

# Mode transforming properties of taper microlensed fibers

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Drowned tapered and microlensed single-mode fibers offer significant manufacturing advantages as waveguide couplers. However, controlled manufacturing requires a better understanding of beam propagation in such photonics devices. The authors investigate the mode transforming properties of drowned tapered and microlensed fiber optics and suggest optimal geometries.

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## 1. Lightwave modes and gaussian approximations

The introduction of the concept of mode is a fundamental requirement for accurate modeling of light propagation in fiber optics. In general terms, a propagation mode is a self-consistent electric field distribution with the specific property that its shape in the transverse direction remains constant during propagation. The simplest type of mode in free space is the plane wave. However, plane waves do not resemble real waves since they have an infinite transverse extent and therefore other modes limited to the transverse spatial dimension are of higher interest.

The simplest type of mode satisfying the above requirements is the Gaussian mode [1]. Gaussian beams contract or expand during propagation, but the amplitude profile is only transversally scaled and has a constant – Gaussian – shape. Gaussian modes are members of families of modes and their number is infinite. The most frequently used mode families are Hermite-Gauss and Laguerre-Gauss. Within a mode family the Gaussian mode is the fundamental mode and during the propagation the higher order modes transversally change in proportion to that of the fundamental mode.

For light propagation in a waveguide the self-consistency condition for a mode is stricter than for free space modes. Mode rescaling is not permitted in waveguides. An overall phase change per unit length – described by the propagation constant  $\beta$  – and losses or gains of total optical power are acceptable. Waveguides have finite number of guided propagation modes and the intensity distribution of each mode has a finite extent around the core of the waveguide. A single-mode fiber has only a single guided mode per polarization direction. Waveguides also have cladding modes and their intensity distributions fill the whole cladding and core regions and exhibit substantial propagation losses at the outer interface of the cladding [2].

Gaussians are radially symmetric distributions with electric field variations given by:

$$E_s = E_0 \exp\left(-\frac{r^2}{\omega_0^2}\right) \tag{01}$$

The Fourier Transform of a Gaussian is also a Gaussian distribution and Gaussian source distributions remain Gaussian at every point along their propagation path. This property is useful in visualizing the field distributions anywhere in optical systems. The intensity of the field is also a Gaussian:

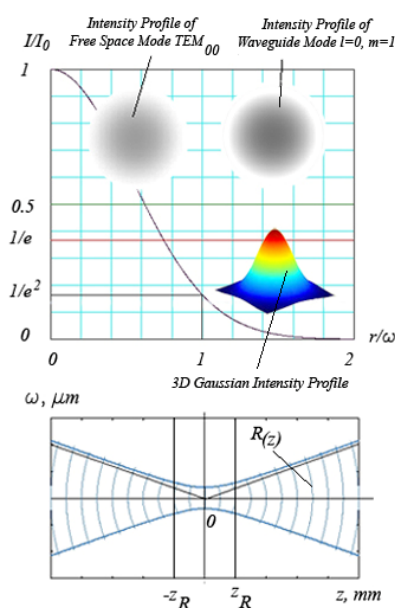


Fig. 1. Gaussian Beams.

$$I_s = \eta E_s E_s^* = \eta E_0 E_0^* \exp\left(-\frac{2r^2}{\omega_0^2}\right) \quad (02)$$

The definition of the size of Gaussians is somewhat arbitrary because the Gaussian has no obvious boundaries. Figure 1 shows the Gaussian intensity distribution of a typical He-Ne laser. The parameter  $\omega_0$ , called the *Gaussian Beam Radius*, is the radius at which the intensity has decreased to  $1/e^2$  of its value on its axis. Because of the unique self-Fourier Transform characteristic of Gaussians, the transverse distribution intensity remains Gaussian and only its radius  $\omega$  and the radius of curvature of the wavefront  $R$  change with the position  $z$ , as shown in figure 1. The equations describing the *Gaussian Beam Radius*  $\omega$  and wavefront radius  $R$  are:

$$\omega(z) = \omega_0^2 \left( 1 + \left( \frac{\lambda z}{\pi \omega_0^2} \right)^2 \right)^{\frac{1}{2}} \quad (03)$$

$$R(z) = z \left( 1 + \left( \frac{\pi \omega_0^2}{\lambda z} \right)^2 \right) \quad (04)$$

