optics (AO) provide evidence that AO can significantly improve image quality, depth penetration, and spatial resolution while reducing phototoxicity in scanning microscopy. However, severe speed limitations render them impractical for real-life applications. Here, we will focus on the development of fast, active compensation methods for specimen-induced wavefront aberrations. High compensation speeds will be realized by using adaptive optics in combination with smart predictive algorithms that take into account all system properties including the scanning nature of the acquisition, the dynamic properties of the deformable mirror based AO and the nature of the optical optimization. To realize the above, academic experts in the area of advanced microscopy (Molecular Biophysics group), adaptive optics (Experimental Astrophysics group) and advanced control systems (Delft Center for Systems and Control) will closely collaborate. The team is further strengthened by the involvement of relevant industrial partners.

The method will be validated in tissue imaging experiments including in-vivo imaging of skin, in-vivo tumour mouse models and isolated arteries. The latter part of the project will be carried out in collaboration with (bio)medical groups.

Smart microscopy
Phase-shifting interferometric wavefront sensing

Tim van Werkhoven
Utrecht University
Sterrekundig Instituut Utrecht
Princetonplein 5, 3584 CC, Utrecht, The Netherlands
t.i.m.vanwerkhoven@astro-uu.nl

Introduction

Microscopy – especially confocal- and two-photon microscopy – has become increasingly more important in biological and biomedical work. Unfortunately, the use of these techniques in in-depth imaging is seriously hampered by specimen-induced aberrations. Current implementations of adaptive optics (AO) provide evidence that AO can significantly improve image quality, depth penetration, and spatial resolution while reducing phototoxicity in scanning microscopy. However, severe speed limitations render them impractical for real-life applications.

We are developing a method to apply a fast, active compensation to the specimen-induced wavefront aberrations. We will combine adaptive optics with smart predictive algorithms to take into account all system properties such as the scanning behaviour and dynamic properties of the deformable mirror.

Method

The backscatter from the microscope objective using a conventional Shack-Hartmann wavefront sensor resulted in too much noise. Instead, we are now attempting to use a phase-shifting interferometric method to measure the wavefront aberration due to the tissue.

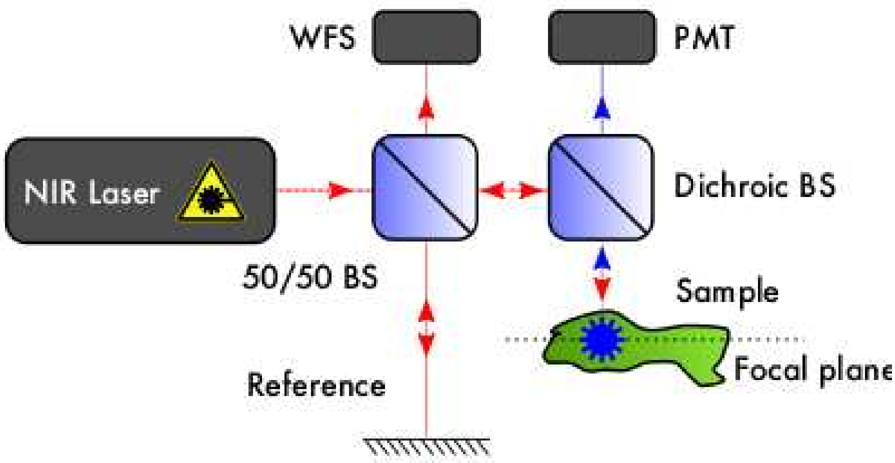


Figure 3: Schematic of the proposed wavefront-sensing method. The reference beam is interfered onto the WFS with the infrared beam scattering back from the sample. The visible light science beam is split and recorded by a PMT.

Because we are using a 140-fs pulsed laser, the interference occurs only when the path length of the two beams are similar to within approximately 40 μm. By recording multiple images with different phase delays, we can reconstruct the wavefront shape while simultaneously discarding light that is not from within this 40 μm focal depth.

Discussion

The phase shifting can be achieved temporally by changing the path length of the reference beam, or spatially by splitting the beam in four and applying a phase delay to each of the beams separately.

The former setup, while optically simpler, is more prone to instabilities that change the path length differences (vibrations, internal seeing). Therefore we are currently focussing on the spatial variant of phase delay.

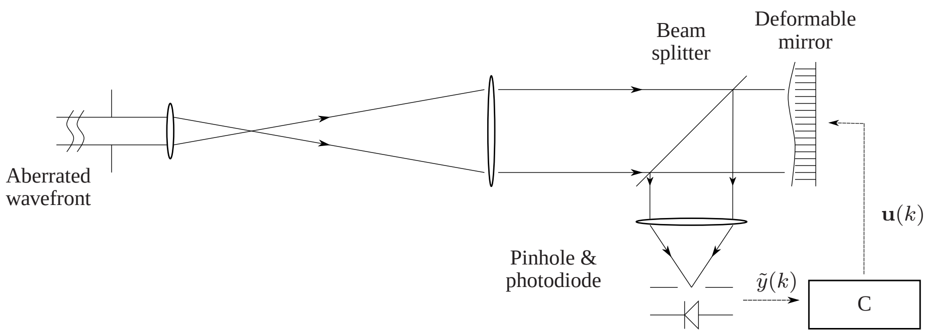
Data driven identification and aberration correction for model based sensorless adaptive optics

Jacopo Antonello
Delft University of Technology
Delft Center for Systems and Control
Mekelweg 2, 2628 CD, Delft, The Netherlands
j.antonello@tudelft.nl

Introduction

Wavefront sensorless adaptive optics methodologies are considered in many applications where the deployment of a dedicated wavefront sensor is inconvenient. Here, aberration correction is achieved by sequentially changing the settings of an adaptive optical element until a predetermined cost function is optimised [1]. Reducing the time required for this optimisation is a research challenge.

System description



An aberrated wavefront is focused into a pinhole aperture, where the irradiance $\tilde{y}(k)$ is recorded with a photodiode. The objective is to modulate the control signal $\mathbf{u}(k)$ of an N channels deformable mirror in order to maximise the $\tilde{y}(k)$.

