TECHNICAL REPORT

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Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 1:
Terms, definitions and fundamental relationships

Optique et photonique — Mesurage interférométrique de composants et systèmes optiques —

Partie 1: Termes, définitions et relations fondamentales

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 14999-1 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental standards*.

ISO 14999 consists of the following parts, under the general title *Optics and photonics — Interferometric measurement of optical elements and optical systems*:

— *Part 1: Terms, definitions and fundamental relationships* (Technical Report)

— *Part 2: Measurement and evaluation techniques* (Technical Report)

— *Part 3: Calibration and validation of interferometric test equipment* (Technical Report)

— *Part 4: Interpretation and evaluation of tolerances specified by ISO 10110*

Introduction

A series of International Standards on "*Indications in technical drawings for the representation of optical elements and optical systems*" has been prepared by ISO/TC 172/SC 1, and published as ISO 10110 under the title "*Optics and photonics — Preparation of drawings for optical elements and systems*". When drafting this series and especially its Part 5, *Surface form tolerances*, and Part 14, *Wavefront deformation tolerance*, it became evident to the experts involved that additional complementary documentation is required to describe how the necessary information on the conformance of the fabricated parts with the stated tolerances can be demonstrated. Therefore, the responsible ISO Committee ISO/TC 172/SC 1 decided to prepare an ISO Technical Report on *Interferometric measurement of optical wavefronts and surface form of optical elements*.

When discussing the topics which had to be included into or excluded from such a Technical Report, it was envisaged that it might be the first time, where an ISO Technical Report or Standard is prepared which deals with wave-optics, i.e. which is based more in the field of physical optics than in the field of geometrical optics. As a consequence, only fewer references than usual were available, which made the task more difficult.

Envisaging the situation, that the topic of interferometry has so far been left blank in ISO, it was the natural wish to now be as comprehensive as possible. Therefore there was discussion, whether important techniques such as interference microscopy (for characterizing the micro-roughness of optical parts), shearing interferometry (e.g. for characterizing corrected optical systems), multiple beam interferometry, coherence sensing techniques or phase conjugation techniques should be included or not. Other techniques, which are related to the classical two beam interferometry, like holographic interferometry, Moiré techniques and profilometry were also mentioned as well as Fourier transform spectroscopy or the polarization techniques, which are mainly for microscopic interferometry.

In order to complement ISO 10110, the guideline adopted was to include what presently are common techniques used for the purpose of characterizing the quality of optical parts. Decision was made to complete a first Technical Report, and to then up-date it by supplementing new parts, as required. It is very likely that more material will be added in the near future as more stringent tolerances (two orders of magnitude) for optical parts and optical systems become mandatory when dealing with optics for the EUV range (wavelength range 6 nm to 13 nm) for microlithography. Also, testing optics with EUV radiation (the same wavelength as they are later used, e.g. at-wavelength testing) can be a new challenge, and is not covered by any current standards.

This Technical Report should cover the need for qualifying optical parts and complete systems regarding the wavefront error produced by them. Such errors have a distribution over the spatial frequency scale; in this Technical Report only the low- and mid-frequency parts of this error-spectrum are covered, not the very high end of the spectrum. These high-frequency errors can be measured only by microscopy, measurement of the scattered light or by non-optical probing of the surface.

A similar statement can be made regarding the wavelength range of the radiation used for testing: ISO 14999 considers test methods with visible light as the typical case. In some cases, infrared radiation from CO_2-lasers in the range of 10,6 µm is used for testing rough surfaces after grinding or ultraviolet radiation from excimer-lasers in the range of 193 nm or 248 nm are used for at-wavelength testing of microlithography optics. However, these are still rare cases, which are included in standards, that will not be dealt with in detail. The wavelength range outside these borders is not covered.

Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 1: Terms, definitions and fundamental relationships

1 Scope

This part of ISO/TR 14999 gives terms, definitions and fundamental physical and technical relationships for interferometric measurements of optical wavefronts and surface form of optical elements.

It explains why some principles of the construction and use of interferometers are important due to the wave nature of the wavefronts to be measured.

Since all wavefronts with the exception of very extended plane waves do alter their shape when propagating, this part of ISO/TR 14999 also includes some basic information about wave propagation.

In practice, interferometric measurements can be done and are done by use of various configurations; this part of ISO/TR 14999 outlines the basic configurations for two-beam interference.

