Highlights

An investigation of the transmission properties of tapered and untapered optical fibres
Piyamas Choochalerm, William E. Martin, Hugh R. A. Jones, Ronny Errmann, Stephanos Yerolatsitis, Christophe Buisset

- Graded-index tapered fibre shows significantly greater transmission than step-index tapered fibre for the same dimensions and taper ratio.

- An optical ray tracing simulation using Zemax approximately reproduces the relationship between numerical aperture and the fibre transmission for a step-index tapered fibre.

- Different fibres show a wide range in throughput versus numerical aperture with measured numerical apertures at peak throughput being smaller than the specifications given by manufacturers.

- Very low numerical aperture measurements present a drop off in transmission due to mode coupling variability in the fibre.
An investigation of the transmission properties of tapered and untapered optical fibres

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ABSTRACT

We measured the throughput of tapered and untapered optical fibres as a function of input numerical aperture. The untapered fibres include single-mode, endlessly single mode, double-clad and plastic fibre as well as graded and step-index fibre. The tapered fibres were fabricated from graded and step-index fibres with 50 μm core diameters. In each case, a gradual 100 mm adiabatic transition between the tapered and untapered regions was formed. The results indicate a range in peak throughput from around 0.5 to 0.8 for the untapered fibre and 0.2 to 0.8 for tapered fibre but with different performance as a function of numerical aperture. We find that the 5:1 graded-index tapered fibre throughput is approximately 2.5 times that of a comparable step-index tapered fibre. Notably the 5:1 tapered graded-index fibre can give a throughput of 0.6 similar to an untapered step-index fibre. Thus suitably tapered graded-index fibre offers a new route for efficient focal reduction of fibre optic signals.

1. Introduction

Optical fibres are increasingly used in astronomical instruments for transferring light amongst very large survey instruments covering thousands of objects at once as well as smaller instruments gathering light from a single object [1]. Tapered optical fibres are well known as a focal reduction and magnification technique [2, 3] and for the application of high power optics such as high power laser coupling [3, 4, 5]. A tapered fibre can be manufactured from the standard commercial optical fibre by heating and pulling very carefully [2, 3, 4, 6, 7]. When the fibre is stretched symmetrically, the core size will be decreased gradually. Under energy conservation along the fibre, the change of light acceptance angle at the fibre end depends on the direction of light propagation. If the light travels from the smaller end or tapered core towards the large end the light emission angle of the fibre or effective numerical aperture (NAeff) will be decreased. Conversely, if the light travels from the untapered core to the tapered core, the light emission angle will be larger [2, 3].

The taper can be customised with different taper ratios and transition lengths and several fibre types with different core sizes can be used as a starting point, depending on the application’s objective. We are developing a prototype high-resolution fibre-fed spectrograph which is designed for 0.10 NA light acceptance and a 10 μm core input fibre. The input beam comes from telescopes with 0.20 NA and seeing limited images size of 20-50 μm and beam-size conversion is required. A tapered fibre is a route to a smaller beam size with good throughput enabling a smaller off-the-shelf optics spectrograph without the need for more complex photonics lantern type devices [2, 8]. Untapered fibres are used in many systems to transfer light amongst the many diagnostic instruments. The fibres tested in this paper are standard commercial products [9, 10] and customised graded-index fibres. The untapered fibres we tested included single mode (SM), multimode step-index (SI) and graded-index (GI), endlessly single mode (ESM), double-clad and plastic fibre. Tapered fibres are formed from the standard bare fibre [9] and include taper ratios of 2.5:1, 4:1 and 5:1. All tapered fibres have 100 mm taper length. We have modelled the step-index untapered and tapered fibres using Zemax [11] scaling up the dimensions 100x. The approach is justified for a geometric optics calculation, dimensions large with respect to this optical wavelengths, and does not take into account fibre modes. We applied the non-sequential mode for a total internal reflection design of a bi-layered cylinder that emulates the geometric optical performance of the fibres.
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We begin with some background information about tapered fibres in section 2. Next, the experimental details and related theory are presented in section 3 including an explanation of the fibre test setup in Figure 2, the NA matching technique and throughput measurement. Lastly, we show and discuss our results with untapered standard fibre and the result for the tapered fibres in section 4.

