Micro-Optics: From High-End to Mass-Market

Wafer-based technology now provides high-quality micro-optics for low-cost consumer products.

Photonics is said to be the most important key technology in the 21st century, some even call the 21st century the "photon century". It might be a bit too early to name a whole century after it, but indeed, photon-based technology has much impact on our everyday life at the beginning of the new century. Chip manufacturing, lighting, health care and life-sciences, space, defense, and the transport and automotive sector rely on photon-based technology. Photonics is also supposed to offer novel solutions where today's conventional technologies reach their limits in terms of velocity, capacity and accuracy.

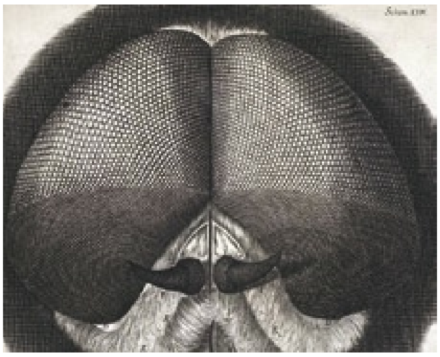

FIGURE 1: **Scheme of a drone fly compound eye as drawn by Robert Hook in Micrographia, published in 1665.**

This journal's name is "optics & photonics". What is the difference between photonics and optics? The term photonics had been proposed as a counterpart of electronics in 1967 by Pierre Aigrain, a French scientist. Using photons instead of electrons to process and transfer signals and information. Optics, a branch of physics, deals with light sources and the manipulation of light by lenses, prisms and mirrors since hundreds of years. Now, since the turn of the century, photonics is frequently used as the high tech term that encompasses, electro-optics, fiber-optics, lasers, solid-state lighting, material science and optics – wherever light is involved.

If science and technology deal with small things, we call this micro or nano: microelectronics, microbiology, micro-optics, nano-optics, nanophotonics – I never heard the term microphotonics. It seems that the term micro was already unfashionable when optics was renamed to photonics. To my understanding these new labels or tags are effective to fulfill the common demand for novelty in research and research funding, even if the ideas behind are well-known since long – just politics. For micro-optics, which we will discuss in detail in the following, most ideas and concepts have been proposed long time ago. However, novel microfabrication and wafer-based manufacturing technology that now allows to realize and commercialize micro-optics in a way scientists have dreamt for generations.

History of Micro-Optics

Micro-optics is actually a very old concept in Nature. Compound eyes first appeared during the Cambrian period, about 540 million years ago. Still today, similar concepts for compound eyes based on microlens arrays are the most appropriate solution for all insects and crustaceans.

The first micro-optics research projects in history were much related to the development of microscopy. In the 17th century, Robert Hooke and Antonie van Leeuwenhoek both developed techniques to manufacture small glass lenses to improve their microscopes. Hooke melted small filaments of glass and allowed the surface tension in the molten glass to form the smooth spherical surfaces required for lenses. These tiny lenses served as front lens in Hooke's microscopes and radically improve the resolution beyond everything seen before. Hooke was the first to observe plant cells, micro-organisms – and also the microlenses of a fly's compound eye. In 1665 he published his famous book "Micrographia" describing his groundbreaking observations. The book was a real bestseller and inspired, amongst many others, also the Dutch Antonie van Leeuwenhoek. Leeuwenhoek further im-

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received his Diploma in Physics in 1989 and PhD in 1994 from the University of Erlangen-Nuernberg, Germany, where he worked at the Applied Optics Institute (Prof. Adolf W. Lohmann, Prof. Johannes Schwider) on holographic optical elements for optical interconnects and backplanes. After his PhD he worked at the Institute of Microtechnology (Prof. René Dandliker, Prof. Hans Peter Herzig) at University of Neuchatel, Switzerland, on micro-optics for biosensors, for optical interconnects, for photolithography system and miniaturized imaging and camera systems.

