Excimer Laser Micromachiner's Optics Primer

Optics Fundamentals

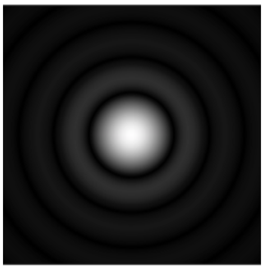
In what follows, we have attempted to condense complex optical theory into a few paragraphs for the non-specialist. This has entailed many omissions, and, in the interests of clarity, some gross oversimplifications. The optics specialist will excuse us, - but then he has no need of this text.

Excimer laser micromachining by **mask projection** at appropriate **demagnification** is a **flexible, non-contact** way of defining the irradiated area on a part. The 'ideal' mask projection system would project a 'perfect' image of the mask, faithful in every detail. This is not possible; performance is always limited by either **optical aberrations** of the imaging system, or by more fundamental effects linked to the **wave nature of light.**

The term **diffraction-limited** is easily interpreted as 'good', but this is a misunderstanding. Any lens can be described as diffraction limited if performance is determined by the diffractive behaviour of light in the lens aperture, rather than by the lens aberrations, which of course get larger in magnitude, and more difficult to correct, as the aperture is increased and rays, (that convenient fiction being perpendicular to the wavefront) trace paths further away from the axis. Thus any lens is diffraction limited at a small enough aperture, for e.g. a 100mm f.l. singlet is diffraction limited up to an aperture of 5mm or so. A lens with more elements which remains diffraction limited at a larger aperture might be described as good,- it certainly will be more expensive.

Why does aperture matter?,- since laser radiation is highly directional one might argue that the laser beam can be directed into quite a small aperture anyway. The answer has to do with the **resolution** of the final image.

For a lens whose performance is limited by aberrations, the attainable image resolution will depend on the specific nature of those aberrations and is difficult to predict in a general way, though characterization tools such as **MTF** (Modulation Transfer Function) exist. For a diffraction-limited lens however, the theory is essentially unchanged since 1834 and allows an accurate prediction of performance, which also depends on the light source characteristics. The first thing to note is that, even in a 'perfect' optical system,- and due to the wave nature of light,- a point source is imaged, not as a point, but as an **Airy pattern**, with strong central maximum and outer rings. The size of the Airy pattern is intimately linked to the ratio of focal length to aperture of the lens,- the f#,- or the **numerical aperture** n.a.=1/2f#.



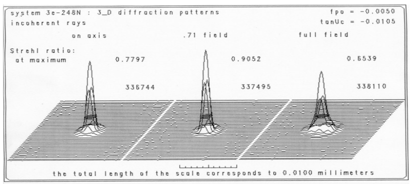
Sharpness of image is a subjective concept that needs a yardstick definition to be useful. The most common remains the **Raleigh criterion**, stating that two point sources (stars, in the original definition) will be just resolved (distinguishable as separate point sources) when the central maximum of the Airy pattern of the second point falls on the first dark ring of the Airy pattern of the first. According to this criterion, the resolution can then be shown to be 1.22 x $\lambda/2$ x n.a. This is an unduly pessimistic view, since it only considers intensity variations along the line joining the image centres; in practice of course the image is a 2D plot and there is no difficulty in telling that there are two point sources, even at closer separation than the Raleigh criterion would suggest, so that the factor 1.22 can be reasonably ignored. The **Sparrow criterion** for just resolvable points is 0.96 x $\lambda/2$ x n.a., and can be safely converted to the more easily-remembered rule of thumb,- **resolution = λ x f#.** Thus the basic resolution limit for a diffraction limited lens,- beyond which nothing can be resolved, is independent of lens type or 'quality', & depends only on wavelength and f#,- nothing else.

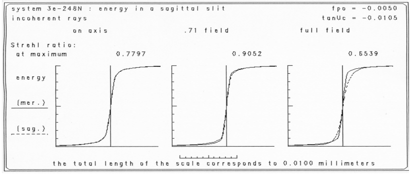
The exact details of image contrast as the resolution limit is approached depend on source characteristics and on the pattern to be projected. For example; if the object happened to be a grating of parallel lines, then, for monochromatic coherent light, a diffraction pattern will be formed, consisting of a central zero order luminous strip, and less intense satellite strips. If the position and aperture of the lens (i.e; the n.a. in object space) are such that only the central strip can enter the lens aperture then there will be ZERO contrast in the image. In the case of an excimer laser with mask projection there is still machining, because there are photons & energy, but no structure, since there is no **information** about the mask(the author has demonstrated this). As line spacing is increased to allow the central strip and the first satellites to enter the lens pupil then the contrast abruptly jumps to that of a **sine grating**; as higher order strips are admitted (either bigger line spacing or increased n.a.) then the detail of intensity distribution in the grating will be developed,- much as the higher order components in the Fourier series representation of a **square wave** are required to bring out that detail. For incoherent illumination, or an irregular array of lines etc., there is typically 50% contrast modulation at the critical point above, weaker at finer spacings, dropping to zero at the resolution limit, and stronger as the ratio between n.a. and spatial frequency increases.

