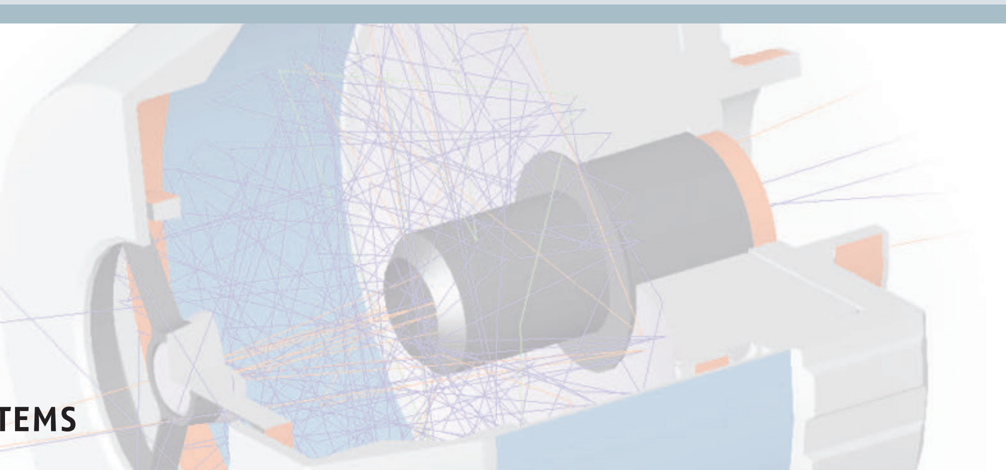


UV Light

DEMANDS ON OPTICAL SYSTEMS

Ultraviolet light is being used more and more in many high-tech applications such as semiconductor processing. Optical components and systems designed specifically for the UV are essential in order to use its significant potential benefits. Optical engineers must therefore have design knowledge appropriate to the UV and also be proficient in the technologies used to manufacture and test UV optics.

THOMAS THOENISS
STEFAN MEWES

Optical systems working with ultraviolet (UV) light below approximately 400 nm have typically been used for the optical detection of electric discharge (solar-blind method), criminalistics (crime scene inspection) or spectroscopic analytics. Over the past few years, however, UV light has also taken over other classic optical system applications, for example, industrial inspection or laser material processing. Another high-tech field, microchip processing, could not be imagined without UV light. The search for larger storage capacities using smaller semiconductor structures is intimately linked with the use of light of ever shorter wavelengths (**Figure 1**). For all these reasons, it is worth taking a closer look at the ultraviolet spectrum.

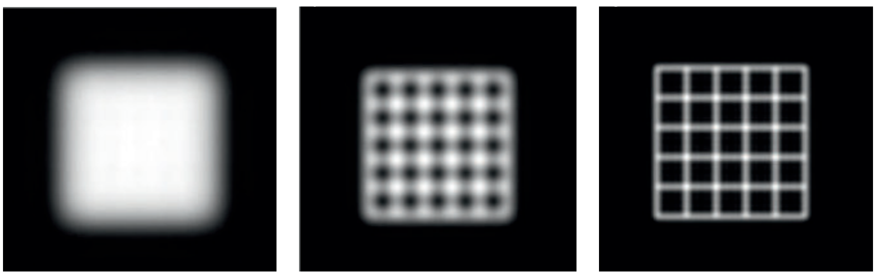
Broadband and narrow-band systems

Optical systems for the UV field can be sub-divided into two categories: Broadband and narrow-band systems. Broadband systems are used when broadband light sources such as Xenon lamps are employed. The light source spectrum can extend itself far beyond the actual UV field from visible light up to infrared light. A typical application is the inspection of wafer surfaces using stray light evaluation. For this purpose, high-resolution optical imaging systems are used that – with regard to their optical requirements – are often similar to classic microscope lenses.

The second category comprises systems that have been developed for specific (laser) wavelengths. Here, the field of application for narrow-band and high-resolution systems is (narrow-band) wafer inspection.

