

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

VANGUARD PRODUCTS GROUP, INC., D/B/A VANGUARD PROTEX
GLOBAL

Petitioner

v.

INVUE SECURITY PRODUCTS, INC.

Patent Owner

Case No.: IPR2020-00069
U.S. Patent No. 10,043,358

EXHIBIT 2017

Numerical Aperture

The numerical aperture (NA) of an optical system (e.g. an [imaging](#) system) is a measure for its angular acceptance for incoming light. It is defined based on [geometrical](#) considerations and is thus a theoretical parameter which is calculated from the optical design. It cannot be directly measured, except in limiting cases with rather large apertures and negligible [diffraction](#) effects.

Numerical Aperture of an Optical System

The numerical aperture of an optical system is defined as the product of the [refractive index](#) of the beam from which the light input is received and the sine of the maximum ray angle against the axis, for which light can be transmitted through the system based on purely geometric considerations (*ray optics*):

$$NA = n \sin \theta_{\max}$$

For the maximum incidence angle, it is demanded that the light can get through the whole system and not only through an entrance aperture.

NA of a Lens

A simple case is that of a collimating lens:

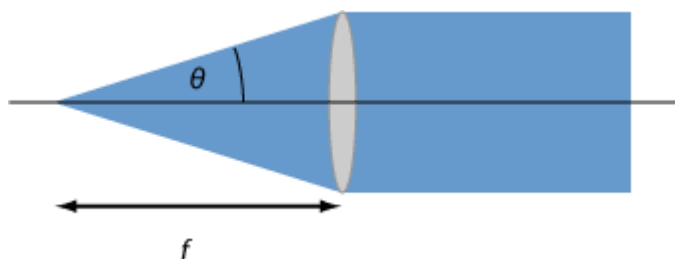


Figure 1: A collimating lens can theoretically accept light from a cone, the opening angle of which is limited by its size.

The extreme rays are limited by the size of the lens, or in some cases somewhat less if there is a non-transparent facet.

It is often not recommended to operate a lens or its full area, since there could be substantial [spherical aberrations](#). The numerical aperture, however, is a completely geometrical measure, which is not considering such aspects.

In the example case above, the numerical aperture of the lens is determined by its diameter and its [focal length](#). Note, however, that a lens may not be designed for collimating light, but for example for [imaging](#) objects in a larger distance. In

that case, one will consider rays coming from that object distance, and the obtained numerical aperture will be correspondingly smaller – sometimes even much smaller. This shows that the numerical aperture depends on the location of some object plane determined by the designer according to the intended use.

Some lenses are used for focusing [collimated laser beams](#) to small spots. The numerical aperture of such a lens depends on its aperture and focal length, just as for the collimation lens discussed above. The input [beam radius](#) w_0 must be small enough to avoid truncation or excessive [spherical aberrations](#). Typically, it will be of the order of half the aperture radius of the lens (or perhaps slight larger), and in that case ($w_0 = D/4 = NA \cdot f/2$) the achievable beam radius in the focus is

$$w_f = \frac{\lambda f}{\pi w_0} = \frac{4\lambda f}{\pi D} \approx \frac{2\lambda}{\pi NA}$$

where D is the aperture diameter, f the [focal length](#) and λ the optical wavelength. The calculation is based on the [paraxial approximation](#) and therefore not accurate for cases with very high NA.

A somewhat smaller spot size may be possible with correspondingly larger input beam radius, if the performance is not spoiled by aberrations. In case of doubt, one should ask the manufacturer what maximum input beam radius is appropriate for a certain lens.

High-NA lenses are required for various applications:

- In players and recorders of optical data storage media such as CDs, DVDs and Blu-ray Discs it is important to focus laser light to a small spot (pit) and receive light from such a spot.
- Lenses with high NA are also required for [collimating laser beams](#) which originate from small apertures. For example, this is the case for low-power single-mode [laser diodes](#). When a lens with too low NA is used, the resulting collimated beam can be distorted (aberrated) or even truncated.

NA of a Microscope Objective

The same kind of considerations apply to [microscope objectives](#). Such an objective is designed for operation with a certain [working distance](#), and depending on the type of [microscope](#) with which it is supposed to be used, it may be designed for producing an image at a finite distance or at infinity. In any case, the opening angle on which the numerical aperture definition is based is taken from the center of the intended object plane. It is usually limited by the [optical aperture](#) on the object side, i.e., at the light entrance.