System modelling and identification

From first principles modelling, $\tilde{y}(k)$ can be approximated by

$$y(k) = c_0 + \mathbf{c}_1^T(\mathbf{x} - \mathbf{u}(k)) - (\mathbf{x} - \mathbf{u}(k))^T Q(\mathbf{x} - \mathbf{u}(k)) + w(k), \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^N$ is the unknown aberration and $c_0 \in \mathbb{R}$, $\mathbf{c}_1 \in \mathbb{R}^N$ and $Q \succeq 0$ are parameters. A data driven identification procedure allows to resolve c_0, $\mathbf{c}_1$ and Q from experimental data.

Aberration correction

An estimate of the unknown $\mathbf{x}$ can be obtained by taking $N + 1$ measurements of $y(k)$ and solving a linear system. This leads to the maximisation of the irradiance.

Bibliography

[1] M. J. Booth, Wave front sensor-less adaptive optics: a model-based approach using sphere packings, *Opt. Express*, **14**, pp. 1339–1352, 2006.

Integrated High-Resolution Observing through Turbulence

Applicants:	Prof. Christoph Keller (Utrecht University) (project leader) Prof. Michel Verhaegen (TU Delft)
Researchers:	Dr. Visa Korkiakoski Federico Pinchetti
Budget:	671k€

Project outline

Dynamic optical aberrations induced by atmospheric turbulence form a major limitation in the achievable resolution of high-end optical imaging instruments, like ground-based telescopes and longrange surveillance cameras. Several techniques have been developed to reduce the effect of these distortions on the imaging quality, including adaptive optics (AO) and post-facto reconstruction algorithms. Although, the two approaches have been combined in the past, they have not been studied as constituents of an overall system, such as to optimize the total system performance. This research proposal aims at an integrated approach of optimization of overall image quality, in which the actions of the AO deformable mirror and the post-facto reconstruction algorithm are geared to one another.

Major improvements in resolution are expected with the joint optimization approach, in particular with the aspects of (i) the use of AO wavefront sensor signal data and deformable mirror signal data as input to post-facto reconstruction and (ii) introducing known phase aberrations during the real-time correction with the AO system to improve the performance of post-facto reconstruction, in particular of phase-diversity algorithms. Moving towards an overall real-time system, (iii) the feedback of wavefront aberration information deduced by post-facto reconstruction into the adaptive optics system is also a very promising aspect. Furthermore, important issues like adaptivity with respect to the timevariant turbulence statistics and the use of robust estimation tools taking into account the uncertainty in the point spread function will be addressed in this research.

The developed techniques will be tested and validated on a laboratory set-up first and later on by performing real-life turbulence experiments on a telescope and with a long-range surveillance camera.

Joint optimization of phase-diversity and adaptive optics: demonstration of potential

Visa Korkiakoski and Christoph Keller
Utrecht University, Astronomical Institute
P.O. Box 80125, 3508 TC Utrecht, The Netherlands
v.a.korkiakoski@uu.nl

Abstract

We study different possibilities to use adaptive optics (AO) and phase diversity (PD) together in a jointly-optimized system. The potential of the joint system is demonstrated through numerical simulations. We find that the most significant benefits are obtained from the improved deconvolution of AO-corrected wavefronts and the additional WFS information that reduces the computational demands of PD algorithms. When applied together, it is seen that the image error can be reduced by 20% compared to traditional PD, working with one focused and one defocused camera image, and the computational load is reduced by a factor of 20 compared to a more reliable PD algorithm requiring more camera images. In addition, we find that the system performance can be optimized by adjusting the magnitude of the applied diversity wavefronts.

Bilinear phase diversity for extended objects

Raluca Andrei, Rufus Fraanje and Michel Verhaegen
Delft University of Technology
Delft Center for Systems and Control
Mekelweg 2, 2628 CD, Delft, The Netherlands
r.m.andrei@tudelft.nl

Introduction

We propose a new method to estimate aberration parameters and unknown object from diversity images [1], which involves solving a bilinear system of equations [2]. When the wavefront aberrations are small, they can be approximated with a linear term which leads to a quadratic point-spread function in the aberration parameters. We expand the wavefront using Zernike basis functions. Our bilinear system is obtained by subtracting from each diversity image one focused image.

Analytical formula for the PSF

The diffraction integral that gives the spatial impulse response $U(x, y)$ in image space is

$$U(r,\varphi) \approx 2T_0^0(r) + 2i\sum_{n,m} i^m T_n^m(r)\left(\alpha_n^m \cos m\varphi + \alpha_n^{-m}\sin m\varphi\right), \tag{2}$$

where $T_n^m(r) = (-1)^{\frac{n-m}{2}} \frac{J_{n+1}(2\pi r)}{2\pi r}$ and $\alpha_n^{\pm m}$ are Zernike coefficients. The PSF is $I = |U|^2$

$$I(r,\varphi) = c_0 + c_1^T\boldsymbol{\alpha} + \boldsymbol{\alpha}^T Q\boldsymbol{\alpha}. \tag{3}$$

Given a grid of size $M \times N$, the intensity PSF can be written as

$$t_0(\boldsymbol{\alpha}) = C_0 + C_1(I_N \otimes \boldsymbol{\alpha}) + Q_t(I_N \otimes \boldsymbol{\alpha} \otimes \boldsymbol{\alpha}). \tag{4}$$

