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Transmission properties of tapered optical fibres: Simulations and experimental measurements

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ABSTRACT

We measured the transmission of tapered and untapered optical fibres as a function of input beam numerical aperture at 635 nm. The tapered fibres were fabricated with an adiabatic tapering process from graded and step-index fibres with 50 μm core diameters to form a 100 mm long taper with 5:1 taper ratio. We tested tapered graded-index and step-index fibres fabricated from commercial Thorlabs products and a custom graded-index taper. The 5:1 tapered graded-index fibre can give a transmission greater than 0.4 for Thorlabs and 0.6 for the custom taper. We simulated the transmission of the tapered fibres and found reasonable agreement with the measured graded-index tapered fibre results across the numerical aperture range of interest. Experimentally, step-index tapered fibres performed relative poorly and considerably below modelling expectations. Based on our examinations this arises because the properties of step-index fibre were not robust to the tapering process. Suitably tapered graded-index fibres may offer a new route for efficient focal ratio reduction of fibre optic signals, e.g., in fibre-fed spectrographs, though we stress that our measurements have been limited to monochromatic light in this work.

1. Introduction

Optical fibre is renowned for signal transfer with small losses.The versatility of fibre and its relatively low material cost also leads to wide usage in astronomical instrumentation for light gathering [1]. In addition, the use of tapered optical fibre is well established as a focal reduction and magnification technique [2,3], as well as in applications such as high-power laser coupling [3–5]. It is possible to fabricate custom fibre tapers, with different taper ratios and transition lengths, from all manner of fibre types, depending on the application. We are developing a prototype high-resolution fibre fed spectrograph named EXOplanet high resolution SPECtrograph (EXOhSPEC) for smaller telescopes (1–3 m) which is designed for 0.10 Numerical Aperture (0.10 NA) light acceptance and a 10 μm core input fibre. The input beam comes from telescopes with a 0.20 NA seeing limited image size of 20–50 μm and beam-size conversion is required. A tapered fibre is a route to a smaller beam size with good enabling smaller 'off-the-shelf' optics reducing the need for more complex devices such as photonics lanterns or adaptive optics [2,6]. The fibres tested in this paper are standard commercial products [7] and customised graded-index fibres. Tapered fibres were formed from the standard bare fibre [7] and custom fibre and include taper ratios of 1.2:1, 2.5:1, 3:1, 4:1 and 5:1. All tapered fibres reported here originate from 100 mm original taper lengths. We have examined direct fabricated tapers from 25 to 100 mm and by cleaving the original tapers to create a variety of tapers ratios and lengths. We have modelled the step-index and graded-index tapered fibres using the wave optics package of COMSOL version 5.6 [8] and also the non-sequential ray optics models in Zemax [9] scaling up the dimensions. We begin with some background information about EXOhSPEC and fibre feeding in Section 2. Geometric optics and Electromagnetic (EM) waveguide simulations are discussed in Section 3. Next, the experimental details are presented in Section 4 including an explanation of the fibre test setup, the numerical aperture matching technique, transmission measurement, and experimental error. Lastly, we show and discuss our results with untapered standard fibre and tapered fibres in Section 5.

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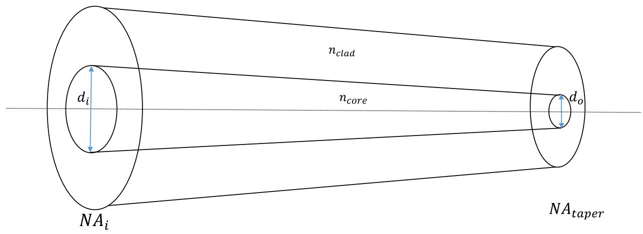

Fig. 1. A diagram to illustrate a tapered fibre. The NA_i is the numerical aperture at the untapered end (manufacturer NA) and NA_{taper} is the effective numerical aperture of tapered end.

2. EXOhSPEC and the fibre feeding

The objective of the fibre investigation is to apply the best tapered fibre design to the fibre-fed system of the high resolution spectrograph prototype EXOhSPEC. There are a number of potential routes to a smaller beam size which have been pursued for this. For example, the successful deployment of adaptive optics systems on a number of telescopes [10], or future use of photonics lantern for focal reduction may facilitate the fibre feeding of astronomical instrumentation [11–13]. Given the promise of some literature results [2,6,14,15] and the relative simplicity of tapering an optical fibre, we further investigate fibre tapers as a route to a smaller beam size and in particular graded-index fibre tapers, which is not commonly used in the fiber-fed spectrograph. There are presently two EXOhSPEC prototypes, one at the University of Hertfordshire and one at the National Astronomical Research Institute of Thailand (NARIT). The overall design concept is described in [16]. The optical design is described by [17]. The mechanical design of the collimator and its performance is modelled by [18] and the data reduction system for processing the raw data is presented by [19]. Tapered fibre coupler systems based on this work have been deployed at Thai National Telescope with the NARIT EXOhSPEC prototype and will be described in a later publication.