In 1999 he founded together with Martin Eisner, Kenneth J. Weible and SUSS MicroTec a joint-venture focusing on research and manufacturing of micro-optics. In 2002 this spin-off changed its name to SUSS MicroOptics SA where he serves as CEO. His main research interests include scientific and technical aspects associated with micro-optics and miniaturized imaging systems. Reinhard Voelkel is member of the German Optical Society (DGaO), the Swiss Optical Society (SSOM), the European Optical Society (EOS), SPIE and the Optical Society of America (OSA).

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proved the lens manufacturing technique and built hemispherical lens for microscopes achieving typically 50x to 300x resolution. Recent studies proved that some of Leeuwenhoek's microscopes were even able to resolve structures in the micrometer range. Leeuwenhoek was the first to observe living bacteria, blood and sperm cells, and therefore is commonly recognized as the father of microbiology. Small hemispherical lenses, more "minilenses" than microlenses, were the key enabling component for revolutionary discoveries and the start of new branch of biology which influences our life until today. It took almost 200 years until Ernst Abbe in 1880 managed to manufacture microscopes with higher resolution then reaching the so-called Abbe-limit.

First endoscopes to look inside the "canals and cavities of the human body" were developed in 1806 by Philip Bozzini in Vienna, Austria. It took another 150 years until the German Karl Storz and researchers at Olympus in Japan were able to provide fully developed endoscopes for medical observation and minimal invasive surgery. A very impressive success story which has much impact until today. Miniaturized lenses, microlenses, rod lenses or fiber bundles are the key components for image transport and illumination in all – now – so-called classical endoscopes. The future generations of endoscopes will use miniaturized CMOS image sensors (CIS) and LED or O-LED illumination. Microlens imprint lithography (SMILE) and wafer-level packaging (WLP) are used to manufacture disposable endoscopes providing high-miniaturization, excellent imaging quality and low costs.

Micro-optics is also a perfect mean for illumination systems. Fly's-eye condensers, also referred as microlens homogenizers, optical integrators and Köhler integrators, were already used in early slide and film projectors to improve the uniformity of the illumination light. In general, a first microlens array splits an incident light beam into beamlets. These beamlets are redirected by a second microlens array superimposed in the focal plane of a large lens. A uniform illumination is achieved in the superposition plane. Today, this microlens-based homogenizer concept is found in a wide range of products from micro beamers in mobile phones to DUV high-end wafer steppers in Semiconductor fabs.

In 1908, Nobel Prize winner Gabriel Lippmann proposed integral photography, a stereoscopic method using an array of small camera lenslets. In 1940, another Nobel Prize winner, Dennis Gabor, invented the Gabor superlens, intended to replace large and bulky lenses by a combination of two thin microlens arrays. Gabor's other – Noble Prize winning – invention of holography in 1947 and the appearance of first lasers inspired Adolf W. Lohmann in 1966 to invent the computer generated holography (CGH), a new concept for design and manufacturing of digital micro-optics which is widely used until today for laser beam shaping and many other applications. In 1977, Kenichi Iga was the first to propose 2-dimensional arrays of surface emitting semiconductor lasers, now referred as VCSELs. In 1982 he suggested to build of stacked planar optics, nothing different than the wafer-level packaging (WLP) of micro-optics.

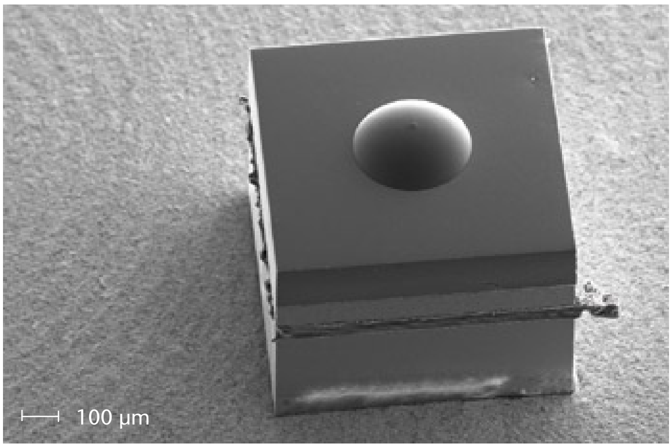

FIGURE 2: **Miniaturized wafer-level camera (WLC) for sensors and disposable endoscopes. German research project COMIKA (BMBF-VDI), 2009.**