2. Tapered fibre

A tapered fibre is defined as a fibre which has a different diameter size between the input and output ends [3, 12]. The tapered fibre can be manufactured by either heating and pulling [2, 6, 7, 13, 14] or chemical etching [15]. The applications for tapered fibres are mostly in high power optics [3, 4] and are related to their good properties for beam shaping and collimation [7, 16]. The transmission along the taper referred to its core size shows promise of low loss [7, 16]. However, we find that quantitative measurements of taper losses or throughput as a function of NA are not commonly available in the optics literature [17].

The Etendue principle is applied to describe the optical geometry of the taper [2, 3, 18]. Figure 1 illustrates the geometrical optics of a tapered fibre. Light travels from the left and is incident on the smaller surface area with \( NA_i \). The light propagates from the narrow core to the enlarged part until it reaches the untapered end with the numerical aperture \( NA_o \). Energy is assumed to be conserved in an ideal tapered fibre (including the cladding). The Etendue can be used to describe light cone characteristics in terms of its size and angle in the optical system. The light travelling in the optical system is characterised by two factors, angular space and light transmitted area. Considering the maximum concentrated energy on an effective surface area \( A \), the Etendue \( G \) can be written in terms of the refractive index \( n \) and the incidence angle \( \theta \) as [2, 3, 19]

\[
G = An^2 \sin^2 \theta = A(NA)^2
\]

when \( NA = n \sin \theta \). The light propagates through material with a refractive \( n \), \( NA \) is the numerical aperture of the optical system. Energy conservation is preserved ideally by a symmetrical uptapered fibre with no loss. The Etendue of both fibre’s ends can be shown as [2]

\[
A_i n_i^2 \sin^2 \theta_i = A_o n_o^2 \sin^2 \theta_o,
\]

where \( A_i \) and \( A_o \) are effective areas, \( \theta_i \) is the acceptance angle of light incident on the fibre core and \( \theta_o \) is the angle that light propagates outward from the fibre core. For a downtapered fibre energy is conserved but both core and cladding light must be considered. The NA of a clad fibre (\( NA_f \)) can be written as [20]

\[
NA_f = (n_{core}^2 - n_{clad}^2)^{1/2}.
\]

Figure 1: A diagram of tapered fibre to illustrate the Etendue principle. The \( NA_i \) is the numerical aperture at the end of the taper with the light acceptance angle \( \theta_i \) and \( NA_o \) is the numerical aperture at the untapered end with the light emission angle \( \theta_o \).
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where \( n_{\text{core}} \) and \( n_{\text{clad}} \) are refractive indices of fibre core and cladding. If the tapering process does not change the core and the cladding indices, then \( NA_i = NA_f \). Considering the fibre core alone and the taper, the effective NA at the untapered end of the fibre can be expressed using the taper ratio \( R \) [4] as

\[
NA_{\text{taper}} = R \cdot NA_i = \frac{d_i}{d_o} \cdot NA_i = \frac{d_i}{d_o} \cdot NA_f.
\]

(4)

Where \( d_i \) and \( d_o \) are the respective tapered and untapered fibre diameters. Note that this effective NA is smaller than expected from an untapered fibre. If light is incident on the untapered end at an NA greater than \( NA_{\text{taper}} \) it appears in the cladding at the tapered end not the core. A simple estimate of the maximum geometric optics transmission of tapered fibres can be obtained from the Etendue. For untapered fibres the maximum transmission will be the same as an untapered fibre with the same core diameter and NA since energy is conserved and the light is emitted at an NA that is \( R \) times smaller than the input. For downtapered fibres the maximum transmission of the tapered core will be \( 1/R^2 \) times the maximum transmission of an untapered fibre core and will have an output NA equal to the untapered fibre.

3. Experimental detail

This section describes details of the experimentation, the fibre test setup, the principle of the NA matching technique applied and how the relative throughput is defined. We characterised the manufactured optical fibre purchased from Thorlabs [9] and Chromis Fiberoptics [10] and custom tapered fibres.