A further important field of application for UV optics is laser material processing. In electronics, printed circuit boards (PCBs) are structured using suitable laser light sources and optical systems such as F-Theta lenses and beam expansion systems. The desire to use light with even shorter wavelengths is justified by the increase in resolution of the processes, in order to detect or generate increasingly fine structures.

Diffraction theory shows that higher resolution can only be achieved by an increase in aperture or by a reduction of wavelength. However, from a technical point of view, the option of higher aperture has either been used already or cannot be implemented. Thus, the only way forward is to reduce the wavelength. Examples of UV lenses are shown in **Figure 2**.



1 Simulation of the resolution increase by reducing the wavelength: Illustration of a test structure at (a) 1064 nm, (b) 532 nm and (c) 266 nm in an aberration-free optical system

Challenges for the optical designer

As with all lens systems, the UV-optical systems achieve high performance through the appropriate combination of optical materials with different refractive indexes and dispersions. In contrast to visible-light systems, only a few crystal materials are available to the optical designer for use in the UV system. The reason for this is that the transmission limit of the optical glasses is approximately 330 nm.

Furthermore, typical UV materials, such as quartz (SiO_2) and calcium fluoride (CaF_2) have a very low refraction index. Therefore, to generate the same diverging or converging effect as with a lens made of a highly refractive flint glass, the surface of the lens must be highly curved or several components have to be used.

Correcting chromatic aberrations is another significant problem, and not only when designing the system for broad spectral range. Even with high-resolution narrow-band laser systems, the laser band-width or picometer deviations in the center wavelength may decrease the resolution significantly. Therefore, color correction is not uncommon for these systems.

Effective mirror systems

The use of pilot or auto focus wavelengths in the visible or infrared spectrum also makes the color correction necessary. Unfortunately, with their dispersion properties, both the main UV materials, quartz and CaF_2, limit the options for chromatic aberration correction considerably, especially with broadband systems. While, due to their material properties, other UV transparent materials, such as LiF, can only be used with significant technological effort.

Finally, below approximately 130 nm, even the optical crystals absorb, so that only mirror systems can be implemented successfully.

Mirror systems (**Figure 3a**) are often a viable alternative to refractive optics. Mirror lenses do not have chromatic aberrations and can therefore be used as narrowband or as broadband over a larger spectral range, depending on the type of mirror coating used. For example, the Schwarzschild type of mirror lenses that are commonly used for micro inspections are noteworthy in two ways: through their comparatively long working distances and by a high transmission because of the few optical surfaces.

When designing UV optics, the optical designer looses an important correcting tool – the cementing of two optical elements made of different materials. Optical adhesive cements that are transparent, have long-term stability in the UV and do not outgas or age are generally not available. As an alternative, the optical elements can be positioned as close to each other as possible consistent with a minimal air gap. This makes the design and production of such systems a special challenge that will be commented on in the following [1].

UV systems demand the highest possible resolution. In imaging systems, stray light that occurs as a result of surface scattering on the lens surfaces or reflections on the mounting elements can be perceived as an incorrect signal by the detector. This results in the image contrast being reduced. Therefore, following optical correction, high-resolution systems also undergo minimisation of the veiling glare. In contrast to classic optics design, special software packages or modules are used here – the non-sequential raytracers such as ›TracePro‹ from Lambda Research (**Figure 3b**).

Challenges in optics production and coating

The processing of optical UV materials is an especially challenging task. Materials such as calcium fluoride are very sensitive and are prone to micro cracks and to crack-outs. They cannot be processed using common polishing materials. Despite taking the greatest amount of care when lapping or polishing, a residual surface roughness on the optical components will always remain after the process.