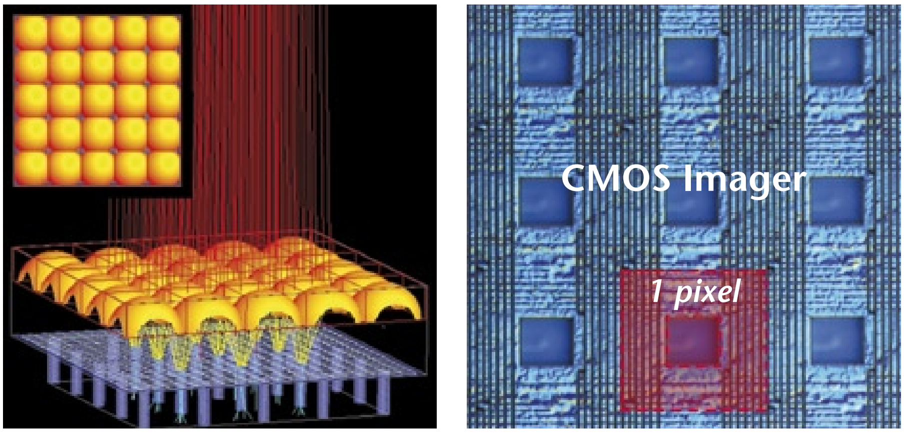

FIGURE 3: **Microlens on CMOS image sensor to enhance fill-factor.**

It is interesting to see how early micro-optics was actually invented. Unfortunately, these inventions were just nice ideas and concepts, but difficult or impossible to realize.

Manufacturing of Micro-Optics

Fortunately, much has evolved since first research groups and university institutes for micro-optics appeared in the 1980s. Researchers started to investigate suitable technology for design, simulation, manufacturing and testing of micro-optics. In the 1990s, a variety of novel techniques for micro-optics were invented and implemented. Consequently, a number of small and medium-size micro-optics companies appeared. The telecom boom, where microlens arrays were required for fibre arrays, optical interconnects and optical switches, emphasized commercialization. Today, microlens arrays are printed on CMOS image sensors to improve the sensitivity of digital cameras; the backlight illumination system of LCD displays consists of several sheets of array optics to ensure efficient and uniform illumination; cylindrical microlens arrays enlarge the viewing angle of screens; microlens arrays collimate and focus light in high-speed photonic switches; microlens beam homogenizers provide flat-top illumination for all kinds of high-power lasers; diffractive and refractive micro-optics in Fused Silica and Calcium Fluoride are key enabling components for high-end DUV lithography systems printing sub 40 nm structures on 300 mm wafers.

In the first decade of the 21st century micro-optical components and modules became enabling key parts for many applications and products. However, micro-optics industry remains still divided into two groups:

a) Small niche players supplying high-quality key components in low volume, e.g. for laser, telecom, medical and metrology. Wafer-based manufacturing technology adapted from semiconductor industry is the preferred approach to manufacture

FIGURE 4: **Mask Aligner MA/BA8 Gen3 dedicated for Wafer-Level Camera (WLC) manufacturing and packaging.** (www.suss.com)