3.1. Fibre test setup

The main aim of our setup is to measure the throughput of the fibre as a function of the effective input NA dependence. Table 1 describes the notation we use in the remainder of the paper. The description for all measured fibres is presented in Table 2 for untapered fibres and Table 3 for 100-mm-length tapered fibres. The tables present specifications from Thorlabs and Chromis Fiberoptics including the manufactures’ numerical aperture (denoted as \( NA^\dagger \)), core diameter in \( \mu \text{m} \) (denoted as Core) and part number. In Table 3, the taper ratio and final core diameters are also presented.

The setup shown in Figure 2 comprises a 635 nm laser diode source, a beam expansion telescope, an adjustable iris diaphragm, a three-axis adjustable translation stage and 4x or 10x microscope objective lenses. A 2° uncoated deviation prism is used to sample the input beam power and standard optical power sensors with digital outputs [9] were used for the input and output measurements. The output from the beam expansion telescope is a 9.7 mm diameter collimated beam.

The fibre cladding contains light that can influence the measurement accuracy. The objective of this work is to quantify the transmission of the fibre core. We applied two ways to suppress the cladding light. Firstly, we controlled the light collection of the detector optics and we suppressed the light in the cladding while retaining the core light. The output detector used for fibre characterisation had 9 mm diameter and we fixed the detector at two distances 20 mm and 40 mm for core and cladding light discrimination. At 20 mm from the output fibre end, the light is detected at 0.24 numerical aperture (denoted as 0.24NAO). At 40 mm from the fibre end, the light is collected at 0.12 numerical aperture (denoted as 0.12NAO). By comparing these two outputs the contribution of cladding light to the transmission of the taper core can be estimated and controlled. Typically, an index matching gel [9] was also used to remove the cladding light near the taper end. The fibres are held rigidly at the light input point and the exit point is held at a fixed distance from the detector.

3.2. Numerical Aperture matching technique

A principle factor for throughput of an optical system is the NA. If the NA and image size of the optical system matches the fibre’s NA and core size then maximum coupling to the fibre core is possible. In other words, if the beam is incident at a suitable convergence angle on the fibre it can propagate along the core without leaking into the cladding. In the test apparatus, we vary the numerical aperture of the focused beam from the source to a fibre by adjusting an iris stop diameter at a fixed focal length from the microscope objective lens.

1Chromis Fibreoptics product [10]
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Figure 2: The fibre test setup comprises a 635 nm red diode laser, a beam expander consisting of a two lens-telescope using achromatic doublets, an adjustable iris diaphragm, a beam splitter, a microscope objective lens (4x or 10x magnification), a three-axis translation calibrated stage and two power detectors.

Table 1
Description of the important abbreviation terms used in this paper

<table>
<thead>
<tr>
<th>Abbreviation term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA_{eff}</td>
<td>Effective numerical aperture of the characterized fibre, the measured NA</td>
</tr>
<tr>
<td>NA^*</td>
<td>Effective numerical aperture based on 80% of maximum measured transmission of the fibre</td>
</tr>
<tr>
<td>NA_{MOL}</td>
<td>Microscope objective lens numerical aperture</td>
</tr>
<tr>
<td>NA_taper</td>
<td>Numerical aperture of tapered fibre at the tapered end</td>
</tr>
<tr>
<td>T_{max}</td>
<td>Maximum transmission of the characterized fibre</td>
</tr>
<tr>
<td>Core</td>
<td>Core size of fibre from manufacturer specification</td>
</tr>
</tbody>
</table>

The effective numerical aperture (NA_{eff}) of our optical system is calculated by the following equation,

$$\text{NA}_{\text{eff}} = \text{NA}_{\text{MOL}} \frac{d_{\text{iris}}}{d_{\text{MOL}}},$$

where NA_{eff} is an effective numerical aperture. NA_{MOL} is the full numerical aperture of microscope objective lens (MOL). The diameter of iris diaphragm and the internal stop diameter of the microscope objective lens are d_{iris} and d_{MOL} respectively. We used two microscope objective lenses: 4x (NA_{MOL} 0.10) and 10x (NA_{MOL} 0.25) in order to take wide-ranging NA_{eff} data related to transmission ratio. The microscope objectives were carefully measured to confirm the manufacturers NA_{MOL} specification.