The mathematical formulation of optical waves by the concept of the complex amplitude as well as the basic equations of two-beam interference are established to explain the principles of deriving the phase information out of the measured intensity distribution, either in time or in space.

Both random and systematic errors may affect the results of interferometric measurements and error types to be clearly differentiated are therefore described in this part of ISO/TR 14999.

2 Wave propagation and some topics on electromagnetic theory

2.1 Parameters, symbols, units and constants, operators and computational procedures

Basic parameters, symbols, units and constants are given in Table 1.

Operators and computational procedures are given in Table 2.

Table 1 — Parameters, symbols, units and constants

Parameters	Symbols	Recommended unit, constant
Electric field vector	E	V/m
Magnetic field vector	H	A/m
Electric displacement or electric flux density	D	$C/m^2 = As/m^2$
Magnetic induction or magnetic flux density	B	$T = Wb/m^2 = Vs/m^2$
Dielectric constant or permittivity [a]	ε	F/m = As/Vm
Dielectric constant in the vacuum	ε_0	$8{,}854 \times 10^{-12}$ F/m
Relative dielectric constant (relative permittivity)	ε_r	1
Magnetic permeability [b]	μ	H/m = Vs/Am
Magnetic permeability in the vacuum	μ_0	$1{,}257 \times 10^{-6}$ H/m
Relative magnetic permeability	μ_r	1
Velocity of the wave in the medium	c	m/s
Velocity of the wave in the vacuum	c_0	$2{,}997\,924\,58 \times 10^8$ m/s
Absolute refractive index	n	1

[a] Mathematical relationship: $\varepsilon = \varepsilon_0\, \varepsilon_r$.

[b] Mathematical relationship: $\mu = \mu_0\, \mu_r$.

Table 2 — Operators and computational procedures

Operator	Definition/Computational procedures	Name (type)
∇	$\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$	Nabla (vector)
$\Delta \Psi$	$\equiv \left(\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2}\right)$ $\nabla \cdot \nabla \Psi = \nabla^2 \Psi$	Laplacian (scalar)

2.2 Maxwell's equations

Maxwell’s equations are the fundamentals for the electromagnetic wave propagation. Maxwell's equations for an electromagnetic wave propagating in a medium which does not involve any charge or current and has vanishing conductivity are expressed by:

$$\left.\begin{aligned} &\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = 0 \\ &\nabla \times \boldsymbol{H} - \frac{\partial \boldsymbol{D}}{\partial t} = 0 \\ &\nabla \cdot \boldsymbol{D} = 0 \\ &\nabla \cdot \boldsymbol{B} = 0 \end{aligned}\right\} \tag{1}$$

The mathematical relation between $\boldsymbol{D}$ and $\boldsymbol{E}$ as well as between $\boldsymbol{B}$ and $\boldsymbol{H}$ is given by:

$$\left.\begin{aligned} \boldsymbol{D} &= \varepsilon \boldsymbol{E} \\ \boldsymbol{B} &= \mu \boldsymbol{H} \end{aligned}\right\} \tag{2}$$

in a linear medium.

2.3 Electromagnetic fields in a medium

For media in which the dielectric constant ε and magnetic permeability μ are uniform, Equation (1) gives the following wave equations:

$$\left.\begin{aligned} \nabla^2 \boldsymbol{E} - \varepsilon\mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0 \\ \nabla^2 \boldsymbol{H} - \varepsilon\mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2} = 0 \end{aligned}\right\} \tag{3}$$

2.4 Velocity of the wave

The velocity in an optically homogeneous and isotropic medium is given by:

$$c = \frac{c_0}{\sqrt{\varepsilon\mu}} \tag{4}$$

Analogously, in a vacuum the velocity is given by:

$$c_0 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \tag{5}$$

2.5 Refractive index

The ratio of the propagation velocities in vacuum and in the medium with ε and μ

$$n = \frac{c_0}{c} \tag{6}$$

is called the refractive index of the medium or the absolute refractive index.

2.6 Scalar wave equation

As mentioned before, $\boldsymbol{E}$ and $\boldsymbol{H}$ are vectors. In many applications one deals with linearly polarized light, which can be fully described by one vector component. Equation (3) then reduces to the scalar wave equation. In the general form, the scalar wave equation may be written as:

$$\nabla^2 \psi - \frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} = 0 \tag{7}$$

Equation (7) is in conformity with a second-order differential equation. ψ is called the light disturbance.