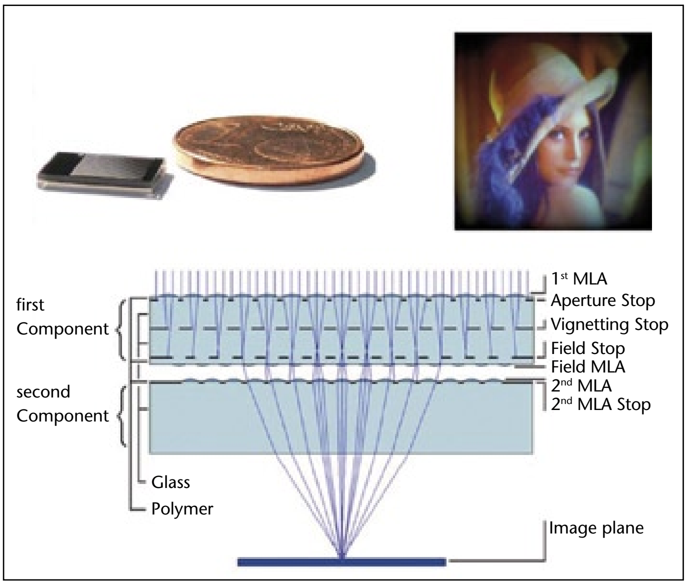

FIGURE 5: **Ultraflat WLC inspired by Gabor superlens and compound eyes, invented at Fraunhofer IOF, Jena, Germany. [Opt. Exp., Vol 17, No 18, 2009]**

this high-quality micro-optics with nanometer accuracy for niche markets.

b) Big companies supplying high-volume and low-costs micro-optics for the consumer market. Roll-on stamping machines, embossing, casting and other mass-production techniques are used to manufacture micro-optics at very low cost.

In both market segments, the availability of standardized "off-the-shelf" micro-optics is very poor. Micro-optics is manufactured on customer's request. Micro-optics is often a difficult-to-implement and exotic solution. A small supplier base, high prototyping costs, unwanted diffraction or interference effects, and difficulties to measure and classify the quality are the major drawbacks.

Wafer-Level Cameras (WLC) for Mobile Phones are the Incitement for a New Micro-Optics Industry

Today, we see a new area of micro-optics manufacturing on the horizon. New wafer-based manufacturing technology like microlens imprint lithography (SMILE) and wafer-level packaging (WLP) allow to manufacture high-quality micro-optics at very low costs, and – even more important standardized manufacturing processes will also allow to manufacture low-volume niche products in these micro-optics fabs. In the near future, standardized micro-optics will be available in high-quality and low-cost, both for high-volume and niche markets.

The driving force behind this recent development is the mobile phone industry and its demand for cheap cameras. When the first camera phones appeared on the market in 2002, the camera was just another gimmick with limited value for the mobile phone user. Today, about 80% of the mobile phones have a camera inside. For high-end mobile phones, a camera is an indispensable part; moreover, such phones are usually equipped with two types of cameras, a main or primary Mega-Pixel camera, used for photography and a sub or secondary CIF or VGA camera, used for video. For 2009 the amount of sub-cameras is estimated to be around 210 millions. Here costs and size are the major issues. Such low-cost cameras also serve as primary camera in budget phones, webcams, security, toys and mobile gaming platforms.

Some years ago, a leading mobile phone company promoted wafer-level cameras (WLC) as being the ultimate technology for mobile phone cameras.

The wafer-level camera (WLC) approach sounds rather simple: All components are manufactured on 8″ wafer by microlens imprint lithography, deposition, lift-off, screen printing, powder blasting and glues dispensing. The optical wafers are then mounted together with micrometer accuracy in a mask aligner. The camera wafer stack is mounted by wafer-level packaging onto a full CMOS image sensor wafer, or the camera wafer stack is diced into individual optics modules and then mounted onto individual CMOS image sensors. The complete mobile phone camera, including color filters optics, is manufactured and packaged on wafer-level using wafer-based technology. Despite WLC technology is still not mature, an estimated 80 million WLC modules have been delivered in 2009. The expected growth rate for WLC is so attractive, that most CMOS camera suppliers are now investigating WLC solutions.

The simplicity of the WLC concept often leads to the misinterpretation that CMOS manufacturers just have to use their highly developed semiconductor technology to manufacture the 8″ Opto-Wafers. Compared to CMOS manufacturing, the WLC with some bulky lenses should be rather simple to do. Unfortunately, these assumptions are not valid. New manufacturing equipment and processes had to be developed until technology frontrunners in WLC manufacturing, like Heptagon, Anteryon, Aptina, Tessera and VisEra, were able to deliver first WLC camera modules to the market.

