



**MICRO/LAS**

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TECHNICAL INFORMATION



**RESOLVING POWER AND  
MODULATION TRANSFER  
FUNCTION**

## Microstructuring using UV light

Excimer UV light has become one of the most important non-invasive „tools“ for microstructuring by imaging a mask containing the pattern of interest onto a film or the surface (target) to be processed. Other means are X-rays, electron beams or neutrons. The power of imaging is due to the fact that structurizing a 2-D area becomes possible in one exposure, at the same time the control of the imaging parameters allows selecting the image size, e.g. by demagnifying.

However, the resolution achievable by the optical system limits the imaging quality: inspecting the image in detail shows that sharp edges or corners in the mask will be imaged into less sharp (blurred) edges or corners on the target. Similarly, tiny slits or holes will be transformed into slit or spot images with slightly blurred edges or circumferences, irrespective of attempts to focus as sharp as possible. This means that the light emerging from a point or slit source is never exactly focusable into a point or slit image but results in some intensity distribution or spread-out into adjacent areas. Therefore, in order to realize ambitious goals in microstructuring using imaging, an analysis of the image quality-limiting properties of an optical system is necessary.

There are a number of system parameters which influence the imaging quality as discussed below. Before listing them it is useful to describe a method to measure imaging quality. A widely accepted characterization is obtained by measuring the modulation transfer function (MTF) of the optical system.

### Modulation Transfer Function (MTF)

The experimental access to MTF is by imaging a bar code-like grating (in x-y plane, fig. 1) onto a finegrained film using white (natural) light. The illumination intensity is such that the blackening of the film is

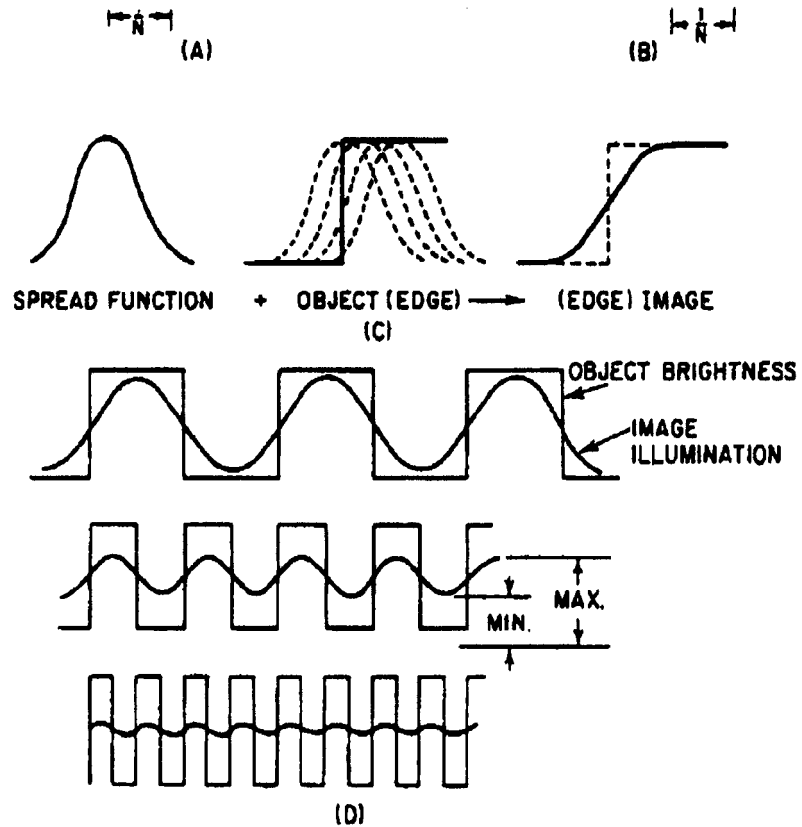


Fig. 1: The imagery of a bar target. (a) A typical bar target used in testing optical systems consists of alternating light and dark bars. If the pattern has a frequency of  $N$  lines per millimeter, then it has a period of  $1/N$  millimeters, as indicated. (b) A plot of the brightness of (a) is a square wave. (c) When an image is formed, each point is imaged as a blur, with an illumination distribution described by the spread function. The image then consists of the summation of all the spread functions. (d) As the best pattern is made finer, the contrast between the light and dark areas of the image is reduced. (Ref. 1)

within the linear section of its sensitivity response function. The grating consists of equally spaced black bars called „lines“ and white (or transparent) „spaces“ of the same width as that of the bars; for imaging the optical system to be characterized is used.