3. Tapered fibre simulations: geometric ray tracing and EM waveguides

The tapered fibre can be manufactured by either heating and pulling [2,3,20–23] or chemical etching [24] and can provide beam shaping and collimation [14,21]. The transmission along the taper shows promise of low loss even if the core size is small [14,21]. However, we find that quantitative measurements of taper losses or transmission as a function of effective numerical aperture are not commonly available in the optics literature [25] and graded-index tapers are absent. In this section, we simulated the 5:1 step-index and graded-index tapered fibre by classical geometric optics and wave optics using two different software packages: Zemax and COMSOL. We use a variety of acronyms for numerical aperture and these are defined in the appendix in Table A.1.

3.1. *Geometric optics ray tracing*

The Etendue principle can be applied to describe the optical properties of the taper [2,3,26]. Fig. 1 illustrates the geometry of a tapered fibre. Light travels from the left and is incident on the bigger surface area with NA_i. The light propagates from the wider core to the narrowed part until it reaches the tapered end with the numerical aperture NA_{taper}. In this case, which is light propagating from untapered end toward to tapered end, energy conservation applies when light propagation in both core and cladding are considered together.

If the tapering process does not change the core and the cladding indices, then NA_i is manufacturer's numerical aperture. Considering the effective tapered numerical aperture when the light injected into untapered end, NA_{taper} can be expressed using the taper ratio R [4] as

Table 1

Tapered and 'cut back' tapered fibre descriptions. The SI MM and GI MM fibres are from Thorlabs and are based on a 50 μm core with 125 μm cladding. The Custom GI MM is based on tapering a custom 50 μm core graded-index fibre with 600 μm cladding. Cut back tapered fibres have original 100 mm taper transition length. All fibres have a 50 μm core diameter and are tapered by the adiabatic heating process at the University of Bath [20].

Type	NA†	Part number	Taper ratio	Final core (μm)
Tapered fibre				
SI MM	0.22	FG050LGA	5:1	10
GI MM	0.20	GIF50E	5:1	10
Custom GI MM	0.30	custom fibre	5:1	10
Type	NA†	Part number	Taper ratio	Final cladding (μm)
Cut back tapered fibre				
SI MM	0.22	FG050LGA	3.1:1	40
SI MM	0.22	FG050LGA	2.5:1	50
SI MM	0.22	FG050LGA	1.25:1	100
GI MM	0.20	GIF50E	3.79:1	33
GI MM	0.20	GIF50E	1.47:1	85
Custom GI MM	0.30	custom fibre	4.4:1	135
Custom GI MM	0.30	custom fibre	3:1	199
Custom GI MM	0.30	custom fibre	2.4:1	250
Custom GI MM	0.30	custom fibre	1.6:1	370

Table 2

The result of tapered fibre characterisation. All tapers are fabricated from 50μm core diameter fibre. NA† is the manufactured numerical aperture. NA_{taper} is the taper numerical aperture defined in Eq. 1. NA_{max} is the measured numerical aperture at T_{max}. T_{max} is the maximum measured transmission at NA_{max}. NA^* is the measured NA at 80% of T_{max}.

Type	NA†	NA_{taper}	NA_{max}	NA^*	T_{max}
Tapered fibre					
SI, 5:1	0.22	0.044	0.03	0.050	0.17
GI, 5:1	0.20	0.040	0.05	0.088	0.44
Custom GI, 5:1	0.30	0.060	0.05	0.096	0.66
Cut back tapered fibre					
SI, 3.13:1	0.22	0.070	0.04	0.069	0.19
SI, 2.5:1	0.22	0.088	0.03	0.077	0.35
SI, 1.25:1	0.22	0.176	0.06	0.20	0.30
GI, 3.79:1	0.20	0.07	0.07	0.16	0.79
GI, 1.47:1	0.20	0.05	0.06	0.016	0.79
Custom GI, 4.4:1	0.30	0.07	0.09	0.16	0.48
Custom GI, 3:1	0.30	0.10	0.06	0.14	0.69
Custom GI, 2.4:1	0.30	0.12	0.05	0.12	0.69
Custom GI, 1.6:1	0.30	0.18	0.06	0.18	0.72

$$NA_{taper} = R\,NA_i = \frac{d_o}{d_i} NA_i. \tag{1}$$

Where d_i and d_o are the respective untapered and tapered fibre diameters. Note that this effective numerical aperture is smaller than expected from an untapered fibre. If light is incident on the untapered end at a numerical aperture greater than NA_{taper} it appears in the cladding at the tapered end not in the core. A simple estimate of the maximum geometric optics transmission of tapered fibres can be obtained from the Etendue. For uptapered fibres the maximum transmission will be the same as an untapered fibre with the same core diameter and numerical aperture since energy is conserved and the light is emitted at a numerical aperture 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 numerical aperture scaled from the untapered fibre based on Eq. 1. Hence, the tapered numerical aperture of 5:1 Thorlabs step-index (originally 0.22 NA) and graded-index (originally 0.2 NA) tapers in