The basic problem of light propagation is thus simply the determination of the manner in which a wave propagates from one surface to another.

2.7 Amplitude, angular frequency, wavelength, wave number

We suppose a sinusoidal plane electromagnetic wave propagating in the z direction. The light disturbance ψ is determined as a function of position z and time t

$$\psi(z,t) = U \cos\left[\omega\left(t - \frac{z}{c}\right) + \delta\right] \tag{8}$$

where

U is the amplitude;

ω is the angular frequency;

δ is the phase constant of the wave.

The angular frequency ω is defined as $2\pi\nu$, where ν is the frequency, i.e. the number of waves per unit time. The wavelength λ is given from Equation (9):

$$\lambda = \frac{2\pi\nu}{\omega} = \frac{2\pi c_0}{n\,\omega} \tag{9}$$

The wave number k is defined as

$$k = \frac{2\pi}{\lambda} \tag{10}$$

In many applications of the concept of waves, as in diffraction or in interferometry, Equation (8) is used to define “wavefronts”. In this case for a given position z the phase constant δ is a function of the lateral spatial coordinates, e.g. $\delta = \delta(x,y)$. This concept is useful, if $\delta = \delta(x,y)$ is measured, as in the case of interferometric measurements. Here $\delta = \delta(x,y)$ is the phase-difference of two interfering waves and x and y are the coordinates of the detector.

Sometimes it is more convenient to look for a “surface” in space $z = z(x,y)$, where the value for the phase $\delta = \delta[x,y,z(x,y)]$ remains constant. Such a surface defines the “shape” of a wavefront, which can be spherical, plane or aspherical, only to mention the most simple cases. This concept is used in 2.11 to 2.13 for discussing the question of the propagation of waves. Here it is shown, that the “shape” of the wavefront changes with z, with the only exception of a(n) (infinite) plane wave with constant amplitude.

In a more general case, also the amplitude U of the light stimulation might be a function of the lateral coordinates x,y, e.g. $U = U(x,y)$. If U is not constant with x,y, it is referred to as an “inhomogeneous wave”. In practice, the variation of U is of minor importance, where the variation of δ is the quantity to be measured.

2.8 Complex notation, complex amplitude

The expression in Equation (8) can be written in complex form as

$$\psi(z,t) = \mathrm{Re}\left[\, u(z)\,\mathrm{e}^{\mathrm{i}(\omega t)}\,\right] \tag{11}$$

and

$$\begin{aligned} u(z) &= U(z)\,\mathrm{e}^{\mathrm{i}\,\phi} \\ \phi &= -\left(\omega\frac{z}{c}\right) + \delta \end{aligned} \tag{12}$$

where

$u\,(z)$ is called the complex amplitude of the wave;

U is the spatial dependent modulus (e.g. amplitude);

ϕ is the spatial dependent phase.

This complex notation is much more convenient than the notation in Equation (8) with real quantities. Nevertheless, only the real parts of Equations (11) and (12) have a physical meaning.

2.9 Irradiance

The irradiance I is given by the relationship

$$I = E/A \times \Delta t$$

where

I is the irradiance;

E is the energy;

A is the area;

Δt is the time interval.

A medium for direct recording of the field amplitude does not exist, since the frequency of the light stimulation is too high to be resolved. So the most common detectors register the irradiance which is proportional to the field amplitude absolutely squared:

$$I \propto |u|^2 = U^2 \tag{13}$$

The correct relation between the complex amplitude and the irradiance is given by:

$$I = \left(\frac{\varepsilon c_0}{2}\right) u \cdot u^* \tag{14}$$

where u^* is the conjugate complex amplitude.

2.10 Poynting vector

The vector $\boldsymbol{S}$ is known as the Poynting vector. $\boldsymbol{S}$ represents the amount of energy which crosses a unit area, normal to the directions of $\boldsymbol{E}$ and $\boldsymbol{H}$, per second

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H} \tag{15}$$

$\boldsymbol{S}$ can be interpreted as the density of the energy flow. The magnitude of the Poynting vector is a measure of the light intensity, and its direction represents the direction of propagation of the light.