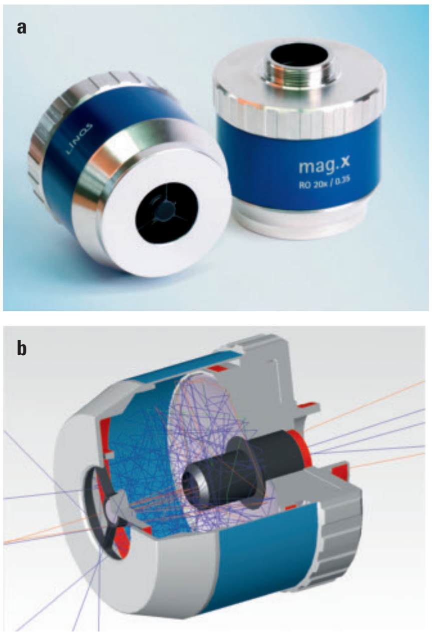
With imaging systems for visible light, the typical surface roughness lies between 1 and 2 nm. Compared to the light that contributes to the imaging, the proportion of light scattered at these micro structures is negligibly small. Transmission loss and contrast reduction are kept within a justifiable range.

However, the scattering capability of a surface increases considerably with decreasing wavelength [2]. This requires

a

b

2 Example of a UV-VIS broadband camera lens for 240 up to 700 nm (a) and a high-resolution long-distance inspection lens for 266 nm (b)



3 UV-VIS mirror lens (a); evaluation of the stray light distribution in a mirror lens using non-sequential raytracing by TracePro software (b)

▶ an advanced surface quality. Micro roughnesses between 1 and 0.1 nm are achieved using special complicated and in some cases, multi-stage polishing procedures (super polishing).

As with the optical materials, the absorption losses of the coating materials also increase considerably in the UV. For this reason, the overall transmission of the optical system is reduced, along with the damage threshold of the individual components. The challenge when coating optics with reflection reducing or with highly reflective coatings at shorter wavelengths lies in the significantly reduced number of usable coating materials available – just as is the case for the optical design.

Typical oxide materials for vapor deposition that are used with visible wavelengths cannot be chosen for many UV applications as they have considerable absorption loss at 193 nm. Conventionally deposited fluoride materials can reduce the absorption, but as a result of their layer growth characteristics (layer morphology), they suffer from increased scattering and the generation of micro cracks.

As a result of the limited materials selection for shorter wavelengths and the large spectral range with broadband systems, more complicated layer designs have to be created to ensure a high degree of transparency, or with mirror systems, a high degree of reflection (Figure 4).

The demands on the coating process itself are more stringent, as that process has a considerable influence on the surface quality (cleanliness, micro roughness) and even on the actual shape of the surface of the optical components.

The extreme performance requirements of the UV systems mandate optical components that, in some cases, have a surface accuracy way below $\lambda/10$. The coating process must be optimized so that this surface quality is also maintained after the coating.

Precise mounting technologies

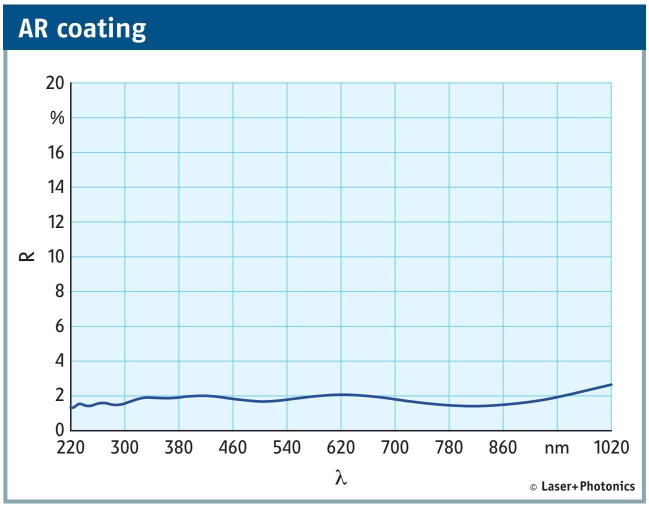
The performance requirements for optical systems make a precise mounting technique indispensable. The smallest positioning error can lead to a considerable loss of the imaging quality. UV systems pose additional challenges. In the previous section, we mentioned that refractive UV systems utilise gaps that are as narrow as possible. These narrow air gaps between the optically active surfaces can be extremely sensitive and are sometimes only a few microns in width.