Ideally, the image would be also a grating in a plane parallel to the x-y plane, the grating width depending on the (de)magnification and the film being blackened (defined 100%) at the image of the spaces and clear (0%) at that of the black bars; thus, the intensity function is expected to be a rectangular trace. The intensity modulation or contrast of such an image, defined by the expression

$$(1) M = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})}$$

would amount to 1.

However, as mentioned above, a high-resolution densitometer trace

across a real image on the film reveals that the edges of the bars are slightly blurred. This does not impair the quality of an image for practical use as long as the dimensions of the pattern of interest are large in comparison to the extension of the blur.

However, when the number of lines and spaces per length in the object plane is increased – corresponding to a more densely patterned object – the blur zones are no longer negligible. A scan of the intensity function of the image of lines and spaces shows a bell-shaped trace, with the maxima below 100% and the minima above 0%. Clearly, this leads to a modulation or contrast  $M < 1$ . Consequently, plotting  $M$  as a function of

(2)  $v$  = number of line/space pairs per mm, called spatial frequency, as being measured with the optical system under investigation, yields a

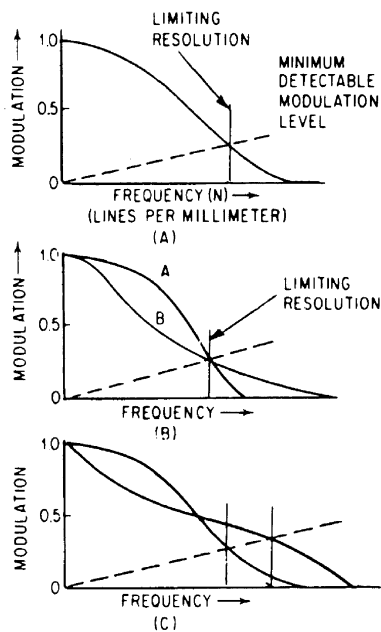


Fig. 2: (a) The image modulation can be plotted as a function of the frequency of the test pattern. When the modulation drops below the minimum that can be detected, the target is not resolved. (b) The system represented by (a) will produce a superior image, although both (a) and (b) have the same limiting resolution. (Ref. 1)

curve decaying from  $M = 1$  to zero with increasing  $\nu$  of the type shown in fig. 2. This curve is an MTF of the optical system obtained along one axis.

In order to achieve a complete characterization, the measurement must be performed over the whole image plane with a grating oriented along the x as well as the y axis. If CCD cameras are used, care must be taken that the pixel size of the CCD does not determine the limit of resolution (therefore, fine-grained films and high-resolution densitometry were mentioned above) – otherwise, the MTF of the camera would be measured.

The modulation transfer function is defined for an incoherent illumination. However the illumination can be arranged to underfill the NA of the objective lens. This leads to a contrast function which is represented by a rectangle shape. Higher contrast for low frequencies and lower contrast for high frequencies. The so called partial coherence factor for an illumination/imaging

system describes the ratio of filling the lens' NA.

$$k = \text{NA illum} / \text{NA lens}$$

( $k = \infty$  incoherent,  $k < 1$  partially coherent)

The MTF curve allows the determination of the minimal structure or maximum spatial frequency  $\nu$  which can be successfully imaged.

Obviously, this value is immediately related to the minimal M, the modulation or contrast, which can be recognized by a suitable recorder coupled to a microscope. In the case of vision, one speaks of minimal visibility.

However, what is the minimal contrast which can be „successfully“ recognized? Some reflections on the definition of resolution are necessary.