The irradiance, I, is given by Equation (16) as follows:

$$I = \overline{S} \cdot n \tag{16}$$

where

n is the surface normal of the detector;

$\overline{S}$ is the time-averaged magnitude of the Poynting vector $\boldsymbol{S}$.

2.11 Propagation of plane waves

Waves, which have a constant phase at a fixed time t over each of the planes normal to the direction of propagation, are called plane waves (see Figure 1).

Let $\boldsymbol{r}\,(x,y,z)$ be a position vector of a point P in space and $\boldsymbol{n}\,(n_x,n_y,n_z)$ the normal unit vector of the wavefront in a fixed direction (see Figure 2). Wavefronts represent surfaces with constant phase. Any solution of Equation (7) of the form

$$\psi = \psi(\boldsymbol{r} \cdot \boldsymbol{n}, t) \tag{17}$$

describes a plane wave since, at each instant of time, ψ is constant over each of the planes which are perpendicular to the normal unit vector $\boldsymbol{n}$:

$$\boldsymbol{r} \cdot \boldsymbol{n} = \kappa \tag{18}$$

where

κ is a constant.

The planes described by $\boldsymbol{r} \cdot \boldsymbol{n} = \kappa$ are defined as the wavefronts of the plane wave.

The disturbance $\psi\,(x,y,z,t)$ of a harmonic plane wave that propagates in the $\boldsymbol{n}$ direction is given by

$$\psi(x, y, z, t) = U \cos(2\pi \nu t - k\boldsymbol{n} \cdot \boldsymbol{r} + \delta) \tag{19}$$

The argument of the cosine function is termed the phase term; δ is the phase constant.