Bilinear problem

We assume we have one focused image d_0 and defocused images $d_k = t_k(\boldsymbol{\alpha}) * f + n_k,\ k = 1 \dots N_\alpha + 1$, where t_0 in (4) and $t_k(\boldsymbol{\alpha}) = t_0(\boldsymbol{\alpha} + \boldsymbol{\alpha_{dk}})$ are the PSFs and $\boldsymbol{\alpha_{dk}}$ are known quantities. We subtract the pairs of images to get

$$d_{dk} = d_k - d_0 = (p_k + 2(\boldsymbol{\alpha}|v_k)) * f + n_{k0},\ k = 1 \dots N_\alpha + 1, \tag{5}$$

where $v_k = \left[v_{k1}\, v_{k2} \dots v_{kN_\alpha}\right]^T$, $v_{ki} = Q_t(I_N \otimes e_i \otimes \boldsymbol{\alpha_{dk}}),\ i = 1 \dots N_\alpha$, $p_k := C_1(I_N \otimes \boldsymbol{\alpha_{dk}}) + Q_t(I_N \otimes \boldsymbol{\alpha_{dk}} \otimes \boldsymbol{\alpha_{dk}})$. In the Fourier domain, we have

$$D_{dk} = \left(P_k + 2\sum_{i=1}^{N_\alpha} \boldsymbol{\alpha_i} V_{ki}\right) \odot F + N_{k0}, \tag{6}$$

or, with $d := \mathrm{vec}(D_{dk})$, $y := \left[1\, \boldsymbol{\alpha}^T\right]^T$, $x := \mathrm{vec}(F)$, (6) becomes $d_j = \boldsymbol{y}^T A(j)\, \boldsymbol{x},\ j = 1, \dots, M_{\mathcal{F}} N_{\mathcal{F}}$.

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[2] E.-W. Bai and Y. Liu, “On the least squares solution of a system of bilinear equations”, *Proc. 44th CDC and ECC*, December 2005.

Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems

Applicants:	Prof. Rob Munnig Schmidt (TU Delft / ASML) (projectleader) Prof. Michel Verhaegen (TU Delft) Prof. Maarten Stijnbuch (Eindhoven Univ. of Technology Dr. Nick Rosielle (Eindhoven Univ. of Technology
Researchers:	Johan Vogel (TU Delft) Ruxandra Mustata (TU Delft) Geert-Jan Naaijkens (Eindhoven Univ. of Technology)
Budget:	1000k€

Project outline

The goal of this research is to come to an integral mechatronic design methodology which is generally applicable to opto-mechatronic systems but specifically supports the development of key technologies that increase resolution in high speed imaging systems. The project objective is motivated by the fact that the semiconductor industry is constantly trying to reduce the minimum size, also known as Critical Dimensions (CD), of features that are used to fabricate Integrated Circuits (ICs). A reduction in feature size will result in higher information density and speed as well as reduced power consumption and cost of the IC. These effects improve performance of consumer electronics such as laptops, cellular phones and MP3 players which subsequently lead to increased mobility and economic productivity of society.

In the production process of ICs, photolithography is seen as the crucial and limiting step in realizing smaller feature size. In order to facilitate the decrease in CD and improve cost effectiveness of the production process, lithography equipment manufacturers are continuously developing imaging machines with ever increasing resolution and wafer throughput. Up to now, these specifications are achieved by increasing the numerical aperture of the lens and using laser sources with lower wavelengths. Furthermore, the mechatronic system architecture around the lens is optimized to reduce optical aberrations.

Considering the ITRS roadmap for lithography, it is clear that ever stringent demands with respect to overlay and CD control are pushing lithography equipment manufacturers to their technological limits. In order to improve conformity of the projected mask image - also known as aerial image - with the wafer surface topology, a number of performance limiting factors need to be tackled. Specifically, static optical path distortions due to lens imperfections and wafer unflatness as well as dynamic distortions due to dynamic deformations and hysteresis of optical path components must be reduced. However, overcoming these effects is becoming increasingly difficult due to the limitations of lens and wafer polishing techniques, use of friction-based (optical) component interfaces and higher component acceleration levels inside lithography equipment to achieve the desired wafer throughput.

The push into these extreme machine operating regimes has made it evident that the conventionally applied mechatronic design concepts and technologies have difficulties in tackling the above described problems. In order to be able to develop next generation lithography systems, the current mechatronic approach for imaging systems needs to be enriched with novel opto-mechatronic design rules using Adaptive Optics (AO). Considering its correction potential, the required bandwidth and its proven track record in astronomy [5], AO is seen as the key technology to reduce rapidly changing optical path distortions inside lithography systems whilst keeping complexity and cost to a minimum.

To research novel opto-mechatonic design methodologies and investigate the applicability of AO inside high speed lithography systems, the project will utilize a multi-disciplinary approach to simultaneously and iteratively tackle a number of research challenges.

Firstly, the use of opto-thermo-mechanical models for adaptive optic actuator and controller design is researched. Specifically, the trade-off between model accuracy and complexity will be investigated.

Secondly, the research will focus on the development of an adaptive optic actuation concept for lithography systems at photomask level. Moreover, emphasis is placed on the identification of the actuator number and location that enables an optimized system performance. During this study, additional challenges such as energy dissipation, cost at a minimum of complexity will require dedicated attention.

Thirdly, research is required on efficient algorithms to facilitate the multivariable control of, as well as real-time multivariable system and disturbance identification techniques for, high bandwidth AO systems inside lithography equipment. Finally, a metrology system through high speed real-time surface measurement must be developed. It is expected that the above approach will lead to a unique trend change in opto-mechatronic system design methodology and novel technologies for high end optical equipment to meet future requirements of nanometer (nm) level overlay and sub-50 nanometer focus deviations.

Deterministic Reticle Clamping

Geert-Jan Naaijkens

Eindhoven University of Technology

Control Systems Technology

PO Box 513, WL 0.68

5600 MB Eindhoven, The Netherlands

g.j.p.naaijkens@tue.nl

Introduction

In semiconductor industry, the critical dimension of Integrated Circuit (IC) patterns etched onto wafers is moving towards the sub-45 nm regime [1]. Each IC requires multiple lithography exposures resulting in multiple layers. Each layer has to be exposed on top of the previous layer with a high alignment accuracy (= overlay). Overlay requirements are becoming ever more stringent [2]. In the reticle stage of wafer scanners, accelerations occur that are high compared to the positioning accuracy. These accelerations need to increase for increasing throughput requirements [3]. Deviations in the optical path are, among others, caused by non-correctable reticle deformations and drift. These previously less critical influences become a dominant limiting factor for overlay performance.