### Resolved or not resolved?

Scanning a pattern of two overlapping lines, situations as shown in fig. 3 may occur: in (A) the scanned structure is clearly not resolved (full

line), in (D) it is, and in (C) it is a matter of definition whether the full curve measured may be considered a resolved line pair which arises from the two components shown in the dashed curves. In addition, „scanning“ is meant to trace the „true“ curve without integration – hard to realize in any optical setup. Case (C) with the percentages displayed is known as the *Rayleigh criterion* for resolution; it arises from consideration of the ultimate resolution which can be obtained with an optical system.

Physically, the resolution ultimately achievable – that is after complete elimination of all technical lens aberrations – is limited by diffraction of the light at the lens' aperture, most impressively demonstrated by the diffraction pattern seen when a tiny slit is illuminated from one side and imaged onto a screen on the other side. On the screen, on both sides of the central maximum (peak) small intensity oscillations occur, the intensity approaching zero by destructive interference between the maxima. When the slit is continuously

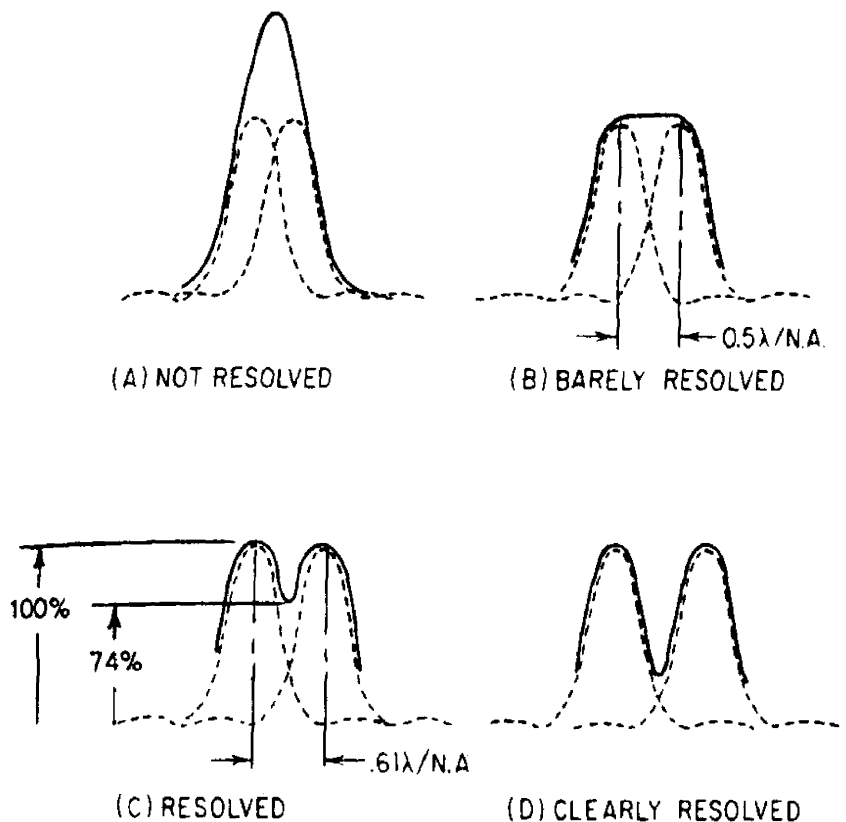


Fig. 3: The dashed lines represent the diffraction patterns of two point images at various separations. The solid line indicates the combined diffraction pattern. Case (b) is the Sparrow criterion for resolution. Case (c) is the Rayleigh criterion. (Ref. 1)

closed, the diffraction pattern spreads out and vice versa. If there are two independent but overlapping diffraction patterns resulting from two slits (which are coherently illuminated each but incoherently with respect to each other) then the corresponding peaks are considered resolved according to the Rayleigh criterion when the central peak of one pattern falls into the first minimum aside the main peak of the other pattern. Under that condition and with calculation of the exact diffraction pattern (Airy function, see fig. 4 & 5) the percentages displayed in fig. 3 (C) result. Diffraction limits the imaging quality of any optical instrument, e.g. the image of a star is not a point but a small Airy disk.