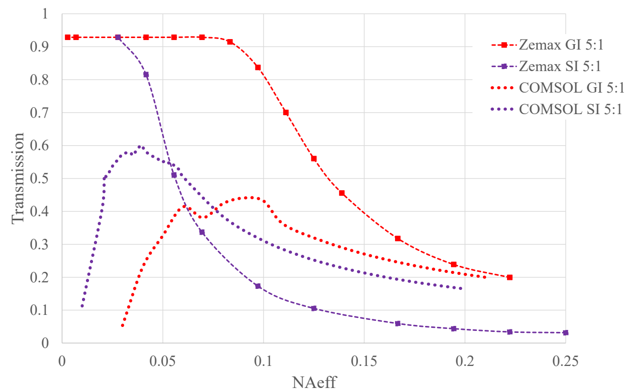

Fig. 2. The Zemax and COMSOL simulations of transmission and NA_{eff} of the 50 μm step- and graded-index 5:1 tapered fibre. Both simulations agree on the drop off transmission of step-index taper is about 0.04 NA_{eff} whereas the drop of transmission of graded-index taper is about 0.08 NA_{eff}. Zemax results shows no transmission loss and reach maximum transmission nearly 95% while the COMSOL results considered coupling loss by a taper itself and results in lower transmission overall compared to the Zemax results.

our work are 0.044 and 0.040 respectively. The description of the tested fibres is in Table 1 and NA_{taper} shows in Table 2. We used the non-sequential mode of Zemax version 19.8 to simulate a scaled up version of the fibre optics configuration similar to the setup in the experiment. With this approach of scaling up the fibre dimensions, waveguide mode propagation is not considered. The non-sequential mode was chosen because: 1) The ray trace order is not defined thus the light scattering and diffraction are fully considered, 2) Multiple standard 3D components are available such as the cylinder and rod which we modelled as the fibre as well as a variety of sources, and detectors. The composite optical model had a 0.5 mm rod with a cylinder of 0.5 mm inner radius and 1.25 mm outer radius with 1 m lengths. The refractive index of the core and cladding were chosen to imitate the 0.22 NA of step-index fibres. The graded-index simulations use a typical parabolic profile for the core refractive profile to imitate the 0.20 NA of graded-index fibre. A wavelength of 635 nm was used with 100,000 rays to perform the calculations for tapered geometries. Details of the model calculations and the Zemax model files are found in Github.[1] The Zemax results of step- and graded-index 5:1 tapered fibre are shown in Fig. 2 along with the COMSOL EM waveguide simulations considered in the next section.

3.2. Wave optics modelling

The Etendue principle applies to highly multimode optical fibre systems in general. However, some care is needed when considering optical fibre tapers with small dimensions and in particular electromagnetic wave optics modelling should be considered. The well-known V parameter ($V = \frac{2\pi}{\lambda} rNA$, where r is wave guide core radius)[27] is used to determine number of modes propagated along the fibre by its physical geometry: core size, numerical aperture and the wavelength in a free space. Geometric optics calculations will have errors of more than 5% for waveguides with $V < 20$[28], i.e., single mode or small number (<100) of modes waveguides [27]. Our work is investigating the 10 μm taper core custom grade-index, Thorlabs graded-index and Thorlabs step-index tapers with 0.10 NA_{taper}, 0.04 NA_{taper} and 0.044 NA_{taper}, respectively. Thus, V of our custom graded-index, graded-index and step-index tapered fibre is 4.9, 9.9 and 10.9, respectively, i.e., V is <20 for our tested tapers and wave optics solutions will be required. The COMSOL 5.6 wave optics module was used to model the tapers in 3D and

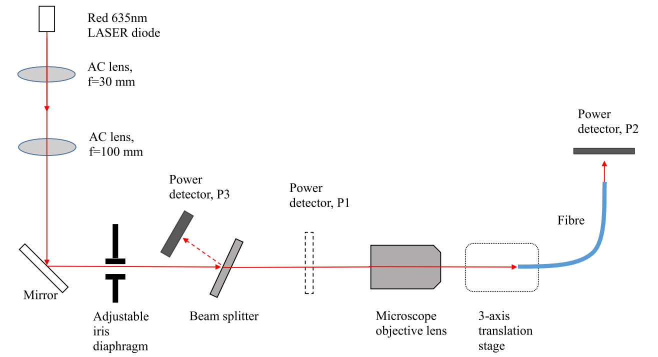

Fig. 3. The fibre test setup comprises a 635 nm red diode laser, a collimated-beam expander consisting of a two lens-telescope using achromatic doublets, an adjustable iris diaphragm, a beam splitter, a microscope objective lens (4× or 10× magnification), a three-axis translation calibrated stage and two power detectors.