In many cases, the light input comes from air, where the refractive index is close to 1. The numerical aperture is then necessarily smaller than 1, but for some microscope objectives it is at least not much lower, for example 0.9. Other microscope objectives for particularly high image resolution are designed for the use of some immersion oil between the object and the entrance aperture. Due to its higher refractive index (often somewhat above 1.5), the numerical aperture can then be significantly larger than 1 (for example, 1.3).

The NA of a microscope objective is important particularly concerning the following aspects:

- It determines how bright the observed image can be for a given illumination intensity. Obviously, a high-NA objective can collect more light than one with a low numerical aperture.
- More importantly, the NA sets a limit to the obtained spatial resolution: the finest resolvable details have a diameter of approximately $\lambda / (2 \text{ NA})$, assuming that the objective does not produce excessive image aberrations.
- A high NA leads to a small [depth of field](#): only objects within a small range of distances from the objective can be seen with a sharp image.

Photographic Objectives

In photography, it is *not* common to specify the numerical aperture of an objective, because such objectives are not thought to be used with a fixed working distance. Instead, one often specifies the aperture size with the so-called [f-number](#), which is the [focal length](#) divided by the diameter of the [entrance pupil](#). Usually, such an objective allows the adjustment of the f-number in a certain range.

Numerical Aperture of an Optical Fiber or Waveguide

Although an optical [fiber](#) or other kind of [waveguide](#) can be seen as a special kind of optical system, there are some special aspects of the term *numerical aperture* in such cases.

In case of a [step-index fiber](#), one can define the numerical aperture based on the input ray with the maximum angle for which [total internal reflection](#) is possible at the [core-cladding](#) interface:

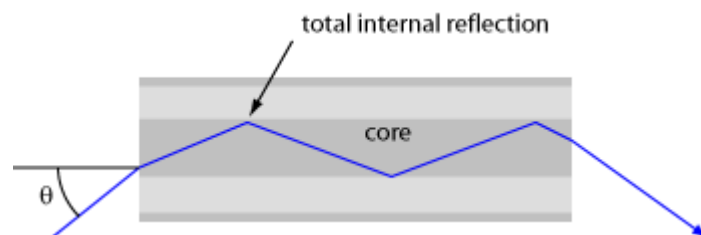


Figure 2: An incident light ray is first refracted and then undergoes [total internal reflection](#) at the core–cladding interface. However, that works only if the incidence angle is not too large.

The numerical aperture (NA) of the fiber is the sine of that maximum angle of an incident ray with respect to the fiber axis. It can be calculated from the [refractive index](#) difference between core and cladding, more precisely with the following relation:

$$NA = \frac{1}{n_0} \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$$

Here, n_0 is the [refractive index](#) of the medium around the fiber, which is close to 1 in case of air. Note that for a different input medium with higher refractive index, the maximum input angle will be smaller, but the numerical aperture remains unchanged.

Calculation of the NA of a Fiber

Core index:Cladding index:

The equation given above holds only for straight fibers. For bent fibers, one may use an approximate modified equation, which also contains the bend radius R and the core diameter:

$$NA = \frac{1}{n_0} \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2 \left(1 + \frac{r_{\text{co}}}{2R}\right)}$$

For fibers or other waveguides not having a step-index profile, the concept of the numerical aperture becomes questionable. The maximum input ray angle then generally depends on the position of the input surface. Some authors calculate the numerical aperture of a graded-index fiber based on the maximum refractive index difference between core and cladding, using the equation derived for step-index fibers. However, some common formula in fiber optics involving the NA can then not be applied.

Light propagation in most optical fibers, and particularly in [single-mode fibers](#), cannot be properly described based on a purely geometrical picture (with [geometrical optics](#)), because the wave nature of light is very important; [diffraction](#) becomes strong for tightly confined light. Therefore, there is no close relation between properties of fiber [modes](#) and the numerical aperture. Only, high-NA fibers tend to have modes with larger [divergence](#) of the light exiting the fiber. However, that beam divergence also depends on the core diameter. As an example, Figure 1 shows how the mode radius and mode divergence of a fiber depend on the core radius for fixed value of the numerical aperture. The mode divergence stays well below the numerical aperture.