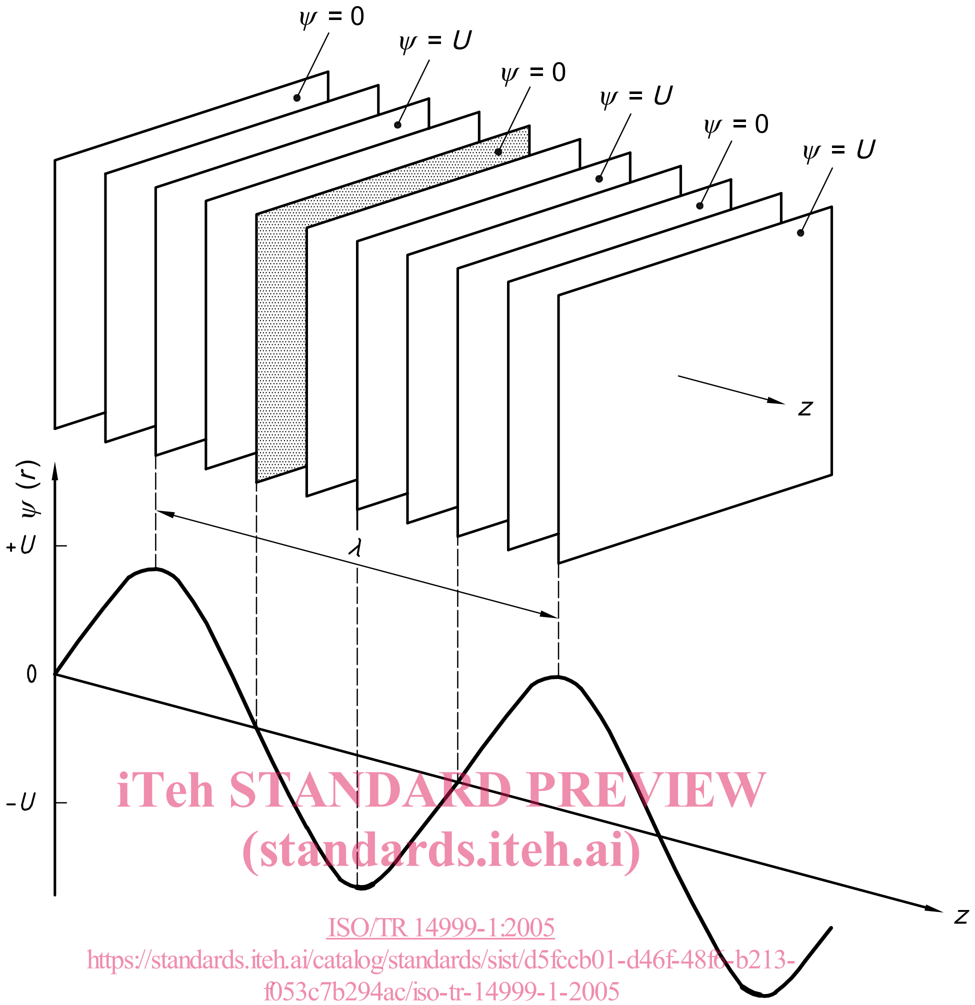

Figure 1 — Plane waves at the time $t = 0$

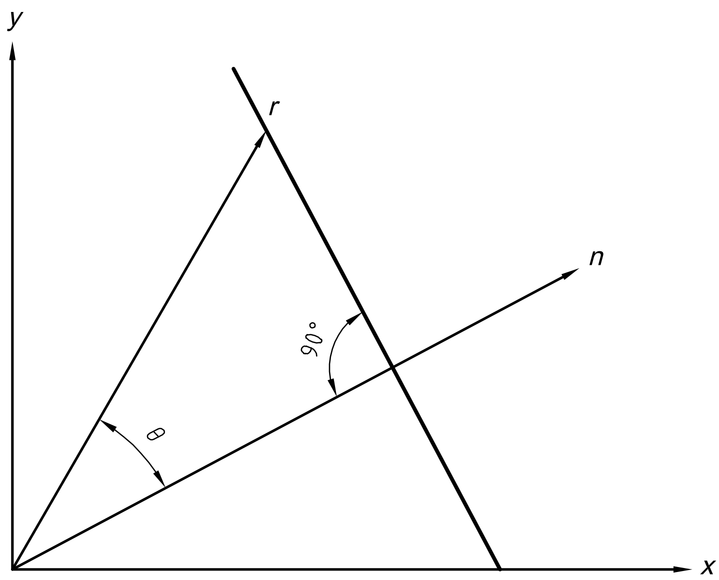

Figure 2 — Illustration of the condition $\boldsymbol{r} \cdot \boldsymbol{n} = \kappa$

2.12 Propagation of spherical wave

A spherical wave, illustrated in Figure 3, is emitted by a point source O.

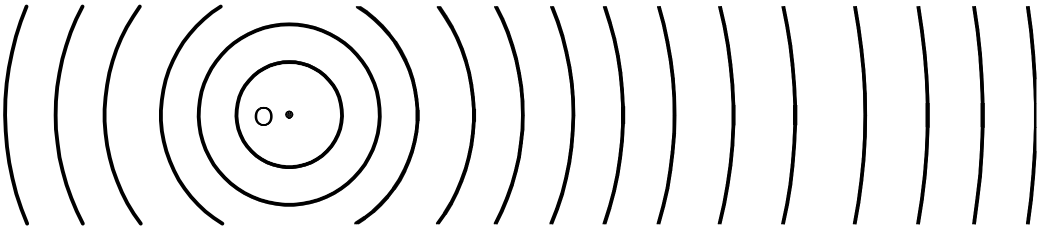

Figure 3 — Spherical waves

The complex amplitude representing a spherical wave should be of the form:

$$u = \frac{U}{r}\,\mathrm{e}^{-\mathrm{i}kr} \tag{20}$$

where r is the radial distance from the point source. The phase of this wave is constant for r equal to a constant, i.e. the phase fronts are spherically centred at the point source O. The r in the denominator of Equation (20) expresses the fact that the amplitude decreases as the inverse of the distance from the point source.

Consider Figure 4, where a point source is lying in the x_0,y_0-plane at a point of coordinates x_0,y_0. The field amplitude in a plane parallel to x_0,y_0-plane at a distance z will then be given by Equation (20) with

$$r = \sqrt{z^2 + (x - x_0)^2 + (y - y_0)^2} \tag{21}$$

where x, y are the coordinates of the illuminated plane. The approximation for the phase is carried out by a binomial expansion of the square root; when r is approximated by the first two terms of the expansion, the Fresnel approximation of the diffraction phenomena is obtained. In the amplitude factor [see Equation (21)], r may be replaced by z, because $(x - x_0)$, $(y - y_0) << z$. The complex amplitude of the field in the x,y-plane resulting from a point source at x_0, y_0 in the x_0,y_0-plane is then given by:

$$u(x,y,z) = \frac{U}{z}\,\mathrm{e}^{-\mathrm{i}kz}\,\mathrm{e}^{-\mathrm{i}(k/2z)\,[(x-x_0)^2+(y-y_0)^2]} \tag{22}$$