the results are shown in Fig. 2. The model inputs were based on 50 μm core and 125 μm cladding diameter step and graded index profiles of NA 0.20 with a total taper length of 50 mm. The shorter length was chosen to reduce computing time and in separate calculations results in only small changes (∼ 2%) with these long adiabatic taper lengths. A wavelength of 635 nm was used. Details of the model parameters and the COMSOL model files are found in Github.[2] The model produces input and output modal patterns and transmission for each mode with an effective index n_i propagating in the fibre structure where i is the mode number. We converted the individual mode results into transmission versus numerical aperture as follows: The effective numerical aperture for an individual mode is found from the effective index n_i (effective refractive index of mode i) as $NA_i = \sqrt{n_{core}^2 - n_i^2}$ with a transmission or coupling efficiency of t_i. n_{core} is fibre core refractive index. The overall transmission for the fibre structure at a given numerical aperture NA is then determined by summing over all the modes that can be excited $0 \leqslant NA \leqslant NA_{eff}$. Thus

$$T(NA) = \sum_{0}^{NA} t_i * C_i(NA) * \Delta NA_i, \tag{2}$$

where $C_i(NA)$ is a slowly varying function expressing the variation in coupling efficiency with mode number when exciting multiple modes simultaneously in measurements with a fixed optical configuration. The 3D COMSOL models are shown with $C_i(NA)=1$, i.e. no corrections for mode coupling efficiency. In Fig. 2 it can be seen that the consideration of wave optics makes a very significant difference with the COMSOL modelling predicting a lower and different shaped transmission as a function of numerical aperture. The details of individual mode transmission are important in low mode number regime being considered. The calculations included all modes that propagated through the taper with transmission $t > 1\%$. The summation of overall transmission is small at $NA_{eff} < NA_{taper}$ as a result in significant drop transmission in this range shown in Fig. 2. The Figure also indicates that the difference between step and graded index should be relatively small.

4. Experimental detail

This section describes details of the experiment, the fibre test setup, the principle of the numerical aperture matching technique applied, the relative transmission definition and the experimental error. We characterised optical fibre obtained from Thorlabs [7] and custom tapered

[1] https://github.com/Piyamas-Ch/Tapered-and-untapered-fibre-investigation/tree/master/Zemax.

[2] https://github.com/Piyamas-Ch/Tapered-and-untapered-fibre-investigation/tree/master/COMSOL.

fibres from the University of Bath. The main aim of our setup is to measure the transmission of the untapered and tapered fibre as a function of the effective input numerical aperture dependence. The setup drawing shown in Fig. 3 comprises a 635 nm laser diode source, a beam expansion telescope, an adjustable iris diaphragm, a three-axis adjustable translation stage and 4× or 10× microscope objective lenses. A 2° uncoated deviation prism was used to sample the input beam power and standard optical power sensors with digital outputs (Thorlabs-SN120B and Thorlabs-SN120UV) [7] were used for the input and output measurements. The output from the beam expansion telescope was a 9.7 mm diameter collimated beam. Table 1 presents description of 100-mm-taper-length tapered fibres including 'cut back' set of tapers prepared from the 100-mm-length tapered fibre samples. The table present the manufactures' numerical aperture (denoted as $NA^{\dagger}$), part number, taper ratio and final core diameters. The tapered fibre ratios mentioned in the remainder are from the original 'recipe' specification from the adiabatic tapering machine of the University of Bath [20]. We determined the taper ratios of 'cut back' fibres from the cladding diameter measurements made with a micrometer and find that these are consistent with our more difficult microscope measurements of the fibre core.

4.1. Numerical aperture matching technique

A primary characteristic determining the transmission of an optical system is the Numerical Aperture (NA). If the numerical aperture and image size of the optical system matches the fibre's numerical aperture 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. The collimated beam and focusing lens combination can vary the NA of the focused beam on the fibre core depending on the aperture stop. This is the typical technique used in experimental works [2,3,11,12]. In our test apparatus, we vary the numerical aperture of the focused beam from the collimated source to a fibre by adjusting an iris stop diameter at a fixed distance from the microscope objective lens. Thorlabs presented a beam profile measurement setup which is very useful for our setup reference [29]. The effective numerical aperture (NA_{eff}) of our optical system is calculated by the following equation,

$$NA_{\mathrm{eff}} = NA_{\mathrm{MOL}}\frac{d_{\mathrm{iris}}}{d_{\mathrm{MOL}}}, \tag{3}$$