Research subject: deterministic reticle clamping

Reticle interfacing for high acceleration stages and concepts to minimize the above mentioned overlay performance limiters are elaborated upon. The requirements of overlay and throughput result in increasingly contradictory specifications for reticle clamping. For increasing alignment accuracy, increasing stiffness is necessary as well as decreasing non-correctable reticle deformations. Furthermore it is necessary to minimize drift, potentially caused by accelerations.

Activities

Novel design solutions complying with all identified specifications have been developed, resulting in a modular reticle clamping design. The design solutions and corresponding reticle clamping design will be presented and discussed. The first three dedicated testrigs of the most challenging functionalities have been designed and partially realized. Promising tests have been performed with the first test-setup. The results of these tests will be presented and discussed.

Acknowledgements

This research project is technically and financially supported by Eindhoven University of Technology TU/e, ASML N.V. and STW.

Bibliography

[1] International Technology Roadmap for Semiconductors, `http://www.itrs.net`.
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Mode shape excitation measurement with sub-nanometer precision

Johan Vogel and Jo Spronck
Delft University of Technology
Department Precision and Microsystems Engineering (PME)
Mekelweg 2, 2628 CD, Delft, The Netherlands
`j.g.vogel@tudelft.nl`

Introduction

As the resolution of lithography systems has to grow continuously, steps have to be taken to reduce static and dynamic error sources in the optical pathway that compromise the illumination. One of these error sources is the distance between the lens and the wafer that is being illuminated. The wafer is carried by a plate — the chuck —, which is currently seen as a rigid body [1]. In reality this chuck has finite stiffness and due to the bending modes there will be an error in measured distance. As a lighter chuck would be favourable and with the prospect of the wafers and therefore the chuck becoming lager, this problem is becoming more relevant. The deformation of the chuck being measured, it can be compensated for, for example by applying actuation between chuck and wafer.

Mode shape measurements

The deflection of the chuck can be calculated from measurements of the mode shape excitations. For this the first six (non-rigid-body) modes are the most important. Challenging is the high precision that is needed for the measurements. The out of plane movements have to be measured with sub-nanometer precision. There are basically two categories of measurements solutions, external and internal. The external measurements could be done upward —with respect to the stable metrology frame—, downward —with respect to the long stroke actuator, whose position and deformation are not well-known however— and with respect to an extra to be introduced body. The internal measurement solutions are based on relative deformations inside the plate and include measurement of strain, stress, displacement, angle and acceleration. As the deformations of the plate have to be measured with subnanometer resolution, strains are typically as low as 2 nϵ, stresses as 300 Pa and accelerations 0.3 mm/s^2, which is challenging. Internal measurement is interesting, in the sense that it is absolute and the coupling with the rigid body motion is only small.

Measurement methods

At the moment, different possibilities for internal measurement methods are being investigated. These possibilities include fibre bragg grating strain sensors, capacitive sensors, accelerometers and sensors based on birefringent materials, piezo electric foils and parallel mirrors.

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Distributed control of wafer deformations in photolithography systems

Ruxandra Mustaţă, Rufus Fraanje and Michel Verhaegen

Delft University of Technology

Delft Center for Systems and Control

Mekelweg 2, 2628 CD, Delft, The Netherlands

r.i.mustata@tudelft.nl

Introduction

The trend in the semiconductor industry is to constantly reduce the nanometer-scale critical dimensions of the features used in fabricating integrated circuits (IC) [1]. Photolithography is seen as the crucial step for resolution enhancement in the ICs production process. The principle of photolithography consists in transferring the geometrical pattern from a photomask to a photoresist, by photomask illumination. Due to different sources of disturbance along the optical path, unconformity between the projected image and the wafer surface topology occurs. Adaptive optics (AO) is considered to be the key technology to compensate for rapidly changing optical path distortions.

System description

One important factor which dynamically contributes to the image unconformity at the wafer plane is the illumination scanning. The wafer substrate locally deforms around the focal point during the illumination. We are interested in compensating for the heating-induced deformations at the wafer surface. A distributed actuation strategy that is able to perform local active wafer surface deformations is proposed. The actuation can be implemented by means of piezoelectric elements integrated into the wafer stage support structure. The strategy shows similarities with the deformable mirrors present in many AO applications. The objective of the control system is to minimize the distance between the projected image and the wafer surface, while taking into account the dynamics of the heating-induced wafer deformations.

System modeling

For simplicity, the one-dimensional case is considered, where the wafer vertical displacements are modeled as vibrations of a homogeneous beam and the scanning heat wave is modeled as a vertical force propagating along the beam's length. The dynamics of the beam is described by a PDE which is further discretized using the finite differencing method. The model is then augmented with the discretized representation of the time delay, describing the heat wave. The structure of the resulting model can be further exploited for implementing computationally efficient numerical methods [2].

Experimental results

First, the control problem is solved using optimal LQG control methods. The performance indicators of these methods will serve as benchmarks for the evaluation of the subsequent methods. Then, because of the structure in the wafer scanning illumination as well as the wafer dynamics, efficient distributed methods are used for modeling the system and real-time controlling the optical path length.

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Smart Multilayer Interactive optics for Lithography at Extreme UV wavelengths (SMILE)

Applicants:	Prof. Fred Bijkerk (FOM Rijnhuizen / University of Twente) (project leader) Dr. R. Sobierajski (FOM Rijnhuizen) Dr. F. van Goor and Dr. C.J. Lee (University of Twente) Prof. D.H.A. Blank, Prof. A.J.H.M. Rijnders (University of Twente)
Researchers:	Muharrem Bayraktar
Budget:	1069k€

