

Optics compared to Quantum mechanics

Intro

Optics normally treats the behaviour of packages of light waves (photons). However, when passing through appropriately shaped fields, particles may behave similar as photons. A beam of electrons that is not too dense will under such conditions behave similar to light beams that pass comparable lenses. In a dense beam the electrons will influence each others path via their own Coulomb field.

The OTF

Cylinder symmetric lenses act as Fourier transformers of the information that pass its active surface. The aperture of the lens cuts the hologram that exists in that surface and contributes to the Fourier transform. The images formed are a convolution of the Fourier transform of what enters the active surface and the Fourier transform of the shape of the aperture. This means that the image at some distance from the active surface is blurred with the Fourier transform of the aperture.

This story only works when the photons interfere in order to generate the image. A small hole can do the job. Its aperture is small, so the energy flux of the passed wave packages is small. A possibility is to use a glass lens to create this effect. Glass lenses have a front active surface and a back active surface. Further the optical properties in these surfaces are not spatially uniform. A cylinder symmetrical lens suffers from Seidel aberrations and chromatic aberrations. The aberrations increase with the distance of the passage of the package to the centre of the aperture. Thus the formed image is not blurred with the Fourier transform of the shape of the aperture, but instead with the representative of the transmission characteristics of the area of the aperture. This Fourier transform characterises the optical properties of the lens. It is called the Optical Transfer Function (OTF).

The OTF as a function

The OTF is a two parametric function of the spatial frequencies $OTF(f_x, f_y)$

The OTF varies with the angle in which the impinging wave package enters the surface of the active aperture.

The OTF varies with the radial position at which the impinging wave package enters the surface of the active aperture.

The OTF varies with the radial position with the frequency of the waves contained in the package that enters the surface of the active aperture.

Also the coherence of the waves in the package influences the OTF.

When a flat beam of monochromatic light enters the active aperture, the lens focuses that light into a spot. That spot has a distribution which is the Fourier transform of the active aperture. It is called the Point Spread Function (PSF) of the lens for that light. For different frequencies of the light the lens might focus at different focus points.

If the beam enters under an angle, then the focus point lays excentric. The focus points constructed in this way form a convex surface.

The light packages that depart from a convex surface whose centre coincides with the centre of the active aperture form focussed images on a convex surface at the output side of the lens.

The MTF and the PTF

The OTF has a modulus, the Modulation Transfer Function (MTF).

The OTF has a phase, the Phase Transfer Function (PTF).

Each cut through the centre of the MTF is symmetric. At the centre of a cylindrical imaging system the MTF is also rotational symmetric. The MTF is usually specified in one or two curves. One specifying half of the broadest MTF cut and the other specifying the thinnest MTF cut.

Contrary to the MTF the PTF is hardly ever used for normal imaging purposes. However, for the production of holograms the PTF is indispensable as a quality measure for the imaging device. For these purposes the active aperture must act as a uniform phase transformer.

Chains of imaging devices

When two or more imaging devices in a sequence produce an image, then the OTF of the total is the product of the OTF's of the constituting parts. When one more of the parts absorb or (re)create the image, then the rule only holds for the MTF's. Thus in these applications the MTF is a useful quality characteristic in the same sense that a frequency characteristic is a useful tool for one-dimensional instruments such as amplifiers and filters. This also indicates that the MTF is a proper quality measure for image receptors such as silicon image detectors, image generators such as video screens and image convertors such as image intensifiers.

Measuring the OTF

Measuring the OTF is done by taking the Fourier transform of the PSF that corresponds to a point source of radiation. Since this offers very little energy to measure the effect, instead of a point source a thin slit is used as a source. The slit itself has a two dimensional sinc function as its Fourier transform. It is wide where the slit is thin and it is small where the slit is extended. It comes down to the fact that the measuring result is a slice through the OTF in the direction perpendicular to the direction of the slit. By rotating the slit, the full OTF can be measured.

It is already indicated that the OTF varies with the position in the image surface. This limits the length of the slit that can be used. And it limits the area for which the measuring result is valid. In fact it depends on the accepted measuring inaccuracy.

The measured OTF can further depend on the homogeneity of the source surface or on the homogeneity of the detection surface.

A simple apparatus for measuring the modulation transfer factor

When the image of a slit runs over a checkerboard pattern that is turned 45 degrees with respect to the orientation of the slit, then the signal falling through is a blurred triangle wave function. When the image of the slit is blurred enough the third harmonic of the triangle wave is filtered away and a proper sine wave results. What is left is to measure the amplitude (or the rms) of the signal. This apparatus works for a single spatial frequency.

The slightly more complex Odeta apparatus works on the same principle by rotating two plates with parallel lines in opposite direction. The lines create a diamond pattern that varies in its basic frequency. Odeta stands for Old Delft Transfer Analyzer.

Ruggedness of measuring equipment

The Odeta is a delicate instrument that finds its application area in lab environments. The Modulation Transfer Factor meter can be constructed in a ruggedized format. It can be used in a factory manufacturing line. It is limited to a single spatial frequency, which is usually taken at about $2/3$ of the spatial bandwidth of the test specimens.