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: 4× (NA_{MOL}=0.10) and 10× (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 by measuring the exit pupil diameter and the focal length. Coupling light into the fibre cores requires care to achieve consistent results with multimode fibres. We used a truncated Gaussian beam propagation calculation [30] (found in Github[3]) to estimate input coupling variations. The set up will produce the largest spot size with a Gaussian ($1/e^2$) waist of 47 μm and with the iris diaphragm set at 1 mm using the 4× microscope objective lens. The 4× measurements will thus have some coupling losses at this setting for fibres having smaller core diameters than 50 μm. The focal spot sizes for the 10× objective were less than 20 μm for all iris settings. We also measured the focal spot sizes directly with a scanning small core fibre and these agreed with the calculations. Note we make no attempt to exactly match the fibre core diameters with the Gaussian waists from the two focusing objectives so

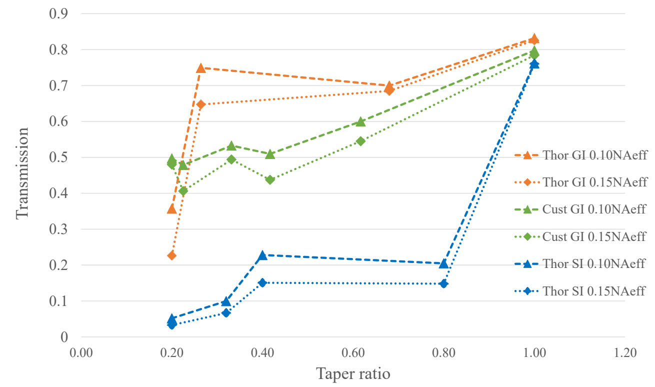

Fig. 4. Transmission of the cut back tapers versus the taper ratio expressed as a fraction, e.g. 5:1 is 0.20, 1:1 is 1.0, etc. The presented result is by 0.12NAO setup. The taper ratio in this graph is the ratio between untapered end and tapered end diameter. Cut back measurements are shown for the custom graded-index fibre, Thorlabs step-index and graded-index fibre at the 0.1NA_{eff} and 0.15NA_{eff}. All tapered fibres have 50 μm untapered core diameter.

that our transmission measurements will be smaller than the absolute maximums that could be theoretically achieved for the lowest order modes in multimode fibres and in single mode fibres. Our principal objective was to achieve consistency across a large range of fibre and taper geometries. The experimental results at very low NA_{eff} (NA_{eff}<0.05 for untapered fibre and NA_{eff}<0.02 for SI taper and < 0.05 for GI taper reveal a significant drop in transmission due to inefficient mode coupling to low order modes, i.e. the mode profile is not matched at all diameters of the iris diaphragm. To couple the same mode into the fibre for each iris diameter (NA_{eff}) is extremely time consuming. Since, we are principally interested in $NA_{\mathrm{eff}} > 0.05$, the setup is valid to identify the best performed tapers for the EXOhSPEC. The spectrograph has a 0.1NA acceptance so we used a method to measure light at different numerical aperture outputs at 0.24 NA and 0.12 NA by variation of the detector distance. The output detector used for fibre characterisation had 9.5 mm diameter and we fixed the detector at two distances 20 mm and 40 mm. At20 mm from the output fibre end, the light was detected at 0.24 numerical aperture (denoted as 0.24NAO). At 40 mm from the fibre end, the light was collected at 0.12 numerical aperture (denoted as 0.12NAO). This emulates the transmission of taper into the spectrograph NA limitation (0.12NAO) compared to the entire output of the taper (0.24NAO).

4.2. Relative transmission

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

$$T = \frac{P_2}{P_1} = \frac{P_2}{\alpha P_3}. \tag{4}$$

The transmission measurement includes all input and output losses and fibre absorption losses. The latter are very small with the one metre lengths used for testing. The measurements are done repeatedly each time the iris is adjusted. The power output of P_2 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.

[3] https://github.com/Piyamas-Ch/Tapered-and-untapered-fibre-investigation/blob/master/Zemax/Gaussian-spot_calculations.JPG.