3.3. Relative throughput

Each fibre is characterised based on the transmission or throughput versus NA_{eff} of the input beam. We measured the power at the fibre end and sampled the input beam with the beam splitter. The power at the position after the beam splitter is defined as P_1. P_2 is the power output after the fibre end and P_3 is the power output of the reflected beam from the beam splitter. The intensity of beam after the beam splitter P_1 is directly proportional to the intensity P_3 with proportionality constant α. The parameter α is determined from the measured beam with the two detectors at different
Table 2
Untapered fibre descriptions.

<table>
<thead>
<tr>
<th>Type</th>
<th>Core (μm)</th>
<th>NA†</th>
<th>Part number</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>2.8-4.1 at 488 nm</td>
<td>0.10-0.14</td>
<td>SM450</td>
</tr>
<tr>
<td>SM</td>
<td>3.6-5.3 at 633 nm</td>
<td>0.10-0.14</td>
<td>SM600</td>
</tr>
<tr>
<td>SM</td>
<td>4.0 ± 0.5 at 630 nm</td>
<td>0.13</td>
<td>630HP</td>
</tr>
<tr>
<td>ESM</td>
<td>0.09 ± 0.02 at 1064 nm</td>
<td>12.2</td>
<td>ESM-12B</td>
</tr>
<tr>
<td>Double-clad</td>
<td>9 (1st)/ 105 (2nd)</td>
<td>0.12/ 0.2</td>
<td>DCF13</td>
</tr>
<tr>
<td>SI MM</td>
<td>10</td>
<td>0.10</td>
<td>FG010LDA</td>
</tr>
<tr>
<td>GI MM</td>
<td>25</td>
<td>0.10</td>
<td>FG025LJA</td>
</tr>
<tr>
<td>SI MM</td>
<td>50</td>
<td>0.22</td>
<td>FG050LGA</td>
</tr>
<tr>
<td>GI MM</td>
<td>50</td>
<td>0.20</td>
<td>GIF50E</td>
</tr>
<tr>
<td>GI MM</td>
<td>62.5</td>
<td>0.275</td>
<td>GIF625</td>
</tr>
<tr>
<td>GI MM plastic</td>
<td>62.5</td>
<td>0.185</td>
<td>POF-62SR†</td>
</tr>
<tr>
<td>Custom GI MM</td>
<td>50</td>
<td>0.30</td>
<td>custom fibre</td>
</tr>
</tbody>
</table>

Table 3
Tapered fibre descriptions. Thorlabs commercial fibres were used for the first four tapers. The fifth fibre in the table is based on tapering a 50 μm core graded-index fibre with 600 μm cladding. All of fibres are tapered by the adiabatic heating process of the University of Bath [6].

<table>
<thead>
<tr>
<th>Type</th>
<th>Core (μm)</th>
<th>NA†</th>
<th>Part number</th>
<th>Taper ratio</th>
<th>Final core (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI MM</td>
<td>50</td>
<td>0.22</td>
<td>FG050LGA</td>
<td>2.5:1</td>
<td>20</td>
</tr>
<tr>
<td>SI MM</td>
<td>50</td>
<td>0.22</td>
<td>FG050LGA</td>
<td>5:1</td>
<td>10</td>
</tr>
<tr>
<td>GI MM</td>
<td>50</td>
<td>0.20</td>
<td>GIF50E</td>
<td>4:1</td>
<td>25</td>
</tr>
<tr>
<td>GI MM</td>
<td>50</td>
<td>0.20</td>
<td>GIF50E</td>
<td>5:1</td>
<td>10</td>
</tr>
<tr>
<td>Custom GI MM</td>
<td>50</td>
<td>0.30</td>
<td>custom fibre</td>
<td>5:1</td>
<td>10</td>
</tr>
</tbody>
</table>

positions and is written as $\alpha P_3 = P_1$. The transmission is the ratio of power output to input, which is

$$T = \frac{P_2}{P_1} = \frac{P_2}{\alpha P_3}. \quad (6)$$

The measurements are done repeatedly each time the iris is adjusted. The power output of $P_3$ and $P_3$ are recorded five times for each measurement. The mean and standard deviation of each recorded data point is calculated. The same apparatus and procedure was used for all fibres.