Project outline

Without doubt, Extreme UV Lithography represents today's most advanced optical imaging method, operating at the shortest wavelength ever employed for high-resolution and wide field imaging. The technique, being considered indispensible for the fabrication of the next generation of semiconductor circuits, represents a major challenge for optics development in general. Typically, sub-tenth nanometer precision is required for the optics' accuracy and positioning, while, simultaneously, kilowatt-power level EUV light sources cause tremendous thermal loads on the optics, leading to distortions of the fine imaging process. The obvious, though so far unexplored, solution to this challenge is to add adaptive functionality where it is most effective, namely in the EUV-reflective multilayer coatings. These Bragg-reflecting layers, for which the team holds a world reflectivity record, have enabled the success of early EUV wafer scanners. Yet, they must now be modified to include adaptive figure and spectral functionality to reach the required accuracy and stability. We propose a rigorous new multilayer composition, including piezo- and pyro-electrical materials so that the periodic Bragg structure can be interactively manipulated. Steering such control layers by external electrical or thermal signals will then allow wavefront corrections and localized reflectivity changes. The aim of this project is to achieve an integrated system, where adaptive optics specifically suitable to the EUV are individually manipulated to obtain optimized EUVL system performance. These 'interactive-EUV' multilayer optics will need to be grown with layer-thicknesses that have a precision well into the sub-nanometer range, while at the same time having chemical and thermal stability, and atomically sharp optical index profiles. To meet these requirements, fundamental challenges in optics, materials science, and thin-film physics must be resolved. In the SMILE project, the essential elements are uniquely combined to achieve these goals:

- a unique thin film deposition and analysis instrumentation, as well as a proven deposition technology, ideally suited to produce the ultrathin layers from the complex piezo materials while preserving their adaptive properties,

- a positive assessment of critical adaptive and multilayer control concepts, showing more than adequate dimensional change effects for the proposed adaptive multilayer coatings, including a patent on this adaptive EUV optics,
- a new analysis technique in the form of state-of-the-art EUV interferometry with picometer resolution,
- substantial support from our industrial partner on design, analysis, and system engineering,
- a proven track record of the team in transfer of know-how to industry.

Reflectance Tuning at Extreme Ultraviolet Wavelengths with Active Multilayer Mirrors

Muharrem Bayraktar[1], Chris J. Lee[1], Fred A. van Goor[1], Gertjan Koster[1], Guus Rijnders[1], Fred Bijkerk[1,2]

[1] Laser Physics and Nonlinear Optics Group, MESA+ Research Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands

[2] FOM Institute for Plasma Physics Rijnhuizen, P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands

bayraktar@utwente.nl

Introduction

Extreme ultraviolet lithography (EUVL) is the next generation process to satisfy the high demands of the semiconductor industry. At EUV wavelength (13.5 nm) multilayer mirrors are commonly used. Multilayer mirrors are composed of many bilayers (high refractive index and low refractive index) which are designed according to the Bragg law [1]. The Bragg formula defines the interference condition for waves reflected from different layers and relates the layer thickness to the angle of incidence and the wavelength. The thicknesses of the layers are critical for the reflectance so that they are susceptible to environmental changes such as temperature. Here we propose a new active multilayer structure which can be adjusted to compensate for reflectance changes. This multilayer structure makes reflectance tuning with an integrated piezoelectric layer that can change its dimension with external voltage.

Active multilayer structure

In the reflectance tuning process, the thickness of the piezoelectric material is of primary interest for the phase difference and for the reflectance tuning range. In order to see the effect of the piezoelectric material thickness on the reflectance let's define a specific structure as in Fig. 4 a) for 13.5 nm which is illuminated at normal incidence. The reflectance, $R(z)$, is plotted as a function of the piezoelectric layer ($BaTiO_3$) thickness, z, in Fig. 4 b). Depending on the thickness of the $BaTiO_3$ layer, the degree of interference changes, so that the total reflectance has maximum and minimum values. In order to have the maximum reflectance tuning range, first we select a minimum acceptable reflectance value (R_{min}) and then we find the number of bilayers for upper and lower MLM stacks (N_1 and N_2 respectively) that gives the maximum slope above R_{min}. For example, if we select $R_{\text{min}} = 60\%$ then

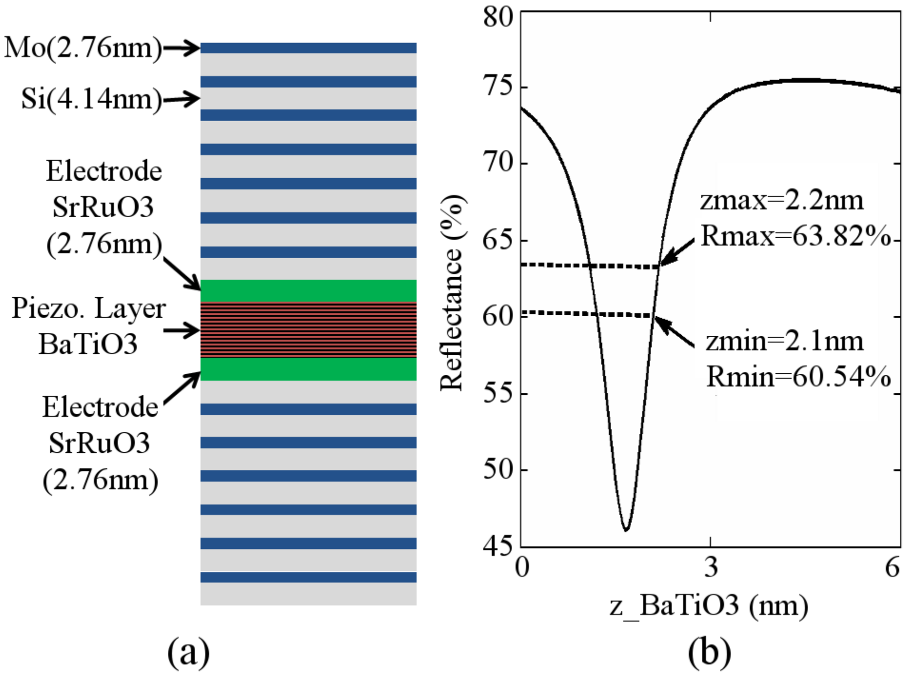

Figure 4: a) Active multilayer structure which can be defined from top to bottom as: Mo/Si multilayer stack, top electrode, piezoelectric layer, bottom electrode and bottom Mo/Si multilayer stack. The period of the Mo/Si MLM's, the thickness of Mo and the thickness of Si are 6.9 nm, 2.76 nm and 4.14 nm respectively. b) Reflectance as a function of $BaTiO_3$ layer thickness. By applying voltage, the thickness of the $BaTiO_3$ layer can be changed from 2.1 nm to 2.2 nm resulting in a reflectance increase from 60.54% to 63.82%.