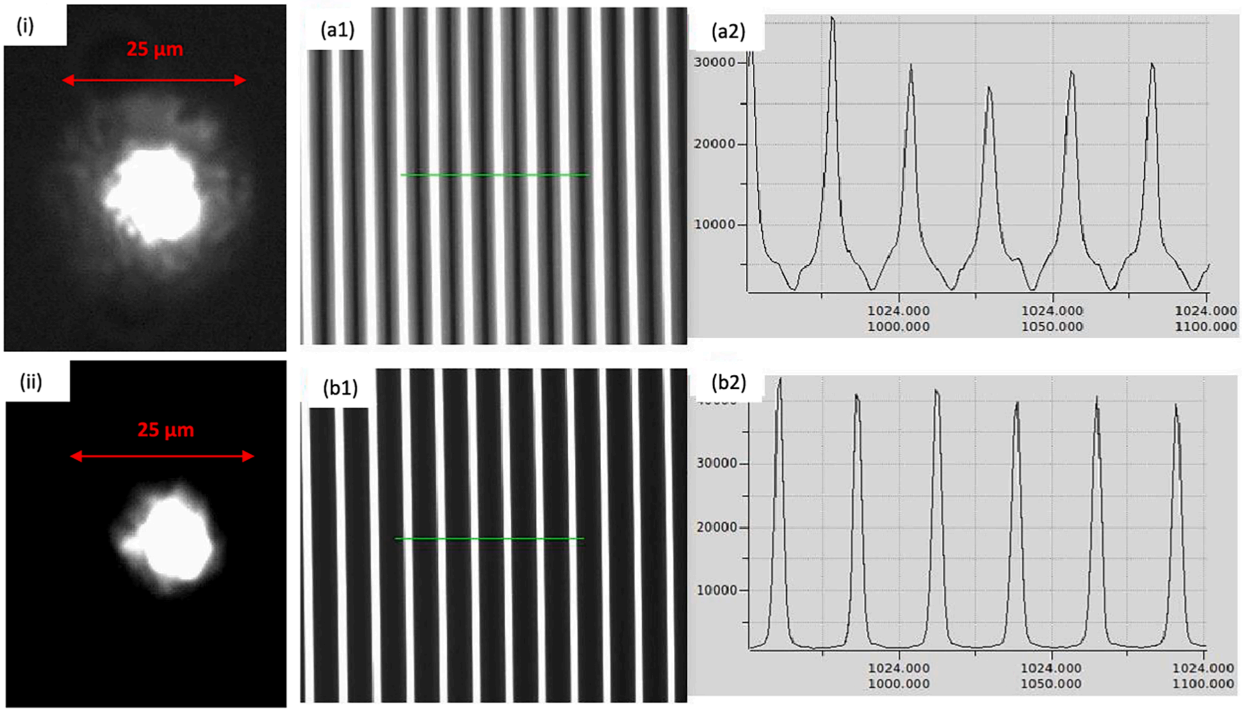

Fig. 5. Visualising the impact of cladding light: Output light distribution at the end of the tapered region for a Thorlabs graded-index 5:1 tapered fibre without (i) and with (ii) index matching gel applied to the transition to suppress the cladding light. The image of cross dispersed spectral orders of Tungsten for a tapered 5:1 graded-index fibre and for an untapered 10 µm core fibre as shown in (a1) and (b1), respectively. "Line out" traces along the green lines shown in (a1) and (b1) are plotted in (a2) and (b2), respectively. In these spectra, we see that the cladding light present in the tapered fibre output broadens the spectral lines, causing 'wings'.

4.3. Cut Back measurement

An additional set of measurements was performed on three tapered fibres to look at how the transmission characteristics change with taper ratio. The configuration of the tapers was a lead-in of untapered fibre of length 400–500 mm followed by the 100 mm taper. All samples have 50 µm core diameter and were tapered to 5:1 taper ratio. We cut back and carefully cleaved each sample to decrease the taper ratio from the original taper ratio 5:1 to 1:1 (until all the 100 mm tapered length was cut off). For each 'cut back' the transmission is measured as well as the fibre size (and thus the new taper ratio is determined). The beam inputs for the cut back measurements were 0.10 and 0.15 NA_{eff}. The 'cut back' results are shown in Table 2 and Fig. 4.

4.4. Cladding light

A key element of fibre construction is to ensure that light remains in the fibre core and is not significant in the cladding. This is particularly the case for a high resolution spectrograph where cladding light will degrade the resolution. Fig. 5 presents a number of images chosen to represent our measurements of cladding light. The top row of 'typical' images present the impact of cladding light of a tapered fibre taken 'face-on' (i) and in a prototype EXOhSPEC spectrograph image appearing as 'blurred' orders of tungsten light in (a1). The green 'line out' trace from (a1) is displayed in (a2) showing very significant 'wings'. These images can be contrasted with those in the row below where cladding light is relatively absent. In the left-hand example images we show the cladding light from a 5:1 Thorlabs graded-index taper fibre with no index matching gel around the cladding (i) and with index matching gel (ii). Based on (i) and (ii), we can use the Maxlm DL6 [31] aperture analysis function to compare the intensity of the core and cladding area. With our $0.1NA_{\mathrm{eff}}$ input setup, we found that the cladding light in this example (considering outer ring area in (i) and (ii)) decreased to 1.8% from 4.3%. For the 'worse' case of a 5:1 step-index taper we find about 9% cladding light contamination before applying the index matching gel. So, although we can ameliorate and measure the impact of a cladding light it remains a key factor to consider in the tapered fibres.