4. Results and discussion

There are two major factors that give rise to uncertainty in the experiment: (1) the influence of the physical optics (2) environmental conditions. The optical signal in the fibre has noise because of mode interference [21]. We found the measured throughput varied by approximately 3 percent in repeat measurements on the same fibre. The initial alignment of the fibre was performed by maximising the output to the detector by varying the focus (z) and position (x,y) of the input fibre with respect to the microscope objective. This position was then fixed during the measurements and varied again when the iris diameter is changed. The $NA_{\text{eff}}$ of the beam launched into the fibre is changed by varying the diameter of the iris diaphragm. The numerical aperture that matches the maximum throughput is called $NA_{\text{max}}$.

External environmental influences such as bending or movement of the fibre can effect the throughput. The fibres were contained or installed in very clean and stable grips. The set up allowed only relatively small impacts from any external mechanical factors on the fibre such as touching or bending. A standard cleaning process was used for the fibre since dust is an important issue on the fibre face potentially producing fluctuating results. Another concern is the effect of air flow, temperature and pressure variation in the room.

The results of the measurements of $NA_{\text{eff}}$ and transmission of the fibre are presented in Figure 3, 4 and 5. Table 4 summarises results for both untapered and tapered fibre. The $NA_{\text{max}}$ are presented as maximum transmission for each fibre shown in Table 4. We note that all values of $NA_{\text{max}}$ are smaller than the manufacturer quoted $NA^\dagger$ in Table 4 and
Table 4
The result of untapered and tapered fibre characterisation. $NA_{\text{max}}$ is the measured NA at $T_{\text{max}}$. $T_{\text{max}}$ is the maximum measured throughput at $NA_{\text{max}}$. $NA^*$ is the measured NA at 80% of $T_{\text{max}}$.

<table>
<thead>
<tr>
<th>Core ($\mu$m)</th>
<th>NA$^*$</th>
<th>Type</th>
<th>$NA_{\text{taper}}$</th>
<th>$NA_{\text{max}}$</th>
<th>$T_{\text{max}}$</th>
<th>$NA^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>untapered fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.8-4.1</td>
<td>0.10-0.14</td>
<td>SM$_{488-633 \text{ nm}}$</td>
<td>-</td>
<td>0.10</td>
<td>0.46</td>
<td>0.16</td>
</tr>
<tr>
<td>3.6-5.3</td>
<td>0.10-0.14</td>
<td>SM$_{633-780 \text{ nm}}$</td>
<td>-</td>
<td>0.13</td>
<td>0.50</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>SM$_{600-770 \text{ nm}}$</td>
<td>-</td>
<td>0.12</td>
<td>0.54</td>
<td>0.18</td>
</tr>
<tr>
<td>12.2</td>
<td>0.09</td>
<td>ESM</td>
<td>-</td>
<td>0.05</td>
<td>0.60</td>
<td>0.08</td>
</tr>
<tr>
<td>9 (1st)/ 105 (2nd)</td>
<td>0.12 (1st)/0.2 (2nd)</td>
<td>Double-clad</td>
<td>-</td>
<td>0.19</td>
<td>0.74</td>
<td>0.22</td>
</tr>
<tr>
<td>10</td>
<td>0.10</td>
<td>SI MM</td>
<td>-</td>
<td>0.05</td>
<td>0.68</td>
<td>0.096</td>
</tr>
<tr>
<td>25</td>
<td>0.10</td>
<td>SI MM</td>
<td>-</td>
<td>0.04</td>
<td>0.63</td>
<td>0.088</td>
</tr>
<tr>
<td>50</td>
<td>0.22</td>
<td>SI MM</td>
<td>-</td>
<td>0.18</td>
<td>0.77</td>
<td>0.26</td>
</tr>
<tr>
<td>50</td>
<td>0.20</td>
<td>GI MM</td>
<td>-</td>
<td>0.13</td>
<td>0.78</td>
<td>0.22</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
<td>Custom GI MM</td>
<td>-</td>
<td>0.07</td>
<td>0.74</td>
<td>0.15</td>
</tr>
<tr>
<td>62.5</td>
<td>0.275</td>
<td>GI MM</td>
<td>-</td>
<td>0.18</td>
<td>0.78</td>
<td>0.25</td>
</tr>
<tr>
<td>62.5</td>
<td>0.185</td>
<td>Plastic GI MM</td>
<td>-</td>
<td>0.08</td>
<td>0.80</td>
<td>0.19</td>
</tr>
<tr>
<td>tapered fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.22</td>
<td>SI, 5:1</td>
<td>0.044</td>
<td>0.03</td>
<td>0.20</td>
<td>0.050</td>
</tr>
<tr>
<td>50</td>
<td>0.20</td>
<td>GI, 4:1</td>
<td>0.050</td>
<td>0.05</td>
<td>0.66</td>
<td>0.096</td>
</tr>
<tr>
<td>50</td>
<td>0.20</td>
<td>GI, 5:1</td>
<td>0.040</td>
<td>0.05</td>
<td>0.44</td>
<td>0.088</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
<td>Custom GI, 5:1</td>
<td>0.06</td>
<td>0.05</td>
<td>0.66</td>
<td>0.096</td>
</tr>
</tbody>
</table>