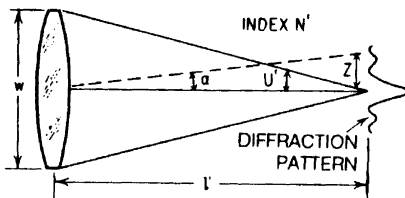


Fig. 4: Definition of NA

Whether two lines are recognized as resolved or not resolved remains, to a small extent, arbitrary since the existence of two instead of one peak may be recognized with higher or lower contrast as shown in fig. 3 (C). However, introducing that contrast (M) into the MTF („limiting resolution“ in fig. 2) of an optical system, the maximum spatial frequency imageable by that system can be found.

### Resolution, numerical aperture (NA) and depth of focus (DOF)

It is useful to notice here the physical law governing the limit of resolution of a lens when all aberrations have been corrected. The larger its aperture, the narrower the diffraction pattern which is caused by the edges of the aperture. For a microscope one finds as the diameter D of the diffraction (Airy) disk belonging to a point source imaged in distance a from the objective in the image plane

$$(3) D = 1,22 (a \lambda / R)$$

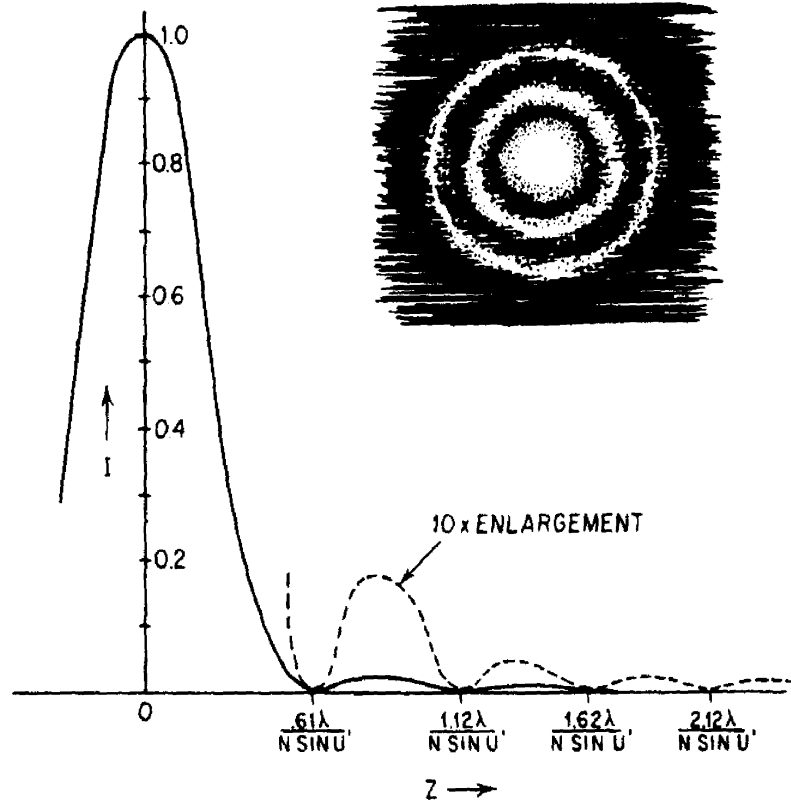


Fig. 5: The distribution of illumination in the Airy disk. The appearance of the Airy disk is shown in the upper right. (Ref. 1)

with R being the radius of the objective.  $R/a$  is close to the sine of the half angle beta (actually it is the tangent, however, the beta is small) under which the objective is seen from the image (which is assumed to lie on the optical axis).

On the object side, this angle corresponds to an angle alpha, half the angle at which the objective is seen from the position of the object, which is usually close to the focus of the objective. The product of the refractive index and the sine of the angle between the optical axis and an optical ray passing the objective at the largest angle is defined as the numerical aperture (NA, see fig. 4) so that

$$(4) D = \lambda / NA$$

holds in good approximation.