4.5. Experimental error

There are two major factors that give rise to uncertainty in the experiment: (1) the influence of the physical optics and (2) the environmental conditions. The optical signal in the fibre has noise because of mode interference [32]. We found the measured transmission varied by approximately three 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 optimised when the iris diameter was changed. The NA_{eff} of the beam launched into the fibre is then changed by varying the diameter of the iris diaphragm. The numerical aperture at the maximum transmission is called NA_{max}. The setup will not give absolute maximum transmissions for core diameters smaller than 50 µm at NA_{eff} less than 0.02. Small core (∼ 10 µm) fibres can be accurately tested at $NA_{\mathrm{eff}}>0.05$ with both 4× and 10× objectives. Also, as presented in Section 4.4 the impact of cladding light will influence the measurements. In the worst case, it increases the measured transmission values by less than 5% for tapered fibres with the index

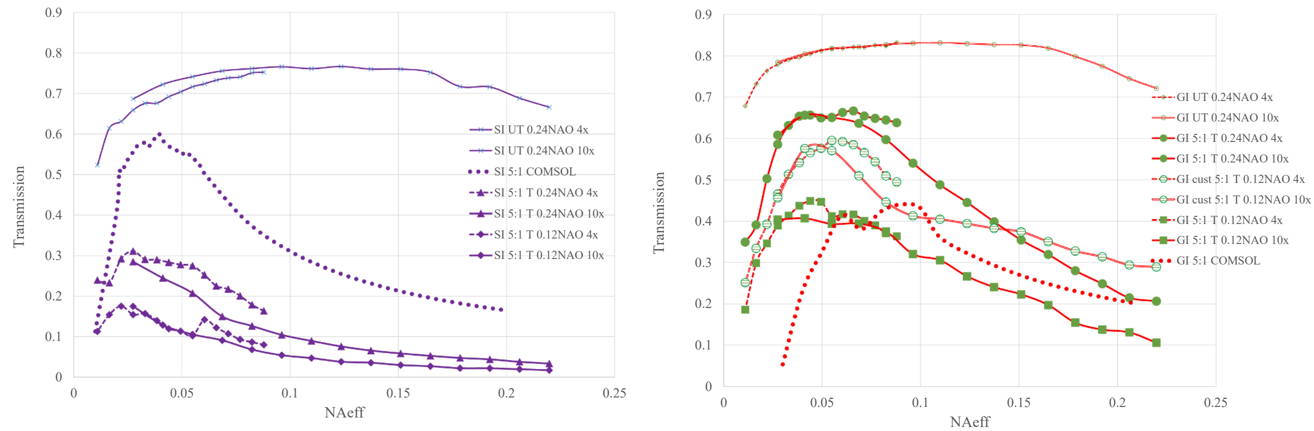

Fig. 6. The transmission and NA_{eff} results of untapered and tapered fibres. Step-index and graded-index fibre results show in left and right graph, respectively. Both untapered fibres have 50 µm core diameter and all tapered fibres presented in both graphs are 5:1 tapers. UT and T denote untapered fibre and tapered fibre, respectively. 'GI cust' abbreviates a 5:1 custom graded-index tapered fibre. The COMSOL graded-index and step-index 5:1 taper simulation results are shown as dotted lines. 4× and 10× are the microscope objective lenses used. One sigma error bars are smaller than the data symbol.

matching gel. In addition, the fibres were contained or installed in very clean and stable grips. The lab environment was temperature stable to ±2 °C with a filtered air supply. The setup allowed only relatively small impacts from any external mechanical factors on the fibre such as touching or bending. We used a standard cleaning process to ensure the fibres remained clean since dust on the fibre face produces fluctuating results. Reproducibility for each fibre transmission measurement is less than 5% error. The error of each repeated measurement is mainly due to external physical movement of the fibre from touching, bending and slight misalignment. The error for 'cut back' measurement is larger than our other measurements and can reach about 5% error in transmission measurement because the cleaving procedure is difficult to perform consistently. The manual cleave does not guarantee an ideal perpendicular flat end.

5. Results and discussion

We quantified the transmission of different fibres with tapers and supplemented these with 'cut back measurements' and effective numerical aperture. The 'cut back' result reveals clearly that the tapered step-index fibre performs poorly with any taper. For example, the 5:1 tapered step-index fibre measurements revealed a peak transmission of 17% compared to 35% for the cut off 2.5:1 taper (see in Table 2 and Fig. 4). The Thorlabs graded-index fibre tapers and the custom graded-index fibre taper showed high transmissions at all taper ratios. The results of the simulations and measurements of fibre transmission related to NA_{eff} are presented in Fig. 6. The untapered fibre measurements provide a firm basis for the more difficult tapered fibre measurements and are also useful in comparing the relative performance of the fibres with a fixed setup and consistent test methodology. The complete measurements of untapered fibres can be found in Github.[4] We note that all values of NA_{max} are smaller than the manufacturer quoted $NA^{\dagger}$ in Table 2 and 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 numerical aperture of fibres from manufacturers. Since we only used two different input coupling lenses for testing it is likely that our peak transmission numbers are not optimum for all fibres because of non-optimum mode matching. The measurements should, however, allow a fair comparison between the various fibre types. The NA_{max} are presented as maximum transmission for each tapered fibre and are shown in Table 2.