the optimum solution is satisfied with $N_1 = 25$ and $N_2 = 48$. Reflectance tuning range is limited by the mechanical properties of the material. Maximum thickness change (maximum strain, ϵ_{max}) for $BaTiO_3$ before any plastic deformation is 4.8% [2]. Therefore, if we define the initial thickness of the $BaTiO_3$ layer and the total reflectance as z_{min} and R_{min} respectively, then maximum thickness and corresponding reflectance can be written as $z_{\text{max}} = z_{\text{min}}(1 + \epsilon_{\text{max}})$ and R_{max} respectively where $R_{\text{min}} = R(z_{\text{min}})$ and $R_{\text{max}} = R(z_{\text{max}})$. Using the configuration in the figure, it is possible to change the thickness of the $BaTiO_3$ from $z_{\text{min}} = 2.1$ nm to $z_{\text{max}} = 2.2$ nm resulting in a reflectance tuning range between $R_{\text{min}} = 60.54\%$ and $R_{\text{max}} = 63.82\%$ as shown in Fig. 4 b). The reflectance tuning range is 3.28% for this $BaTiO_3$ layer thickness however it is possible to achieve higher reflectance tuning with thicker piezoelectric layer which will be explained in the presentation.

In conclusion an active multilayer mirror structure is described to be used at EUV wavelengths. The structure incorporates a piezoelectric layer into the multilayer mirror that allows reflectance tuning. Using this idea, it is also possible to design structures for different wavelengths ranges and multi-element structures for wavefront correction.

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Waveguide-based External-Cavity Semi-conductor Laser arrays

Applicants:	Prof. Klaus Boller (University of Twente) Prof. J.L. Herek (University of Twente) Prof. Michel Verhaegen (TU Delft)
Researchers:	Ruud Oldenbeuving (University of Twente) Hong Song (TU Delft)
Budget:	855k€

Project outline

The need to intensify the exchange of information with higher-speed (internet), the wish to display received information in most brilliant (Laser TV) colors, and most advanced techniques in bio-medical diagnostics, surprisingly, have their common grounds. When looking at their technological heart, one finds that it is the excellence in laser light generation that fosters their potential and growth. As a result there is a strong need to realize highly miniaturized lasers with greatly improved wavelength control, and at most affordable cost. In this project we investigate a novel approach that promises to fulfil many of these demands. For the first time, we use special (vertical cavity) diode lasers (VCSELs) and control their emission with a network of adjustable photonic wires (waveguides) made in a glass-chip. The design of these planar glass-based waveguide ring resonator circuits is that they can tune or lock the laser wavelength at will, via chip-integrated thermo-optical actuators, while at the same time allowing on-chip measurement of the wavelength.

Stable operation, at any desired wavelength, is then done via a so-called smart controller. This is eventually a miniaturized electronic control chip, in which the most advanced control theory is applied for proper functioning of the laser and low cost. The described design allows further unprecedented possibilities; To scale-up the output power, entire arrays of diode lasers can be operated on the same waveguide chip. Mutual coupling combines their output into a single beam, e.g., as highly repetitive light pulses, enabling an easy and efficient conversion into powerful visible light for display purposes.

Waveguide-based External Cavity Semiconductor Lasers

R.M. Oldenbeuving[1,*], E.J. Klein[2], C.J. Lee[1], H.L. Offerhaus[3] and K.-J. Boller[1]

University of Twente

[1]Laser Physics and Nonlinear Optics group, MESA+ Research Institute for Nanotechnology

[2]XiO Photonics

[3]Optical Sciences group, MESA+ Research Institute for Nanotechnology

[*] R.M.Oldenbeuving@utwente.nl

Introduction

Tunable, narrowband diode lasers are widely used in, e.g., telecommunications [1]. In order to achieve wide tuning, high wavelength agility, high side mode suppression and a narrow spectral bandwidth, tunable diode lasers are commonly equipped with an external cavity. Such an external cavity is build using free space optics such as lenses (for collimating and fiber coupling), mirrors (for feedback) and gratings (as frequency selective components for tuning). However, this inherently means that the external cavity will be expensive, bulky, fragile and difficult to align. In order to deal with these problems, we propose an external cavity where a frequency selective mirror is integrated on a waveguide chip and is coupled directly to a laser diode. Although our laser shows large similarities to that of the work of Chu *et al.* [2,3], our design has some significant technological and physical improvements.

Waveguide design

In order to achieve a laser that operates at a high accuracy user-chosen wavelength, we designed a tunable external cavity mirror, based on integrated micro-ring resonators (MRR) [2,3]. We designed our laser such that it should cover the full telecom C-band (1530 nm-1565 nm). In order to be able to adress all wavelengths in this C-band, and taking the laser's spectral gain profile into account, we designed the external cavity with a set of two different MRRs (with radii of 50 μm and 55 μm, respectively). Calculations show that the laser's wavelength would be tunable over 44.6 nm in this configuration. The schematic representation of the laser design is depicted in Fig. 5.

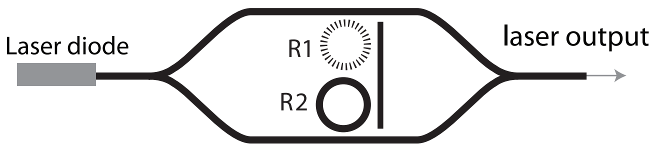

Figure 5: *Schematical representation of the designed laser, with a wavelength tunabililty of 44.6 nm. R1=50 μm, R2=55 μm.*

Results

We have fabricated the described waveguide mirror in TriPleX technology and show that its properties are in agreement with theory. We have coupled the waveguide mirror to a diode laser chip and have analyzed the laser's characteristics in detail and compared them to the values of the free-running laser chip. Currently, we have achieved a maximum fiber-coupled power of 1 mW, with a nominal laser-chip power of 10 mW, to be increased by better mode matching. We found that our laser can be tuned in wavelength over >40 nm, the tuning between two different wavelengths can be done within a time of 0.3 ms, the side-mode supression ratio (SMSR) was 50 dB (compared to 30 dB for the free running laser) and the laser bandwidth was very narrowband: typically 60-100 kHz with a minimum of 30 kHz (compared to 20-25 GHz for the free-running laser), the laser threshold was 5.6 mA (compared to 17.8 mA for the free-running laser). The stability of the output power of the laser was 4.5% (compared to 2.5% for the free-running laser) over 10 minutes.