so we include $NA^*$ which is based on 80% of maximum measured transmission of the fibre. Using 80% allows us to approximately match the quoted NA of fibres from Thorlabs and Chromis Fiberoptics.

We divide the results of transmission and $NA_{\text{eff}}$ into three subsections. Firstly, the untapered fibre experimental result is discussed in section 4.1. Next, in section 4.2 we compare the step-index fibre measurements with the Zemax simulation. Lastly, the result of the graded-index fibre compared to the step-index fibre is presented in section 4.3.

4.1. Untapered fibre result

Figure 3 shows the results for untapered fibre comprising 62.5 $\mu$m plastic [10] and various glass fibres [9]. The glass fibre tested from Thorlabs [9] are single mode fibre (SM), endlessly single mode fibre (ESM) and multimode 10 $\mu$m step-index fibre and 50 $\mu$m step-index and graded-index fibres. We also present the result of customised 50 $\mu$m graded-index fibre (denoted as ‘50 GI cust’) in this figure. The results of untapered fibres such as double-clad fibre, 25 $\mu$m step-index fibre, 62.5 $\mu$m graded-index glass fibre, and other single mode fibres can be found in Table 4 with respect to the fibre information provided in Table 2. Note that two sets of microscope objective lenses were used for the untapered fibre measurement. We used Edmund microscope objectives for the ESM and SM and we used Olympus lenses for the rest. The Olympus lenses are higher quality than the Edmund lenses in terms of consistent performance at larger NA.

In Section 3 we described the test procedure in which fixed-focus lenses were used and the focal distance was held constant during the measurements. In multimode fibres this means the coupling to the changing number of modes in the fibre as $NA_{\text{eff}}$ is reduced will not always be optimum. In separate tests that carefully optimised the coupling into the lowest modes at very low $NA_{\text{eff}} < 0.01$ the transmission versus $NA_{\text{eff}}$ is flat until the $NA_{\text{eff}}$ exceeds the fibre NA just as in the Zemax simulations in Section 4.2. The presence of this modal coupling behaviour cannot be adequately described with geometric optics and changing the coupling lens focal length and realigning the input coupling for every $NA_{\text{eff}}$ value is not a realistic test procedure. Highly repeatable measurements near $NA_{\text{max}}$ and larger values of $NA_{\text{eff}}$ give us confidence that only very low $NA_{\text{eff}}$ measurements are effected by mode coupling variability.

Our measurements of the untapered fibre indicate that the endlessly single mode fibre (ESM) and single mode fibre (SM) have lower transmissions compared to double-clad fibre and multimode step-index and graded-index fibre (MMF). The customised GI fibre has slightly less transmission than the Thorlabs products comparing the same core size and type. We found there is no significant difference between $NA_{\text{max}}$ and manufactured $NA^*$ for SM, ESM and double-clad fibres. However, the $NA_{\text{eff}}$ of multi-mode fibres in our setup is smaller than the manufacturer specification. We thus also present $NA^*$ values based on the numerical aperture at 80% maximum throughput which are
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Figure 3: The transmission versus $NA_{\text{eff}}$ of untapered fibres: 62.5 $\mu$m graded-index plastic fibre (POF) (62.5 GI POF), 10 $\mu$m step-index (10 SI), 50 $\mu$m step-index (50 SI), 50 $\mu$m graded-index (50 GI), 50 $\mu$m customised graded-index (50 GI cust), single mode (SM) and endlessly single mode glass fibres (ESM). All fibres are reported with core light collected onto the detector (0.12NAO). 10x indicates the magnification of microscope objective lens used for the measurement. Note that ESM and SM are tested with Edmund microscope objective lenses and the rest of the fibres are tested with Olympus microscope objective lenses. One sigma error bars are smaller than the data symbol.

generally present values closer to the manufacturer specification.