Microlens Imprint Lithography

Enabling key technology for WLC is a cost-efficient manufacturing and packaging technology for lens, pupil and spacer wafers. The most promising technology is UV replication technology like microlens imprint lithography (SMILE), where a liquid polymer is dispensed on the wafer and the lenses are imprinted by using a transparent stamp or mold and UV-light for curing. Microlens Imprint Lithography allows the manufacturing of lens arrays with a submicron lateral accuracy on 8″ wafer level in a mask aligner. Accurate wedge error compensation and gap setting are crucial for microlens imprint lithography.

For microlens imprint lithography the master tool generation is a critical key technology. In the past, smaller lens arrays are used to build a larger lens master in a step-and-repeat procedure using a NPS 300 Nano-Imprint-Stepper. For 8″ lens masters with a sag height below 100 µm, high-quality microlens wafers manufactured by resist reflow and reactive ion etching (RIE) are well suited. Master lens arrays consisting of aspherical microlenses with profile deviation below 50nm (rms) and surface roughness below 2nm (rms) were demonstrated on full 8″ wafer scale by SUSS MicroOptics, Switzerland. Recently Kaleido Technology, Denmark, presented a first 8″ diamond milled lens master in brass, providing spherical, aspherical and free-form lenses with better than 2 µm lateral position accuracy.

The wafer-scale master wafers are then transferred into a soft stamp, usually made of Polydimethylsiloxane (PDMS) by casting. The PDMS layer serves as a stamp. The polymer lens material must be suitable for high throughput imprint lithography, reflowable and must have long-time stability in harsh environment (heat, humidity and sunlight). For long time, the choice of suitable lens material for microlens imprint lithography was very limited. Front runners in WLC kept their material a secret. Encouraged by high demand for microlens imprint lithography, other suppliers like DELO, Germany and Asahi Kasei, Japan, are now supplying suitable lens material to the market.

The current hype for wafer-level camera (WLC) will help to establish a new generation of micro-optics manufacturing companies. These highly specialized 8″ wafer fabs will master all micro-optics manufacturing and packaging technologies. They will also be able to manufacture most other micro-optical components, modules and devices at very low costs. The 8″ wafer standard will even allow to run small volume jobs with some 10 to 100 wafers only. Similar to the large semiconductor fabs in Asia, these fabs will increase the availability and improve costs for micro-optics. Current micro-optics manufacturers might focus on prototyping and master manufacturing. They might change to fab-light or even fab-less. As today's frontrunners in WLC still have to handle the rapid growth of WLC demand, this trend will not happen in the next 1–2 years. However, the low margins in mobile phone camera business will force them to open their doors for more profitable other micro-optics products very soon.

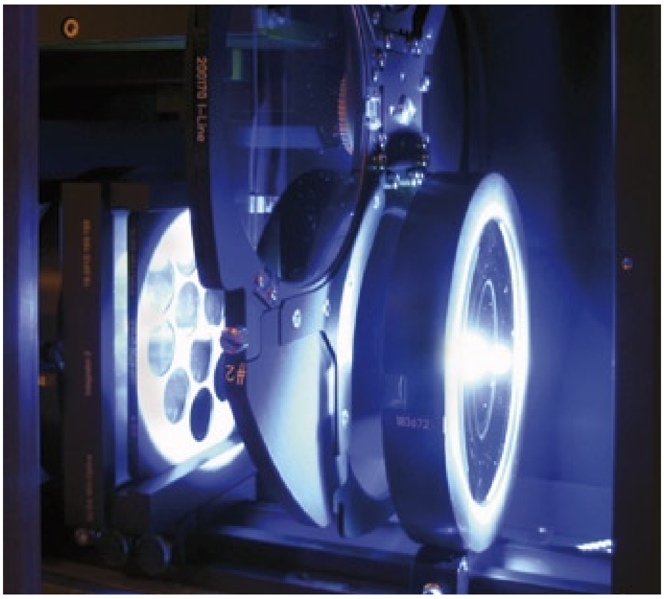

FIGURE 6: **MO Exposure Optics, a new illumination system for mask aligners based on microlens array homogenizers.** (Photo: www.suss.com)