(4) explains why UV light is more suitable for microscopy and microstructuring than light in the visible. High NA is a means to increase the theoretical limit of resolution. However, the problems with optical

aberrations increase. Hence, a compromise must be found.

In imaging any structure, the depth of focus is of interest, that is, the distance by which the image plane can be shifted without considerable deterioration of the image quality. For convenience, the maximal shift is set  $\pm D$ , the diameter of the diffraction disk in the image plane, divided by  $2NA$ . This means that the image plane may be shifted so far that the out-of-focus blur reaches that due to diffraction. With (4) one obtains

$$(5) \text{DOF} = \pm \lambda / 2 (NA)^2$$

Obviously, there is another compromise necessary between the depth of focus, which ideally should be large, and the limit of resolution.

In any case, these considerations have to be adapted to the lens actually used, i.e. have to be discussed together with aberrations which cause deviations from the ideally plane image.

## Microstructuring by ablation using excimer lasers

A laser beam itself has a temporal and spatial coherence which makes the MTF theory not to apply. For example the diffraction at an aperture creates interferences between spatially coherent rays of the illumination on the substrate (eg typical edge interference pattern, see fig. 6). Thus the resolution is further limited or at least influenced.

Homogenizer illumination optics principally cut the laser beam into segments and overlay the segments at the object plane to create a homogenous intensity profile at the illumination field. The homogenizer creates an illumination which originates from several discrete virtual light sources. This allows to arrange a NA of illumination to match with the NA of the imaging objective.

Fortunately the excimer laser provides a beam which has only low spatial coherence of several  $100\mu\text{m}$ . This allows to apply excimer lasers for very efficient high resolution micromachining processes based on imaging optics.

As already mentioned, the decision which contrast is necessary to call a line pair resolved is somewhat arbitrary, the Rayleigh criterion just being convenient. In addition, it depends on the sensor. In the case of

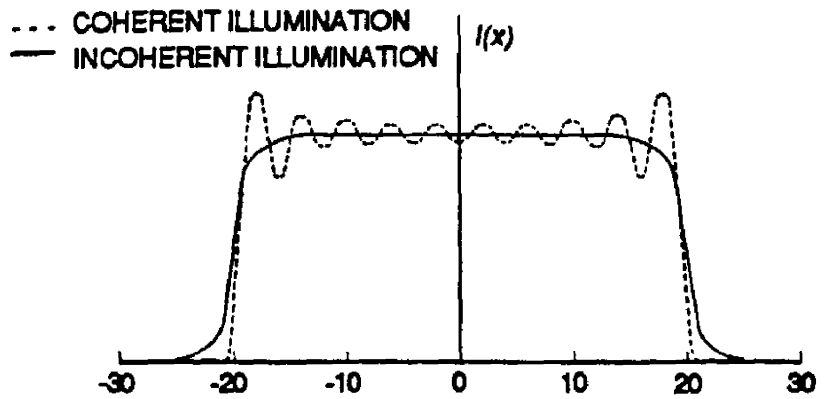


Fig. 6: Theoretical intensity distribution in the coherent and incoherent images of a slit. (Ref. 2)

excimer laser ablation, the sensor is the material to be ablated.

Ablation requires given energy densities per pulse (fluence,  $\text{J}/\text{cm}^2$ ). Once the critical fluence – which depends on the absorptivity of the substrate – is reached, the ablation starts as a non-linear process so that in the microstructure higher contrast values may be reached than would be measured optically. However, the contrast values obtainable by ablation can also be lower, e.g. limited by the structure of the material such as grain size.

This means that the spatial frequency obtainable in microstructuring by the use of a certain optical setup must be specified together with the substrate material to be processed.

A practical optical system is described in the following: The wavelength  $248\text{ nm}$  is applied at an energy density of  $0.8\text{ J}/\text{cm}^2$  in order to micromachine polyimide material (see fig. 7). The MicroLas large field objective  $5\times/18\text{-}248$  provides a diffraction limited resolution at  $\text{NA} = 0.13$ .