4.2. Step-index fibre and Zemax simulation result

The 50 $\mu$m step-index tapered fibres results are presented in Figure 4 along with untapered fibres which have the same core size and type. The Zemax step-index model calculations are also presented in this figure. We tested 50 $\mu$m untapered step-index fibre and 2.5:1 and 5:1 tapered step-index fibre. The result reveals that the transmission of the 2.5:1 taper is more than two times better than the 5:1 taper at $NA_{\text{max}}$.

We simulated a scaled up version of the fibre optics configuration similar to the setup in the experimentation using the non-sequential mode of Zemax. This mode is available for a total internal reflection simulation using two different glasses as a central rod and an outer cylinder. The ray tracing analysis on the detector is also used to simulate the measurement of fibre transmission. The optics parameters such as component dimension, position and the material are defined by the non-sequential Component Editor. The various inputs to the Component Editor information are as follows. The incoherent source is 635 nm wavelength and the power is 1 mW. The source type is ‘two angle source’. We varied the parameters of the source which are X-half width and Y-half width to imitate the iris diaphragm diameter adjustment. The rectangular detector dimensions were 40 x 40 mm with pixel number 500 x 500 and it is placed after the rod’s end. We scaled the model up from micrometer to millimeter by a factor of 100 to perform geometrical optical analysis of the fibre. The cylinder model has 0.5 mm inner radius and 1.25 mm outer radius with 1 m length to imitate the 50 $\mu$m multimode step-index fibre. The material of an inner rod and outer cylindrical volume are N-BK7 and K11, respectively. As the product details of the fibre materials are not revealed by manufacturers, the model is focused on matching the $NA_{\text{eff}}$ with the fibre NA using standard glasses. However, N-BK7 has more loss than silica material, thus the maximum transmission of the simulation is about 0.7. We do not attempt to model the graded-index tapered
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Figure 4: The transmission and $NA_{eff}$ for simulation and experimental results of the 50 $\mu$m step-index fibre. For untapered, 2.5:1 tapered and 5:1 tapered fibre at 0.24NAO. The Zemax models are shown in blue. The untapered experimental results are shown in red and the tapered results in green. One sigma error bars are smaller than the data symbol.

The untapered step-index fibres were expected to have higher transmission than the same fibres that were tapered as predicted by the geometric consideration in Section 2. The tapered fibre transmission is expected to decrease at smaller effective NA since the core size is decreased and the light in the cladding increases. This behaviour was examined more carefully in our Zemax calculations. The model of low taper ratio 2.5:1 tapered fibres shows similar characteristics in the variation of overall transmission versus $NA_{eff}$. The scaled up geometry of the Zemax rod simulates the behaviour of the step index fibre and low ratio tapers reasonably well using only geometric optics properties. There are two areas where the experimental results at very low $NA_{eff}$ and at high taper ratios of 5:1 deviate significantly from the simulations. These are the ‘drop off’ in transmission at small $NA_{eff}$ in our measurements (<0.05) and our measured taper results compared to the Zemax curves for the 5:1 step index tapers. In these cases the wave-optics nature of the optical fibres is prominent. With a 10 $\mu$m core diameter and 25 $\mu$m diameter including cladding, the final dimension of the 5:1 tapered fibre is rather small to be accurately simulated by geometric optics. The very low measured transmission of the 5:1 step index tapers may be due to changes at the core/cladding interface. We observe that it is difficult to identify the core and cladding light separately at the output of these tapers. This leads to the suspicion that the heating and pulling of the tapering process may have modified the interface between core and cladding at the small taper dimensions so that the refractive index difference between core and cladding may have largely disappeared. The resulting ‘cladding’ modes are stripped off by the index matching gel leading to low transmission at all input $NA_{eff}$. Further investigations are needed to determine the maximum taper ratios that can be considered efficient using step index commercial fibres.