Common positioning faults – caused by production tolerances of the optical elements and by integration tolerances such as the longitudinal and lateral shift and the tilt during assembly – can be of the same magnitude as the actual dimension of the air gap. Further reduction of the production tolerances of the mechanical mountings and the optical components is not advisable.

Special technologies are also required to maintain the high imaging performance when assembling such systems. Optical components or sub-systems of a lens can be adjusted while measuring the imaging quality, to maximise performance. To this end, optical components that have a direct influence on certain aberrations are selected in the optical design process. These elements are incorporated in the mechanical design in such a way that a

CONTACT

Linos Photonics GmbH & Co. KG,
D-37081 Goettingen/Germany,
Tel. +49 (0) 5 51 /69 35 -2 00,
Fax +49 (0) 5 51 /69 35 -3 33,
www.linos.de



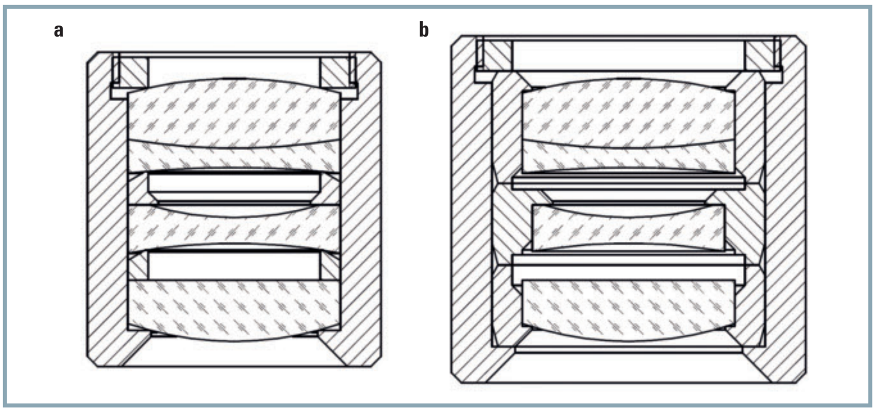
4 Super broadband anti-reflection coating for 220 up to 950 nm

defined lateral or longitudinal shift can be carried out. The elements can then be fixed after the adjustment (**Figure 5a**). In some cases, these adjustment methods are relatively complicated.

A further method is widely used in microscope lens production. The individual lenses of a system are mounted in their own sub-mountings (**Figure 5b**). These are optically aligned on specialized machines and the mounting diameters and lengths are very accurately machined using diamond turning. The individually sub-mounted optical elements now have an accurately defined geometry. If these elements are then assembled in a precise cylindrical outer mounting, the ensuing optical system will have very small errors and therefore near design imaging performance.

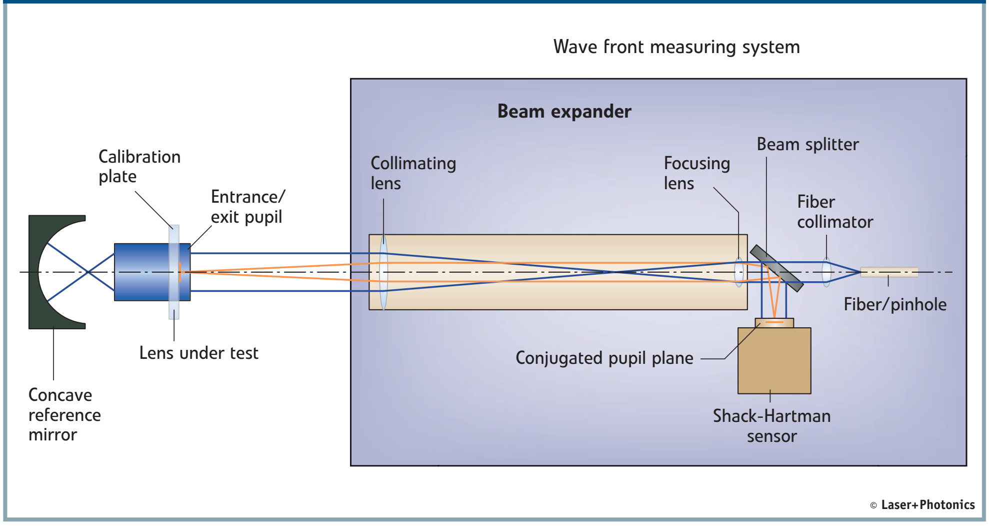
Additional adjustment steps then allow further optimization to be carried out on the imaging performance. Leading German companies and institutes have pushed this technology to the limits in an ambitiously funded project. Typical tolerances using the most up-to-date processing technologies now go as tight as 1 µm [3]. Another challenge is fixing the optical element into the mounting. With simple systems, retaining rings can be used to fix the lenses in their holders with a sufficient degree of accuracy. This accuracy is not good enough for high-performance systems. The conventional method of fixing the lenses into the metalwork, as used in the visible spectral range – glue and then position while observing – is usually not permitted in the UV field. The organic glue materials are immediately exposed to direct or scattered UV light in such systems and are subject to increased aging and outgassing.