The modulation transfer function of the  $5\times/18$  objective for an incoherent illumination is shown in fig. 8.

The frequency of  $250\text{mm}^{-1}$  represents  $2\mu\text{m}$  lines and spaces. The contrast equals  $0.7$  at this frequency. This results in  $I_{\text{max}} - I_{\text{min}} = 0.82$ .



Fig. 7:  $5\times/18\text{-}248$ ,  $18\text{ mm}$  field of view diffraction limited lens,  $\text{NA} = 0.13$

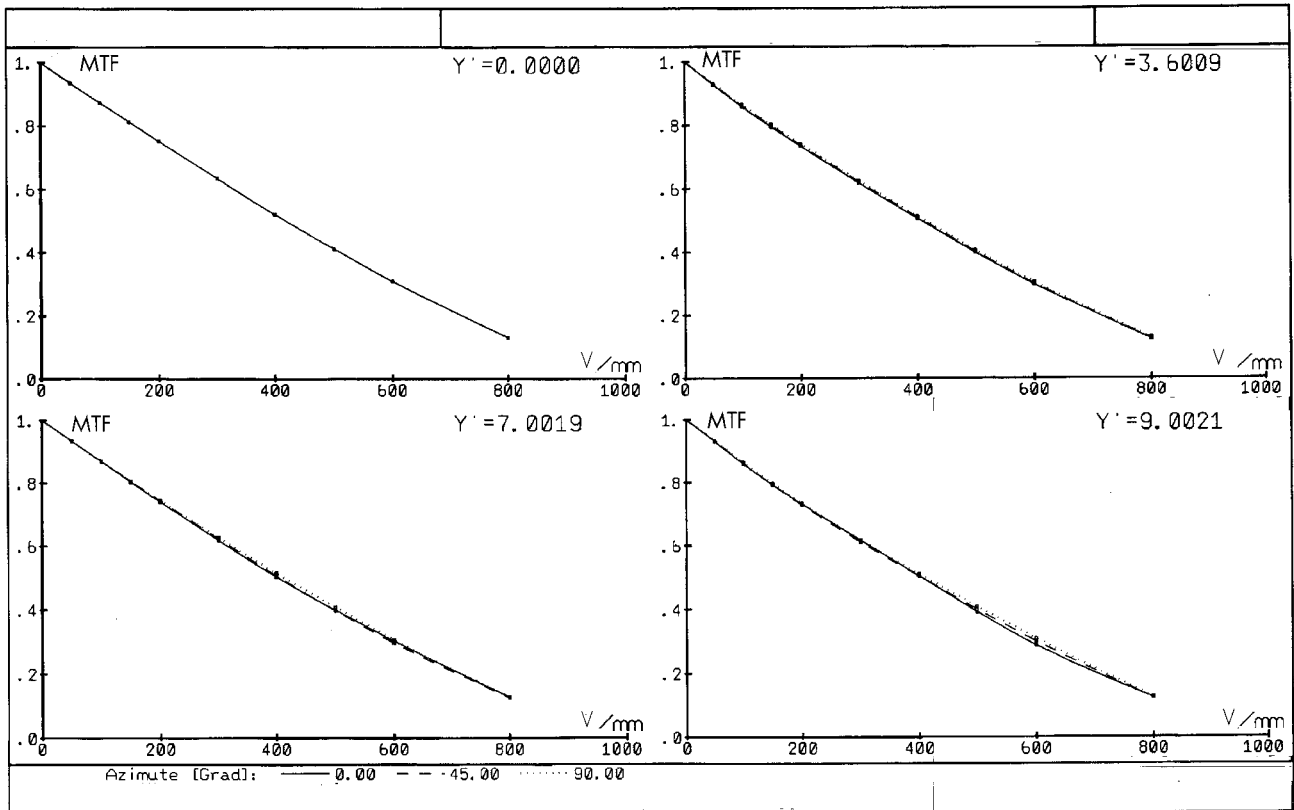


Fig. 8: Modulation transfer function of the projection lens 5x/18-248

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