THE COMPANY

SUSS MicroTec AG

SUSS MicroTec Group is a leading supplier of process and test solutions for micro-structuring applications with more than sixty years of engineering experience. Its solution portfolio covers all performance relevant steps for wafer processing ranging from coating, baking, developing, aligning to wafer bonding and testing and is complemented by specialized add-ons such as photomasks, Microlens Imprint and Nano-Imprint Lithography tools, micro-optics and wafer-level test accessories. SUSS MicroTec supports more than 8,000 installed mask aligners, coaters, bonders and probe systems with a global infrastructure for applications and service. SUSS is headquartered in Garching near Munich, Germany.

For more information,
visit www.suss.com.

Ultra-flat Micro-Cameras based on Gabor Superlens Concept

About 10 years ago natural compound eye concepts inspired micro-optics researchers to investigate ultra-flat imaging systems by combining flat layers of microlens arrays and image sensors [German Patent DE19917890]. Due to fundamental scaling laws in optics, a very flat camera approach is not possible with a single objective. Similar to miniaturized vision systems in Nature, multiple lens channels are used, whereas the image is either superimposed in the image plane or in a subsequent electronic system.

A recent publication from researchers at the Fraunhofer IOF in Jena, Germany, now shows a combination of a Gabor superlens concept and a superposition approach inspired by the compound eyes of nocturnal insects.

Microlens Array Homogenizer for Illumination Systems

In 1893, August Köhler of the Carl Zeiss corporation in Jena, Germany, introduced a new and revolutionary method for uniform illumination of specimen in an optical microscope. The Köhler method allows adjusting the size and the numerical aperture of the object illumination in a microscope independent from each other. Köhler illumination provides uniform illumination of the object plane independent of shape, extension and angular field of the light source. Köhler illumination was a major milestone in the history of optical microscopy and is still widely used today. Köhler illumination is also the basic principle behind laser beam homogenizing.

At the same time different types of fly's-eye condensers were invented to improve the uniformity of the illumination light in early slide and film projectors. The most effective form of a microlens homogenizer is a combination of two identical microlens arrays located at a focal length's distance of each other and a subsequent large lens.