Note that near the resolution limit the image contrast also depends strongly on focus, typically with defocus fringes being formed, sometimes with reversed contrast. The behaviour of through-focus fringe structure remains an excellent indicator of lens defects, and often used in final testing (star test).

Practical Lens Characterization

The theoretical definition of lens resolution refers to points which are 'distinguishable'. However, micromachiners usually expect features to be 'distinct',- which is another matter. To do that the required resolution might be some factor below the desired **feature size**, depending on the complexity of the feature. One can argue that a letter 'a' is more complex than a square, which in turn is more complex than a circle; thus there is no agreed standard for feature size. In many cases, feature size and resolution are confused,- sometimes deliberately so by optics vendors. A useful guide might be to think of the resolution as the rounding one observes in the corner of a square, or the distance over which substantial changes in energy density will take place in the image. Thus it is misleading to quote 'minimum feature size' without specifying the nature of the features in question.





Optec characterizes the performance of projection lenses in several ways. The first is the lens resolution according to the rule of thumb criterion, representing the smallest resolvable distance between two points in incoherent light (approximately the case for an excimer laser). The second is the point spread function, essentially a 3-D view of the Airy pattern modified by those residual aberrations and wavefront distortions, the third is the image energy density profile corresponding to a sharp edge in the mask; the **edge contrast profile**, and its slope at the 50% power point, usually quoted in % per µm, and giving a much clearer idea of the actual performance to be expected. Finally we may also refer to the related **Strehl Ratio** which is a measure of how closely a practical lens design approaches a completely aberration-free equivalent. This is a stringent test; in practice a Strehl ratio exceeding 50% will already perform quite well in practice.

Note that, to a first approximation, the 50% slope of the edge contrast profile is determined by diffraction effects and limited by the n.a. of the system (large aperture), whereas the high and low energy tails are due to lens aberrations (small aperture). A compromise between these conflicting requirements is provided by a process lens iris, which also affects DOF. Note that the actual ablation resolution depends also on the ablation characteristics of the material,- see **artifacts**.

DOF

The **depth of focus** (depth of field in object space, DOF for both) is given in optical theory as 2 x $\lambda/(\text{n.a.})^2$, and represents the distance over which the resolution is not dramatically affected by focus position. Thus, high DOF inextricably means low n.a.(high f#), and therefore some limitation on resolution. A high n.a. diffraction limited lens can always be stopped down(i.e. operated at reduced aperture), but one cannot have big DOF and high resolution at the same time,- a fact known to microscopists for centuries,- and compromises may be required. Sometimes we deliberately use low n.a to enhance DOF.

Scale, Focal Length & Working Distance

It might seem odd that what might seem the most obvious characterizing feature of a lens,- its focal length,- has not been mentioned so far. This is because for a diffraction limited lens focal length as such is NOT a determining element in image resolution. However, aberrations scale linearly with focal length, whereas n.a. does not, so as the system is scaled up it becomes increasingly difficult to maintain the diffraction-limited performance in a given design approach. Conversely, it is relatively easy to design a small focal length lens to be diffraction limited, at least up to the point where the manufacturing difficulty outweighs any advantage.

The **working distance** of the lens cannot be greater than the distance between the last optical surface and the part, but can be longer than the focal length, though it generally on the same order. Therefore for laser processing where one requires adequate working distance to protect the lens from fumes, spatter etc., or for other tooling, somewhat longer focal lengths, often of several cm, are desirable. Controlling aberrations to maintain diffraction-limited performance at adequate n.a. is then a challenging goal. Equivalent n.a. at larger scale also means physically larger lenses, though in general material costs/larger tooling costs do not become a major issue up to a glass diameter of at least a few cm.

A further point about scale is that for good optics lifetime the energy density on the various optical surfaces should be kept well below the energy damage threshold; all other things being equal, energy intensity on any surface scales as the inverse square of focal length. Finally, in the context of laser pattern projection, life is made easier when the lens aperture is on the same order as the size of the laser beam at mask level. All above considerations have often led to a choice of focal length in the range 50-150mm with n.a. on the order of 0.1, rather than the 5-15mm f.l. with n.a. maybe 0.4 and over commonly found in microscope lenses.