Holographic screens

A glass lens usually has two active surfaces, which usually are called principal planes. One is situated near the input side and one is situated at the output side. These planes act as holographic screens. With respect to its action, the space between the two surfaces can be neglected.

Input/output surfaces

In most applications the input surface and/or the output surface is not a convex/concave surface but a flat surface. Further, the use of multi-chromatic light asks for measures against the fact that the focus surfaces depend on the colour. In order to still get a sharp image the lenses are built from several aspherical glass elements. Another solution is the use of fibre optic face plates that are convex at one side and flat at the other. This solution is often applied in high-tech electronic imaging devices.

A lens is characterized by four **cardinal points**: two points where a parallel beam focuses and two points where the principal planes cross the axis.

Useful opening angle

The focussing surface depends on the angular position of the object detail. With a given input and output space and a tolerated blurring measure the useful opening angle is bounded.

Rays

Rays describe the path of wave packages (or particles). The image formed by a lens can also be described by ray tracing. The rays form together the PSF.

Camera obscura and holographic screen

The hole in the camera obscura acts also as a lens. Its active surface acts as a single holographic screen.

This camera produces dynamic three dimensional images of scenes outside the obscured room.

If this picture is taken one dimension higher, then the screen evolves in a screen that coincides with a sphere.

This shows that a camera obscura has much in common with the screen surrounding a black hole. The correspondence works as far as photons are concerned.

Two-holes-lens

When light is falling through two holes the principle is the same. However the transformer has now two components. When they operate as a single unit the influences of the parts get entangled. In that case the light that falls through the holes interferes. The PSF of this 'lens' consist of the interference of the two PSF's of the lens parts.

Slit-lens

A slit consist of a very large series of small holes. Their interference pattern is a double sinc function. It is small in the direction of the slit and wide in the other direction.

Larger circular hole

A larger circular hole consists of a large series of small holes grouped in the area of the larger hole. Their interference pattern has the shape of a first order Bessel function divided by its argument.

Two-slit-lens

The image through two parallel slits consists of the interferences of the two single slit images.

Holograms as lenses

Special types of holograms can act as lenses. The advantage is their large aperture. The disadvantage is their limited opening angle.

References

A more elaborate view on optics can be obtained via <http://en.wikipedia.org/wiki/Optics>.
Subjects related to OTF can be reached via http://en.wikipedia.org/wiki/Optical_transfer_function.

Quantum Mechanics

Normally, optics act in a cylindrical symmetric or a folded or circularly bent tube like format. Thus it acts in two dimensions.

When optics is taken one dimension higher then it becomes much more similar with quantum mechanics. Especially, it becomes similar with the wave part of QM.

When the active surface of a camera obscura is seen as a holographic screen then it has its equivalent in the spherical holographic screen that surrounds a black hole.

The wave function that gives the probability amplitude of the position of the corresponding physical item can be interpreted as the equivalent of a point spread function PTF. The physical fields influence this function when the item moves. The Fourier transform of the fields take the role of the OTF. Thus after the passage through the fields the Fourier transfer of the new wave function equals the product of the Fourier transfer of the old wave function times the Fourier transforms of the fields.

History of the OTF standard

In the seventies NATO felt the need to have an objective standard for measuring the quality of its imaging devices. Beforehand, the quality was estimated subjectively by measuring the spatial resolution in lines per millimetre. That measure appeared unreliable and it gave little information over the quality of image transfer for courser details. The MTF was suggested as a proper alternative, but the outcome of the measurement depends so much on measuring conditions, that most laboratories came with different results for the same measured specimen. This required a standard and the task group for establishing the OTF STANAG 4161 was born.

Wolfgang Wittenstein of the Forschungsinstitut für Optik, Schloss Kressbach, Tübingen was one of the members and I was a member too. We regularly interchanged our roles as proponents and opponents and in several stadia we produced new versions of a prototype standard. In the process we got our secretaries mad because at that moment there existed no text processors. The other members of the group acted as discussion partners and also suggested several inputs. We took several years with each year two sessions at different labs of NATO participants to reach a final result: the STANAG 4161 On the Optical Transfer Function of Imaging Systems, parts I – III, (1979)

The main problem was a pragmatic redefinition of the concept of OTF, because in optics theory books the OTF was usually treated as a spatially uniform function, which it isn't. Further, nearly always the

parameters that influenced the OTF, such as the angular and chromatic distribution and the coherence or inhomogeneity of the object light were neglected. The standard defined the OTF as dependent on the accepted measuring inaccuracy and stated sets of precise measuring conditions.

Soon after this standard completed the ISO standards organisation felt the requirement for an equivalent ISO standard. That standard aimed at optical lenses. Next the IEC took its part by setting a standard for measuring the MTF of electronic imaging devices. Also DIN wanted a standard for lenses and X-ray image intensifier devices. I took part in all these standardization task groups.