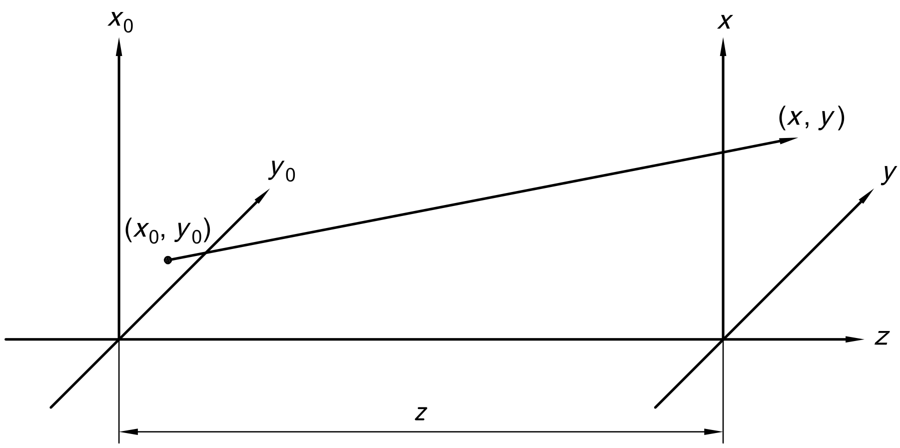

Figure 4 — A point source lying in x_0,y_0-plane

2.13 Propagation of waves with limited extent

The only type of wave that does not change its shape when propagating, is a plane wave with uniform amplitude. Such a wave is infinite in both lateral coordinates. A spherical wave, which is either converging to, or diverging from, its centre of curvature and which is defined on the complete solid angle of 4π is another example of a very special wave. In this case, the phase is altered, but any phase-distribution is similar to the adjacent one. Again, a uniform amplitude distribution should be demanded. These two special cases have been discussed in the previous subclauses.

All other wavefronts, especially plane or spherical wavefronts, which contain a boundary due to any limiting aperture, do alter their shape when travelling along their light path. One example is given in the next two figures, where the well-known Cornu’s spiral is shown, which is a graphical representation of the solution of the Fresnel’s integrals

$$\left.\begin{aligned} x &= \int_0^v \cos\frac{\pi v^2}{2}\,\mathrm{d}v \\ y &= \int_0^v \sin\frac{\pi v^2}{2}\,\mathrm{d}v \end{aligned}\right\} \tag{23}$$

x and y being the Cartesian coordinates of the plot and v being a parameter on the curve. Cornu’s spiral can be used to visualize the complex amplitude of a plane wave diffracted at a knife-edge, as a most simple example.

Look at Figures 5 and 6 simultaneously. At the point of the geometrical shadow, point 0 on the abscissa in Figure 6 and the coordinate centre in Figure 5, the amplitude is dropped to 1/2 of the amplitude far away from the edge in the illuminated region. So, the intensity is dropped to 1/4. The complex amplitude for that point is visualized in Figure 5 by a straight line, joining points Z and 0. The point Z in Figure 5 remains the centre, where all vectors originate. Now going further into the illuminated region, the parameter v grows and with it the modulus of the complex amplitude, since the vectors grow larger. The extreme value is reached at b′, then dropping until a first relative minimum is reached at c′. At the same time the phase of the wavefront changes, since the direction of the vectors changes, when the point moves along the spiral. The gradients of the phase-change take large values in the vicinity of extreme points of the spiral, like points b′, c′, d′ and so on and are nearly zero when the line centred in Z is tangential to the Cornu’s spiral.

Figure 5 shows the phase-change φ that the diffracted wave undergoes between points b′ and B′.

Since the phase is the quantity measured with interferometers, it is clear that the result of such a measurement is affected strongly by diffraction. That is one reason why precision measurements should be avoided where Fresnel diffraction can occur on the wavefronts to be measured. The only way that precision measurements can be performed is to carefully image any limiting aperture to the detector, where the two wavefronts interfere with each other (Fraunhofer diffraction!). This is dealt with in detail in 4.5.