Field

So far, behaviour on-axis has been considered, in general processing over a certain area or 'field' is required. The ideal lens projects images onto a perfectly flat surface, but a practical lens always exhibits some curvature of the field as the image point moves away from the axis, while off-axis aberrations such as coma & astigmatism increase in magnitude to the point where the lens is no longer diffraction limited.

Note that for system scaling, the most useful expression of field is in an angular form, though the process area is usually the parameter of direct interest. Thus, to cover a larger area, a system can always be scaled up at equal n.a., provided the aberrations can be controlled at that longer focal length, as above.

Illumination

For a diffusely emitting object, rays enter the lens pupil in proportion to the n.a. in object space, which thus also affects the intensity of the image. However, for a directional laser beam, failure to direct the beam into the lens pupil will result not in an image of lower intensity, but in a loss of part of the image. Provided this does not occur, one might consider that all the photons go through the lens aperture, so, returning to the question posed early in this text***, why does aperture matter?***

Consider a mask consisting of holes, somewhat above the resolution of the lens. Most photons incident on the mask will simply travel straight through the holes, and provided those are directed into the lens pupil, which might be quite small, the holes will be imaged on the part. However, it is the small percentage of photons which pass close to the edges of the holes which truly define those edges, and those photons will be diffracted, forming an angular cone of scattered radiation in space.

It is the ability of the lens to gather those diffracted photons together and image them correctly onto the mask which constitutes the fundamental resolving power of the lens, related to n.a. as above, the vast majority of photons travelling through the hole away from the edges carry no information about the boundary of the holes, although they are of course useful for machining the material within that defining boundary. We can refer to these as the ‘main beam’ and the others as the ‘scattered beam’, although there is of course no sharp distinction between the two. Firstly, except for arrays of very small holes, the scattered beam is so weak and spread out that it is not observable in the ordinary way. Since the laser beam has controlled direction, a lens just before the mask can be used to converge the main beam into a small imaging lens aperture(defined by an iris), and thus use a low n.a.lens (for e.g. singlet) to image the holes, with no loss of image, or intensity, nor with the aberrations (including distortion) associated with the use of a larger aperture in that simple lens. The answer is that one can do this, but that the resolution of the edge of the holes will can never be better than that predicted by the diffraction-limited optical theory above. No additional optics can direct the scattered photons into the small aperture, whilst widening the aperture to include the ‘diffracted’ photons will simply lead to dominance of aberrations acting on those photons, though not, note, on the main beam.

The lens used to direct the illumination into the lens pupil is generally (with slight imprecision) referred to as a field lens. A true field lens is placed in an optical system at a conjugate image plane, i.e. AT the mask plane, rather than just before it, as is usually the case here.

Telecentricity

A hole can be drilled with the axis normal to the part surface, or inclined axis, either by tilting the part, or by tilting the illumination so that the ‘main’ beamlet passes non-centrally through the lens, and comes in at an angle to the part. For an array of holes, it may be desired to drill all with their axes normal to the surface, so that each beamlet strikes the part normally. The system is then telecentric in image space. As concerns the main beam, that condition can be achieved in a simple lens simply by ensuring that the laser beam is directed to a waist one focal length before the imaging lens,- so that rays emanate from that point and exit the lens parallel to the axis. As concerns the diffraction behaviour, aberrations must then be adequately controlled for rays in that telecentric configuration.

Illumination Uniformity

Multi-segment homogenizers work by dividing the beam into many parts and superimposing those parts in the mask plane. Since each part arrives at the mask from a different direction they will also arrive at the part from different directions, and the various sub-images must be superimposed in exact register. This places somewhat more severe restraints on DOF than the standard theory would suggest, since in the latter departure from correct focus leads to a progressive loss of resolution and modulation contrast,- the former leads to a catastrophic breakdown of the image formation mechanism.

Chromatic correction/confocalicity

Normally there is no attempt at chromatic correction in imaging lenses designed for excimer laser mask projection, partly because the paucity of choice of index in UV transmitting optical materials makes this a daunting task, and partly because the relatively small linewidth of the laser makes it unnecessary at the n.a typically used. However, the best way to view a part being processed, particularly for alignment purposes, is through the imaging lens (TTL image system), so that the lens must have reasonable performance at visible wavelengths. If, in addition, the lens is designed to have the SAME O/I conjugates and demag. at the UV wavelength and in the visible, then TTL viewing is accomplished with the CCD camera and mask in equivalent planes conjugate to the part plane, and this then permits change of demag. by moving lens and O/I optical path length/or part ***without*** moving the CCD camera. The advantage is that a part in visible focus is automatically in UV focus over a range of demag., much simplifying process work. Such a lens is termed (with slight inaccuracy) confocal.