In equations (03) and (04)  $\omega_0$  is the *Gaussian Beam Radius* and  $\lambda$  is the wavelength. The above mentioned parameters occur in the same combination in both equations and they are often merged into a single parameter known as the *Rayleigh Range*,  $z_R$  [1] and at  $z = z_R$ ,  $R$  is minimum:

$$z_R = \frac{\pi \omega_0^2}{\lambda} \quad (05)$$

Optical fibers have two essential parts: the core and the cladding. The core acts as a cylindrical waveguide, while the cladding prevents the guided mode from interacting with anything outside of the fiber. For a constant refractive index difference  $\Delta n$  between the core and the cladding, the mode profile within the core is described by the equation [2]:

$$f(r) = A J_0 \left( n_c^2 k_0^2 - \beta^2 \right)^{\frac{1}{2}} \cdot r, \quad r < a \quad (06)$$

In equation (06),  $J_0$  is the Bessel function of first kind,  $k_0$  is the free space wavenumber, and  $\beta$  represents the propagation constant. For  $r = a$  the profile is represented by:

$$f(r) = A \exp\left(-\frac{r}{\omega_G}\right)^2 \quad (07)$$

The function  $f(r)$  from equation (07) strongly resembles a Gaussian for all  $r$  values, provided the mode width parameter  $\omega_G$  is properly chosen. The Gaussian approximation described by equation (07) provides a convenient single-parameter characterization of the fundamental mode for weakly guiding, step index, single-mode fibers.

A model of beam to guided-mode coupling requires the summation of plane waves to describe the incoming beam and the guided mode and cannot be entirely based on ray optics since beams of finite sizes are made up of combinations of plane waves with different propagation directions. Efficient coupling requires overlapping of the incident beam profile  $f_b(r)$  and the outgoing mode profile  $f_m(r)$ . Henry and Verbeek [03] define the coupling efficiency as the ratio between the power in the guided mode and the power in the incoming beam. If  $f_b(r)$  and  $f_m(r)$  have the same polarization and interface reflection is negligible the coupling efficiency is described by the equation:

$$\eta_c = \int_0^H f_b^*(r) f_m^*(r) dr = \sum_q^N DFT^*(f_b)_q DFT(f_m)_q \quad (08)$$

In equation (08),  $f_b^*(r)$ ,  $f_m^*(r)$  and  $DFT^*$  are the complex conjugates of their respective functions and  $DFT$  is the Discrete Fourier Transform. Henry and Verbeek equation helps identify the main factors affecting coupling efficiency.

## 2. Mode transforming properties in tapered core-cladding single-mode fibers

Several methods are used to manufacture tapered and microlensed single-mode fibers. For typical coupling applications the taper is shaped on a controlled process by drowning the partly melted tip of the fiber [4]. Such approaches generate fibers with tapered core and cladding. Microlenses with spherical surfaces are also generated in the process. The characteristic geometry of a core-cladding taper is shown in Fig. 2.

Manufacturing processes must be able to control the geometry of the taper and microlens as a way to control the spot size of the coupler.

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} + k^2(x, y, z)\phi = 0 \quad (23)$$

For most guided-wave problems, the fastest variation of the field  $\phi$  is the phase variation due to propagation along the guiding axis. Assuming the guiding axis is  $z$ , this fast variation can be factored out by with the slowly varying field  $u(x, y, z) = \phi(x, y, z)/e^{i\bar{k}z}$ .  $\bar{k}$  is the reference wavenumber and represents the average variation of the field  $\phi$ . It is common practice to express the wavenumber in terms of a reference refractive index  $\bar{n}$  as in  $\bar{k} = k_0\bar{n}$ . Under these assumptions one can write the three dimensional Beam Propagation Method (BPM) equation:

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2)u \right) \quad (24)$$

For a given input field  $u(x, y, z=0)$ , the BPM equation (24) describes the evolution of the field in the space  $z > 0$ . Furthermore, the 3D equation (24) can be simplified for 2D by omitting all dependencies on  $y$ .

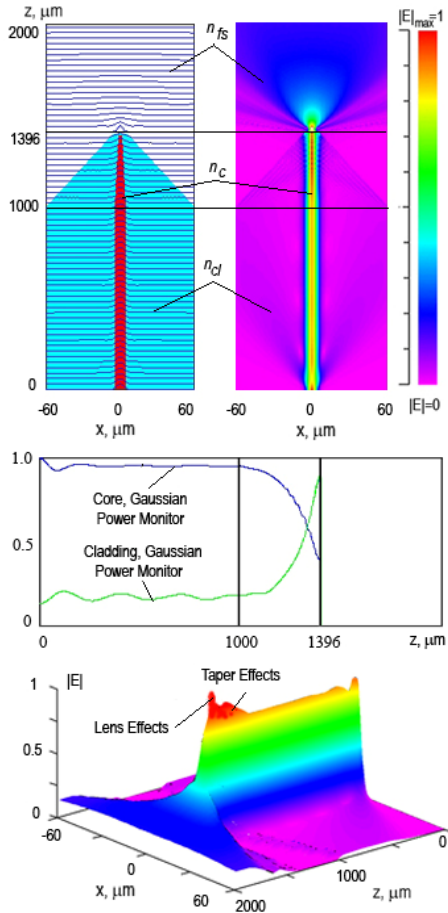


Fig. 5. Taper beam propagation simulation.