Acknowledgements

STW-grant 10442, XiO Photonics, LioniX, DCSC.

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[3] N. Fujioka, T. Chu, M. Ishizaka, J. Lightw. Technol. **28**, 3115–3120 (2010);

Model-based wavelength estimation with tunable color filter and single photodiode

Hong Song and Michel Verhaegen
Delft University of Technology, Delft Center for Systems and Control
Mekelweg 2, 2628 CD, Delft
The Netherlands
m.verhaegen@tudelft.nl
Georg Schitter
Vienna University of Technology, Automation and Control Institute
Gusshausstr. 27-29, 1040 Vienna, Austria
Schitter@acin.tuwien.ac.at

Introduction

Miniaturized tunable lasers have recently received increasing attention in applications like telecommunications, spectroscopy and imaging systems [1]. In the joint project with University of Twente (UT), a waveguide-based external cavity semiconductor laser is being developed, with the wavelength and power accurately tunable but at reduced cost and small size.

Problem formulation

A main challenge in the development of such a laser is to measure the wavelength and power of the laser in realtime, with simple hardware but at high accuracy.

Strategy

A wavelength and power measurement method is proposed as in Figure 6. The incident laser with wavelength λ_0 and P_0 passes through the tunable color filter (TCF) and illuminates the photodiode. The photodiode measures the intensity of the transmitted light, denoted as y_k for time instant k.

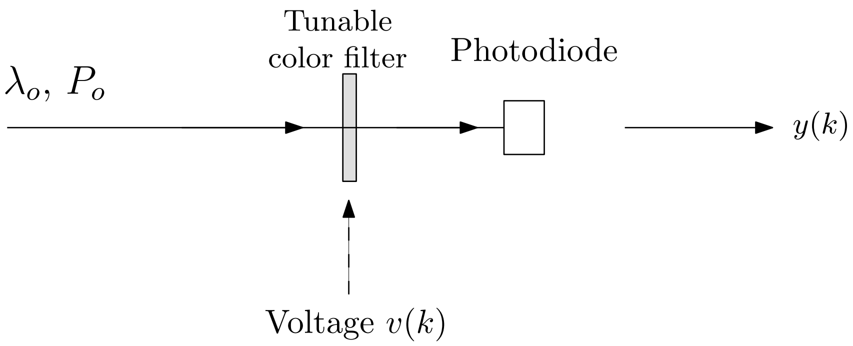

Figure 6: *Schematic of the wavelength/power measurement device.*

By physical modeling, y_k is represented as

$$y_k = P_0 S_k(\lambda_0, v_k) + \eta_k. \tag{7}$$

Here $S(\lambda, v_k)$ is the spectra sensitivity of the combination of TCF and photodiode and η_k is the measurement noise. Note that $S(\lambda, v_k)$ can be changed by the control voltage v_k. For the wavelength and power estimation later on, $S(\lambda, v_k)$ needs to be calibrated by a laser with known wavelength and power beforehand.

The wavelength and power of an incident laser is estimated in two steps: (1) applying a certain number of voltage v_k, $k = 1, \cdots, N$ (N is the number of voltages) to the TCF and collect the corresponding y_k; (2) estimate the wavelength and power based on the v_k, y_k and the calibrated $S(\lambda, v_k)$.

An experimental setup has been built in UT, with 400 wavelengthes tested in a range of $[1549\ nm, 1553\ nm]$. The maximal wavelength estimation error is 0.15 nm, with $N = 21$ tuning voltages, and 95% of the estimation errors are lower than 0.05 nm.

Conclusion

A new method has been proposed for measuring the wavelength and power of the laser with a tunable color filter and single photodiode. Future work will focus on feedback controller design of the tunable laser.

Acknowledgement

Authors would like to thank Ruud Oldenbeuving, Chris Lee, Herman Offerhaus and Klaus Boller from University of Twente for their warm discussions and valuable comments.

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Slides

Slides SOS presentation

Smart Optics Systems

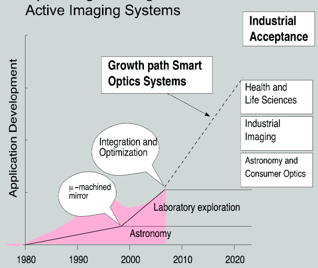
Perspective Programme

Enabling Technology for Clear Vision in the 21st Century

M. Verhaegen (Delft University of Technology)

The Smart Optics Systems Program

Its Scope:
Optimizing the integration of Active Imaging Systems



Program Details
- Program Leader: Prof. M. Verhaegen (Signals and Control)

- Committee Members:
Prof. C. Keller (Astronomy)
Prof. K. Boller (Laser Optics)
Prof. R. Munnig Schmidt (Mechatronics – ASML)
Dr. N. Doelman (TNO)
Dr. G. Vdovin (OkoTech)

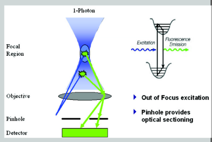
Budget: 5,7 M €
Temporary Scientific Staff: 17
Number of Projects: 6
Period: 2008-2013

Health and Life Sciences

Demands for improved optical imaging instruments:

Health and life sciences Projects:

- **Smart Microscopy of Biological Tissue**
- **Integrated Smart Microscopy**



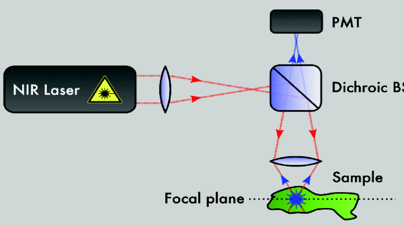
Confocal Scanning Laser Microscopy. Courtesy Stowers Micorscopy Center.