Furthermore, the outgassing can lead to light-absorbing materials being deposited on the optical components. For this reason, special precise mounting technologies are required that work without optical glue. Strain relief techniques must be used as the optical crystals, such as calcium fluoride, are sensitive to mechanical stress.



5 Mounting examples with (a) classical drop-in assemblies and (b) precision mounting technologies with sub-mounted optical components

Wavefront measurement setup



6 Diagram of the wavefront measuring system implemented by Linos for measuring high-resolution lenses for UV applications

Metrology for the ultraviolet spectrum

With imaging systems, the optical imaging performance is generally found by calculating the modulation transfer function (MTF) from the point or edge image evaluation. This classic method can only be used with UV systems to a limited extent. On the one hand, there are hardly any commercial measuring devices available for carrying out MTF measurements in UV light and on the other hand, the resolution is so high that this measurement technique also reaches its physical limits [4]. The evaluation of the wave front generated by the optical system to be tested is the standard procedure, for example, for evaluating high-resolution microscope lenses. For this purpose, interferometers are used that have been designed for a specific wavelength. The evaluation of systems over a greater spectral range or with several discrete wavelengths is generally not possible or only obtained with a great amount of effort.

A feasible alternative is wave front measurement using wavefront sensors constructed according to the Hartmann Shack principle [5, 6]. Such sensors are not only less expensive, due to their principle design, but can also be used over a greater spectral range due to their robust evaluation methods. The adaptation of such sensors to other spectral bands will be possible, a step whose benefits clearly justify the effort involved.

Linos Photonics has implemented a system for measuring high-quality optics that combines concepts from classical interferometry and the Hartmann Shack method (Figure 6). The Linos device enables optical systems to be measured in a double-pass configuration. The return path is generated by reflection from a highly accurate surface – for example, a hollow sphere. The wave evaluation itself is finally carried out by a Hartmann Shack Sensor. ■

Summary: Co-operations and funding projects necessary

The manufacturing of optical systems for the UV is impossible without special know-how and technologies. The technical challenges are growing, as the trend towards even shorter wavelengths and higher resolutions accelerates. For this reason, well-known institutes and companies, such as the Fraunhofer Institute for Applied Optics and Precision Engineering in Jena/Germany, are already working on the next generation of optical systems for the EUV/XUV and even soft X-rays. Here, only mirror systems with specially polished and coated surfaces are used [7]. Further challenges, exclusive to these wavebands, such as avoiding photo contamination by the correct handling of optical components, has not been described in detail. The main driving force for such systems is EUV lithography. The technological effort involved in such systems is enormous and almost impossible for individual companies to handle. Co-operation between different companies and institutes is indispensible and the support of projects in this field by appropriate funding programs is to be highly desired.

AUTHORS

THOMAS THOENISS is head of the development department and STEFAN MEWES is a project manager with Linos in Goettingen/Germany.

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