The authors investigate core-cladding tapered and microlensed devices drawn from Corning SMF-28 fiber with the following specifications:

- Mode-Field Diameter MDF at  $\lambda = 1550$  nm:  $10.4 \pm 0.8 \mu\text{m}$
- Core Diameter:  $8.2 \mu\text{m}$
- Cladding Diameter:  $125.0 \pm 0.7 \mu\text{m}$
- Effective Group Index of Refraction at nominal MFD: 1.4682 nm
- Refractive Index Difference: 0.005
- Numerical Aperture: 0.14

Simulation settings:

- Free Space Wavelength:  $\lambda = 1550$  nm
- Background Refractive Index: 1
- Core Refractive Index: 1.455
- Core/Cladding Refractive Index Difference: 0.005
- Profile: Step Index
- 3D Structure: Fiber
- Crank-Nicholson Implicit Scheme
- Simple Transparent Boundary Condition
- Padé Order: (1,0)
- Mode Calculation Method: Correlation
- Cladding Taper Angle:  $\pi/20$
- Core Taper Angle:  $\pi/360$
- Taper Length:  $395 \mu\text{m}$
- Lens Diameter:  $13.7 \mu\text{m}$
- Lens Radius:  $13.85 \mu\text{m}$

Fig. 5 shows the simulated beam propagation on a tapered core-cladding single-mode fiber terminated with a microlens. Tapering effects – covering the region  $1000 \mu\text{m}$  to  $1395 \mu\text{m}$  – are visible on the Contour Map (upper right) and Height Coded (bottom) images from Figure 5. The evolution of the Gaussian Power Monitors alongside the propagation confirms the validity of the analytical method proposed by Barnard and Lit and obtained by employing the *Local Mode Theory*.

The authors performed the evaluation of the Mode Field Radius  $\omega_l$  of a tapered fiber with the above specified geometry with an LD 8900R Far Field Profiler from Photon Inc. The measurement device is a real time scanning pinhole goniometric radiometer. The instrument is based on a scanning method where neither the detector nor the light source moves, yet the system provides a hemispherical irradiance measurement with 0.05 degree resolution in the angular direction and sub-degree resolution in the azimuthal direction. The measured values are:

- $\omega_{f \min} = 3.07 \mu\text{m}$
- $\omega_{f \max} = 3.49 \mu\text{m}$
- Standard Deviation:

$$\sqrt{\frac{n \sum_{i=1}^n \omega_{fi}^2 - \left( \sum_{i=1}^n \omega_{fi} \right)^2}{n(n-1)}} = 0.135 \mu m, n = 10$$

- *Mean* = 3.28  $\mu m$

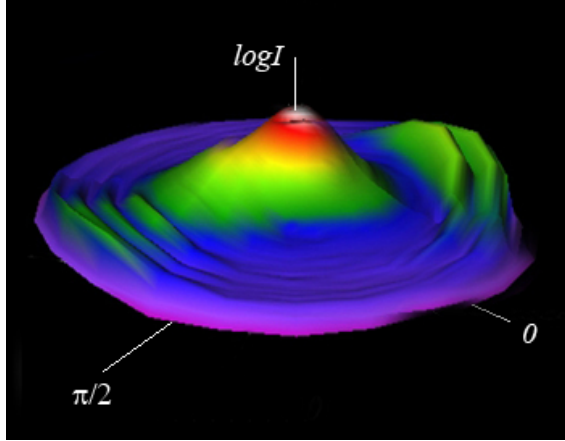


Fig. 6. Measured 3D Mode Field profile intensity.

The predicted value  $\omega_f = 3.23 \mu m$  falls between the minimum and maximum evaluations and close to the mean.

## 5. Concluding remarks

The finite element approach and the experimental results confirm the validity of the analytical methods proposed by Barnard and Lit and allow sound recommendations regarding optimal geometry for tapered microlensed single-mode fibers.

The spot radius is independent of the radius of the lens for a well defined range of taper angles and the result is important for manufacturing.

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