Smart Microscopy

- Project Leader: Prof. H. Gerritsen (UU)
- Partners: University of Utrecht (UU) : Molecular Biophysics Group (Prof. H. Gerritsen) and Experimental Astrophysics Group (Prof. C. Keller)
  Delft University of Technology: Numerics for Control Group (Prof. M. Verhaegen)
- Challenge: Improve spatial resolution (in depth) while reducing phototoxity in scanning microscopy by AO
- Temporary staff members: Tim van Werkhoven (PhD), Jacopo Antonello (PhD), Postdoc.

Scanning Microscopy

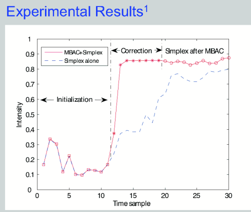
- Localized illumination
- Image tissue using a scanning laser

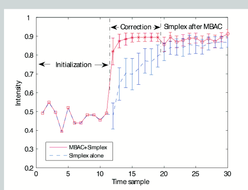


T. Van Werkhoven, et. Al, “Towards coherence-gated phase-shifting wavefront Measurements”, Session V. Wavefront sensors, control systems and strategies

Fast Aberration Correction

Model-based Aberration correction using pinhole measurements only: Experimental Results[1]





MBAC: 0.17 ➔ 0.86 at k=14 (t_c=20ms)
Simplex: 0.17 ➔ 0.86 at k=38 (t_c=55ms)

20 aberrations

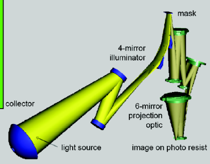
[1]H. Song, et al., Opt. Express, 23, 24070, 2010.

Lithography

Demands for improved illumination, projection and imaging equipment:

Lithography Projects:

- **Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems**
- **Smart Multilayer Interactive Optics for Lithography at EUV**



DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

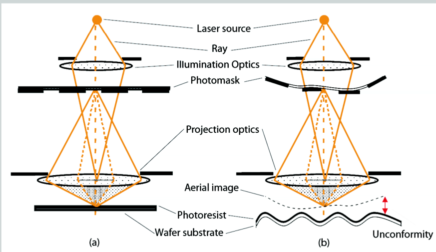
Optical Lithography

- Project Leader: Prof. Rob Munnig Schmidt (TU Delft)
- Partners: Technical University Eindhoven: Control Group (Prof. M. Steinbuch)
  Delft University of Technology: Numerics for Control Group (Prof. M. Verhaegen), Mechatronics Group (Prof. R. Munnig Schmidt)
- Challenge: EUV Lithography - Active photomasks.
- Temporary staff members: Ruxandra Mustat (PhD), S. Ravensberg (PhD), Timmers (PhD).

DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

Active Photomask

"Ideal world" "World relevant at EUV scale"



Overlay, Critical dimension

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DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

Astronomy and Tunable Laser Technology

Demands for improved vision systems:

Astronomy/Laser Projects

- **Integrated High Resolution Observing through turbulence**
- **Waveguide-based ECSL arrays**

Courtesy: philips lighting and design

DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

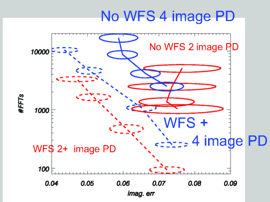
Integrated High Resolution Observing through turbulence

- Project Leader: Prof. Christophe Keller (UUtrecht)
- Partners: University of Utrecht (UU) : Experimental Astrophysics Group (Prof. C. Keller)
  Delft University of Technology: Numerics for Control Group (Prof. M. Verhaegen), Mechatronics Group (Prof. R. Munnig Schmidt)
- Applications: Astronomy and long range camera's.
- Temporary staff members: Visa Korkiakoski (Postdoc) and Rufus Fraanje (Postdoc)

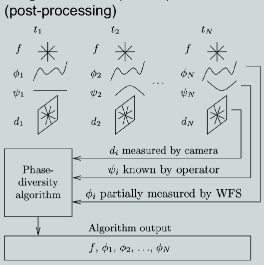
DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

Integrated High Resolution Observing through turbulence

Simulation Results:



Integration of AO (on-line) with PD (post-processing)



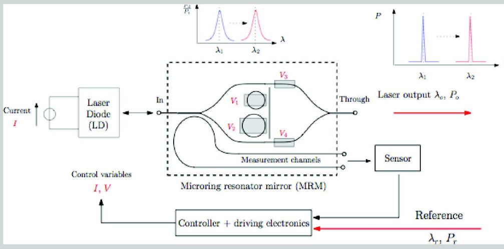
V. Korkiakoski, et. Al, "Joint-Optimization of phase-diversity and adaptive optics: demonstration potential, OSA meeting in Toronto, 2011.

DCSC Delft Center for Systems and Control — SMART OPTICS SYSTEMS Opto–Mechatronics for the 21st century

Waveguide-based ECSL arrays

- Project Leader: Prof. Klaus Boller (UTwente)
- Partners: University of Twente (UT) : Laser Optics (Prof. K. Boller)
  Delft University of Technology: Numerics for Control Group (Prof. M. Verhaegen), Mechatronics Group (Prof. R. Munnig Schmidt)
- Challenges: High performance, low cost tunable lasers.
- Temporary staff members: Ruud Oldenbeuving (PhD), Hong Song (Postdoc).

Waveguide-based external cavity semiconductor laser



Goal: Small size, Low cost+Accurate wavelength/power tuning.→ Sophisticated device and controller design!

WELKOM in Delft

In the near Future …
And maybe for the AOIM workshop in 4 years from now!

The consortium

ASML
FLEXIBLE OKO OPTICAL
Vision Dynamics
NEDINSCO VENLO
PHILIPS
am
TNO
Universiteit Twente
de ondernemende universiteit
Universiteit van Amsterdam
DIMES
Delft Institute of Microelectronics and Submicron Technology
TU/e
technische universiteit eindhoven
TU Delft
Delft University of Technology
DCMM
Universiteit Leiden
Universiteit Utrecht