4.3. Graded-index fibre results

We compared the performance of graded-index and step-index tapered fiber in Figure 5. The result indicates that the graded-index fibre in both untapered and tapered fibre configuration perform better than similar step-index fibres in term of throughput. Comparing the tapered fibre products originally from Thorlabs with the 5:1 taper ratio, graded-
index tapered fibres have a throughput at least two times better than the step-index tapered fibre and experimentally there is no particular difficulty in identifying core light separately from cladding the output. It is also clear that increasing the taper ratio from 4:1 to 5:1 significantly reduces the transmission for the graded-index tapered fibre. If comparing 5:1 tapered fibres, the best performing fibre is the 5:1 customised graded-index fibre. In this case the tapered end of graded-index fibre has a 125 μm diameter and the light loss in the taper is less than 50% across a range of $NA_{\text{eff}}$. The very large difference in the transmissions of the step-index and graded-index fibre will require further investigation particularly in the light of the approximate Zemax calculations which indicate that the 5:1 step index tapers should perform relatively much better than found by experiment. So although our experiments may somewhat overestimate the performance difference between step index and graded index, the measured throughput versus numerical aperture for the custom 5:1 tapered graded index fibre (tapered from a 50 to 10 μm core) speaks for itself with comparable performance to that of an untapered 50 μm step-index fibre.

5. Conclusions and Recommendations

Our investigation of fibre transmission versus numerical aperture was principally aimed at quantifying the expected throughput of a high resolution fibre-coupled spectrograph. Of particular interest to our designs are 50 μm core fibres and tapers from 50 μm to 10 μm. We measured a variety of fibres and tapers for throughput with a numerical aperture matching technique to assess their properties and to help mitigate the issues facing system designers of instruments such as fibre optics spectrometers. All the fibres were tested with the same instrumental apparatus. The results for untapered commercial fibres are consistent with but in general lower than the manufacturer’s specifications for both transmission and numerical aperture at the peak transmission. Since we only used two different input coupling lenses
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for testing it is likely that our peak transmission numbers are not optimum for some fibres. The measurements should, however, allow a fair comparison between the various fibre types. We tested single-mode, endlessly single mode, double-clad, plastic fibre as well as graded and step-index fibre.

The untapered fibre measurements reveal that the graded-index multimode fibres have higher throughput than single mode fibres. Our customised graded-index fibre has transmission greater than 50% but has less transmission than a similar configuration Thorlabs product INTERESTING BUT NOT RELEVANT. All multimode fibres: graded-index, step-index and plastic fibre as well as endlessly single mode fibre reveal smaller $NA_{max}$ than the manufacturer’s specification $NA^*$. $NA_{max}$ of Standard single mode fibres and double-clad fibre match the manufacturer quoted $NA^*$. 

Adiabatic tapers made from commercial step-index and graded-index fibres show a range of characteristics. Step-index fibres with 50 $\mu$m core fibres have good transmission characteristic at 2.5:1 taper but dramatically lower transmission at 5:1 taper ratio. The latter needs further investigation but may be in part due to the tapering process effecting the core/cladding boundary at high taper ratios. Graded-index tapers show a more consistent and higher transmission versus numerical aperture than do equivalent step-index fibres. The step-index fibres are simulated in this work using Zemax geometrical optics. We found the predicted Zemax trends in transmission compared favourably with experimental results of the untapered step-index fibre and 2.5:1 tapered fibre. The 5:1 tapered fibres revealed a peak measured transmission of less than 20% compared to over 0.78% for 2.5:1 tapers. The Zemax geometric optics calculations are not correct for the small core size of the 5:1 tapers since only a small number of modes will be present. Wave-guide modal analysis must be considered in this case.

The performance of the 5:1 graded-index tapered fibre is significantly improved compared to the equivalent step-index fibres with 50 $\mu$m core 5:1 graded-index tapers giving transmissions of over 60% into a numerical aperture of 0.10. A throughput of nearly 0.6 for a 5:1 graded-index taper into this small NA suggests that this is an efficient route for focal reduction of fibre optic signals. Future work might investigate the transmission versus $NA_{eff}$ of fibre at different taper ratios using electromagnetic modal and geometric optics calculations as well as measurements to understand the tapered graded-index fibre characteristics.

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