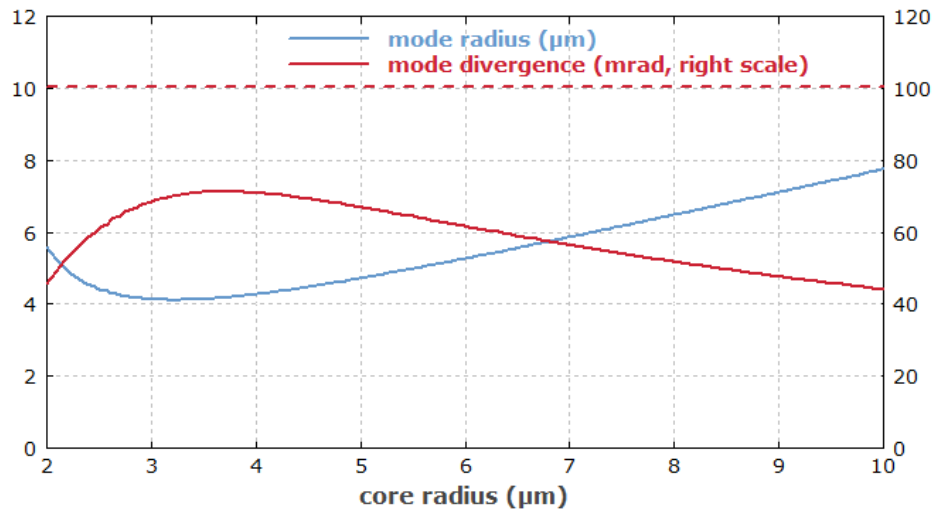


Figure 3: Mode radius and divergence angle for the fundamental mode of a step-index fiber as functions of the core radius for a fixed numerical aperture of 0.1 and the wavelength of 1000 nm.

In Figure 2 one can see that the angular intensity distribution somewhat extends beyond the value corresponding to the numerical aperture. This demonstrates that the angular limit from the purely geometrical consideration is not a strict limit for waves.

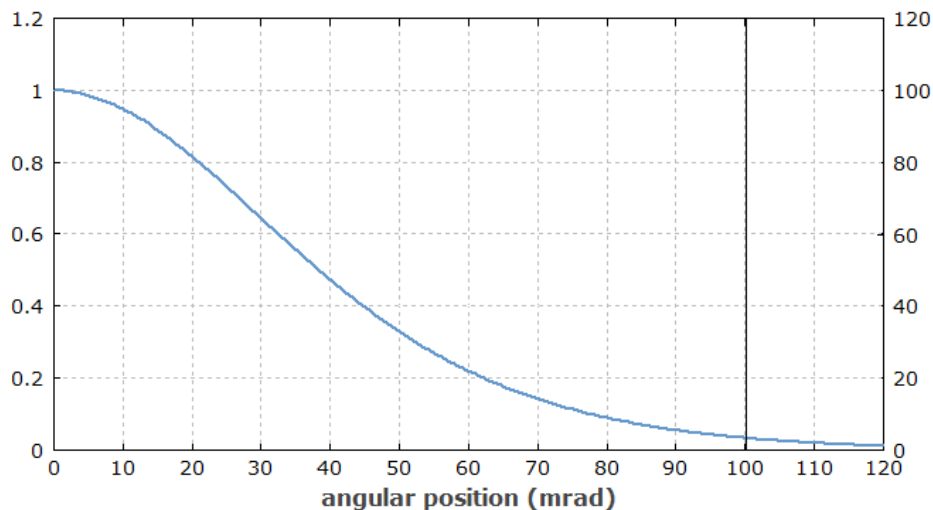


Figure 4: [Far field](#) intensity distribution of a fiber mode at 1000 nm for a core radius of 3.5 μm , a numerical aperture of all 0.1. The intensity distribution somewhat extends beyond the value corresponding to the numerical aperture (see the vertical line).

For a [single-mode fiber](#), the NA is typically of the order of 0.1, but can vary roughly between 0.05 and 0.4. [Multimode fibers](#) typically have a higher numerical aperture of e.g. 0.3. Very high values are possible for [photonic crystal fibers](#).

A higher NA has the following consequences:

- For a given mode area, a fiber with higher NA is more strongly guiding, i.e. it will generally support a larger number of [modes](#).
- Single-mode guidance requires a smaller [core](#) diameter. The corresponding mode area is smaller, and the [divergence](#) of the beam exiting the fiber is larger. The fiber [nonlinearity](#) is correspondingly increased. Conversely, a [large mode area single-mode fiber](#) must have a low NA.
- [Bend losses](#) are reduced; the fiber can be more strongly bent before bend losses become significant.
- The sensitivity of the guidance to random refractive index fluctuations is reduced. (For large mode area low-NA single-mode fibers, it can be a problem.)
- The higher [doping concentration](#) of the fiber core (e.g. with germanium), as required for increasing the refractive index difference, may increase [scattering](#) losses. The same can be caused by irregularities of the core/cladding interface, which are more important for a larger index difference.
- A low NA increases the influence of random refractive index variations. Therefore, fibers with very low NA may exhibit increased [propagation losses](#).