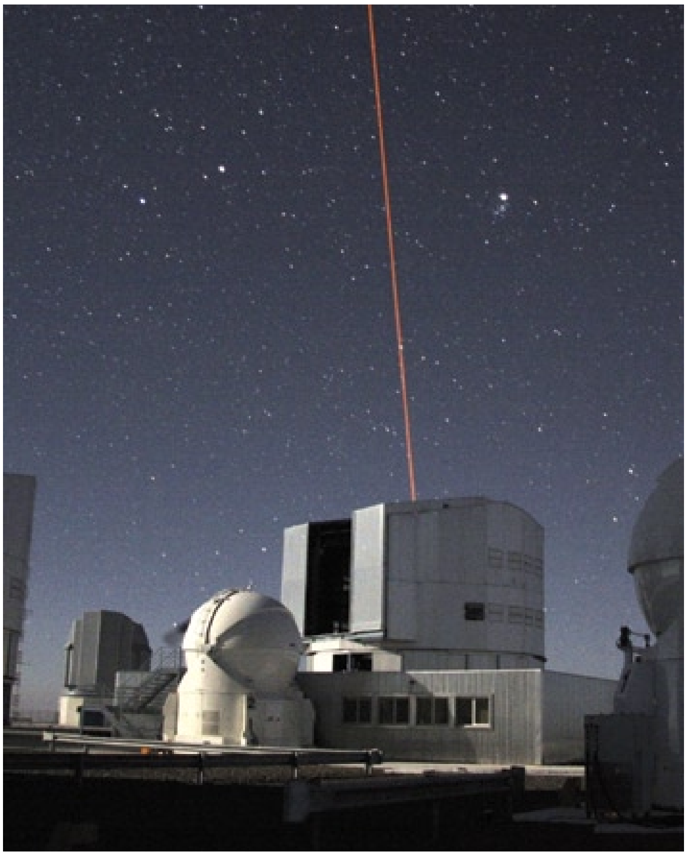

FIGURE 7: **A 50-cm wide yellow laser beam is coming out of ESO's Very Large Telescope (VLT) in Chile. The laser light illuminate Sodium atoms located in the upper atmosphere at 90 km altitude and creates an artificial star. The laser guide star (LGS) is analyzed by Shack-Hartmann wavefront sensors and used to optimize the adaptive optics of the telescope mirrors.** (Image by Sylvain Oberti, ESO)

First microlens array splits an incident light beam into individual beamlets. These beamlets are then redirected by the second microlens array superimposed in the focal plane of the large lens. A uniform illumination, often referred as "flat-top" is achieved in the superposition plane. It is not authenticated if August Köhler also developed fly's eye condensers himself. However, as each channel of the described microlens homogenizer represents a Köhler illumination system, such homogenizers are also referred as Köhler integrators. Today, this microlens-based homogenizer concept is found in a wide range of products from small micro beamers in mobile phones to high-end DUV wafer steppers in Semiconductor fabs.

MO Exposure Optics for Mask Aligners Based on Two Köhler Integrators

Most recently a novel illumination system based on two subsequent Köhler integrators has been introduced for mask aligners. For the new microlens based illumination concept, a first Köhler integrator is placed in the focal plane of the lamp ellipsoid. A second Köhler integrator is placed in the focal – or Fourier – plane of the first integrator. This combination provides both, a uniform light intensity and a uniform angular spectrum of the illumination light.

MO Exposure Optics significantly improves the uniformity of the exposure light (typically ±2 %), decouples the light for lamp position errors, improves telecentricity, and for the first time in a mask aligner, allows customized illumination and optical proximity correction (OPC) for cost efficient contact and proximity lithography. Customized illumination and OPC, both well established methods for high-end stepper lithography, will now also improve process window and yield for about 2'000 mask aligners installed in almost every microtechnology and semiconductor cleanroom and fab worldwide. Again, micro-optics is the key enabling element.

Array Optics for Testing – Shack Hartmann Wavefront Sensors

Micro-optics is also a key enabling technology for ophthalmology and metrology. In 1619, Christoph Scheiner, a Jesuit philosopher and astronomer, analyzed the aberrations of the human eye by using two pinholes. The Scheiner's disk isolates rays, allowing their aberrated direction of propagation to be traced. In 1900, Scheiner's test method was improved by Johannes Franz Hartmann, a German astrophysicist, and used to test the performance of the "Great Refractor", a 80 cm refracting telescope at Potsdam, Germany. Hartmann's method was to perforate an opaque screen with numerous holes. Each hole acts as an aperture to isolate a narrow bundle of light rays so they could be traced to determine any errors in their direction of propagation. Since rays are perpendicular to the propagating wavefront, any error in ray direction is also an error in wavefront slope. Thus Hartmann's method is commonly referred to a wavefront sensor.

In the early 1970s, Roland Shack at the Optical Sciences Center (OSC) in Arizona, USA, tried to improve the Hartmann screen test by replacing the pinhole array with an array of microlenses. At that time, appropriate microlens arrays were not available. Finally, he assigned Ben Platt, a graduate student, to develop the lenslet array for him. The student developed his own polishing machine to manufacture first cross-cylindrical microlens arrays suitable for the Shack Hartmann wavefront sensor. Today, Shack-Hartmann sensors are widely used in ophthalmology, astronomy, adaptive optics, optical alignment, and commercial optical testing. High-quality microlens arrays providing lateral position and beam point accuracy in the nanometer range are the enabling key component.