[4] https://github.com/Piyamas-Ch/Tapered-and-untapered-fibre-investigation/tree/master/Untapered-fibre-results.

The optimum tapered fibre for EXOhSPEC would comprise a 5:1 taper transition from a 50 µm core science fibre from the telescope to the 10 µm 0.10 NA spectrograph. In Fig. 6, we present the experimental results along with the COMSOL simulations. Comparing 5:1 experimental tapered fibres results based on 0.12NAO (results for the EXOhSPEC limitation), the graded-index tapered fibres have a transmission at least two times better than the step-index tapered fibre. The best performing fibre is the 5:1 custom graded-index fibre. The light loss in the taper is less than 40% across a range of 0.06 to 0.09 NA_{eff} shown in Fig. 6. The COMSOL simulations indicate consistency with the experimental data for the graded-index tapered fibre. The 'drop off' transmission for the graded-index and step-index taper simulations is at $0.08NA_{eff}$ and at $0.04NA_{eff}$, respectively. The transmission data for the graded-index tapers extends to lower NA than the simulations. We found there is an additional cladding layer observed in both the step- and graded-index Thorlabs fibres. These undocumented proprietary layer profiles are not included in the simulations but added coures are likely to favour additional low order modes. The maximum transmission for graded-index taper is 45%. We note that the COMSOL result of step-index the 5:1 taper model suggests it should perform better compared to the experiment results, i.e., ideally the step-index taper can achieve about 60% maximum transmission at the $NA_{eff} < 0.05$ and 30% transmission at $NA_{eff} = 0.1$. While the maximum transmission from the experimentation is about 17% at the $NA_{eff} < 0.05$ and less than 10% at the $NA_{eff} = 0.1$ which is significantly low compared to graded-index Thorlabs and custom taper with the same taper ratio (see Table 2). The poor transmission of these tapers is probably due to changes at the core/cladding interface. The design of the Thorlabs step-index fibres is proprietary but a common design is a silica core with a fluorine doped silica cladding and silica 'outer' cladding leading to strong cladding modes. We observe that it is difficult to identify the core and cladding light separately at the far-field image 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}.

6. Conclusions

Our investigation of fibre transmission versus numerical aperture is principally aimed at quantifying the expected transmission of tapers to be used for optical reformatting for 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 transmission 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. Adiabatic tapers made from commercial Thorlabs step-index and graded-index fibres and custom graded-index tapered show a range of characteristics. Graded-index tapers show a more consistent and higher transmission versus numerical aperture than do equivalent step-index tapered fibres. For the experimental results, the Thorlabs graded-index tapers and custom graded-index tapers give transmissions of over 40% and 60% into a numerical aperture <0.10 for 0.12NAO, respectively. The 5:1 step-index tapered fibre should have transmission greater than 50% for the 0.05 NA_{eff} or at the drop-off numerical aperture according to ouPleaser COMSOL simulations. The simulations and the cut back measurements suggest that our step-index tapers are undergoing some deterioration in the tapering process which is disturbing the core/cladding boundary at high taper ratios. A future set of measurements on tapers fabricated from step-index fibre with a germanium doped core rather than a silica core may resolve this issue. Future laboratory work on tapered fibre couplers will investigate the transmission versus NA_{eff} of tapers and injection units using representative (telescope) optics and incoherent light sources with variable point-spread functions.

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CRediT authorship contribution statement

Piyamas Choochalerm: Conceptualization, Investigation, Software, Formal analysis, Writing – original draft. **William E. Martin:** Conceptualization, Methodology, Software, Software, Supervision, Resources, Validation, Writing – original draft. **Hugh R.A. Jones:** Supervision, Project administration, Funding acquisition, Validation, Writing – original draft. **Ronny Errmann:** Formal analysis, Writing – review & editing. **Stephanos Yerolatsitis:** Resources, Writing – review & editing. **Thomas A. Wright:** Resources, Writing – review & editing. **Christophe Buisset:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1.

Table A.1
Description of the abbreviation terms of numerical aperture used in this paper

Abbreviation term	Definition
0.12NAO	Numerical aperture of the light collected at 0.12 numerical aperture at the detector
0.24NAO	Numerical aperture of the light collected at 0.24 numerical aperture at the detector
$NA^{\dagger}$	Numerical aperture of fibre from manufacturer specification
NA_{eff}	Effective numerical aperture of the characterized fibre, the measured numerical aperture
NA^{*}	Effective numerical aperture based at 80% of maximum measured intensity of the fibre
NA_{MOL}	Microscope objective lens numerical aperture
NA_{max}	Effective numerical aperture at the maximum transmission
NA_{taper}	Numerical aperture of tapered fibre at the tapered end
NA_{i}	Numerical aperture of the input end of tapered fibre
NA_{taper}	Numerical aperture of the clad fibre

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