AR Coatings

Any surface reflects $(\mu-1)^2/(\mu+1)^2$ of normally incident light, so that for typical indices in the order $\mu=1.5$, reflection runs at 4%/surface, in addition to bulk losses. For a multi-element lens, such losses become crippling unless dielectric AR coatings are applied, normally reducing R to levels of <0.2%/surface at the chosen wavelength. In a lens designed for TTL vision, double AR coatings may be required, for both UV and visible wavelengths.

Back Reflections

Internal reflections in a lens can give rise to ghost images. In laser processing, rays can be reflected and focussed by a concave surface, to damage another element, even for the low reflection from AR coated surfaces, and, depending on laser power, one may have to consider multiple reflections. The problem becomes difficult to treat for complex lenses, and is a major part of the lens designer's task. It is of particular relevance for short pulse lasers in the ps/fs regime.

Lifetime

Apart from humidity, which can damage lenses and coatings by encouraging fungal growth, a lens for high power UV faces two additional problems;- failure of the coating and progressive absorption in the bulk due to colour centre formation, so the concept of optics lifetime,- usually expressed in numbers of shots, and sometimes termed **laser durability**,- becomes important. Apart from 'bad' coatings, which fail quickly, coatings used at energy densities well within their rated tolerance can have extremely long lifetime if adequately protected from dust and atmospheric fumes, water or oil vapours, smoke etc. At 193nm, ozone formation is an important factor. The ideal is to use the optics in inert gas, usually dry nitrogen, free from dust. Colour centre formation in the bulk depends on trace impurities at ppm level, and is much improved over recent years with certified blank material. Except in very high duty applications (laser running continuously at high rep. rate), it is not nowadays a factor causing undue concern.

MicroMachining Artifacts

- **Ablation curve effects**; - for each material and wavelength/pulse duration one can measure the ablated depth per pulse as a function of energy density. Typically there is a low energy threshold, below which ablation approximates to zero, and a high energy saturation where higher energy density results in little extra ablation. depending on where on the curve one is situated the energy profiles at an edge can give rise to ablation effects with differing resolution compared to the actual optical resolution.
- **Cones & Ripples**;- at low energy density, and particularly in polymers, impurities may give rise to the formation of small cones in the ablated region, a phenomenon analogous with desert erosion. Surface ripples can arise through a complex dynamic process related mathematically to stop-go cycles in heavy traffic flow.
- **Corner effects**; - ablation from an external corner, i.e. step edge, is more efficient than from a flat surface, essentially because there are more possibilities for ejecta to escape, so that rounding of a step edge occurs when the whole surface is irradiated. In the same way, ablation is less efficient from an internal corner, leading to,-
- **Taper**;- the wall angle is never vertical, but has some angle, typically a few degrees. Lowest taper is obtained at highest energy density.
- **Synchronicity**; - at very small feature size, comparable to the photon diffusion depth in the material, it makes a difference if adjacent features are etched simultaneously, by a complex mask, or sequentially, by translating a simple mask. Fir example, a thin dividing wall between 2 deep pits might collapse due to the pressure waves whilst machining the 2nd one, but survive if they are milled together
- **Thermal Effects**; - Thermal effects rarely occur in a single pulse, but may be evident at high repetition rates, depending on the energy density and irradiated area.

Handy Formulae & Definitions

'Perfect' Optical system:- Raleigh limit of 'permissible' imperfections= 1/4wave
Infinity f#:- ratio of lens focal length F to dia. D
Half angle subtended α:- $=\sin^{-1}(D/2F)$ (N.B : for a lens with low aberrations 2nd principal plane will be close to **spherical**.)
Numerical aperture n.a.:- $=\sin\alpha$ (in air,- $n\sin\alpha$ otherwise)

n.a. = 1/(2f#) OR f# = 1/(2n.a.)

Original Raleigh criterion as image falling on first dark ring, leading to LRS $=1.22 \times \lambda \times f\#$
Alternative Sparrow criterion LRS $= 0.96 \times \lambda \times f\#$, or the simple Rule of Thumb:- LRS $= \lambda \times f\#$

Resolution & DOF **LRS = λ/(2n.a.)** or LRS$= \lambda \times f\#$ **DOF = 2 x λ/n.a.^{2}** or $8 \times \lambda \times f\#^2$

Paraxial lens formulae:-
Principal $1/u + 1/v = 1/F$ and $D = u/v$
Secondary $u=(1+D) \times F$ $v=(1+D)/D \times F$ $u+v=$TL(Track Length) $= (1+D)^2/D \times F$

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