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Incoherent light in tapered graded-index fibre: A study of transmission and modal noise

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ABSTRACT

We investigated the impact of taper length on light transmission through tapered graded-index fibres. We tested commercial fibres from Thorlabs and a custom graded-index fibre using both coherent and incoherent light sources. Our experimental results show optimum performance for taper transition lengths of 25 mm, although our simulations suggest further improvement may be possible for even shorter transition lengths. We also measured the modal noise power fluctuations caused by bending the fibre. Here, we observe that the custom fibre tapers have the highest transmission but suffer from the most modal noise. Accordingly, we find that the commercial graded-index fibre tapers promise practical usage as a beam mode-field converter, as they have lower power fluctuations but retain relatively high transmission if compared to commercial small core step-index fibre.

1. Introduction

Tapered fibres are known to be compact and effective beam converters [1,2]. When used in fibre-fed spectrographs, they present a low-loss and compact alternative to other converters [2,3]. It is possible to heat and permanently stretch any fibre to narrow it down over a defined short length; thus, single mode (SM) fibres or multimode (MM) fibres can be tapered to meet the needs of a given application. Photonic lanterns (PLs) adiabatically merge several SM cores into one MM core [4]. Previous studies have shown that these low-loss interfaces between SM and MM systems can be used to fibre link to high-resolution spectrographs [5,6]. However, PLs can be challenging to fabricate, and tapered MM fibres have yet to be explored as a platform for fibre feeding. This study examines the feasibility of using less complicated fabrication methods to produce graded-index tapers which could be used to link to fibre-fed spectrographs.

Our previous work examined the transmission of tapered graded-index fibres as a function of effective numerical aperture (NA_{eff}) for monochromatic light [3]. Here, we expand this study by using a broadband (400–600 nm) incoherent illumination source, a Tungsten Halogen lamp. In addition, we explored modal noise in these tapered fibres, which arises from interference between the light in different spatial modes [7–10]. For decades, researchers have studied modal noise in multimode fibres, both theoretically [11,12] and experimentally using step-index [13] and graded-index [12] MM fibre. However, we are not aware of any studies that explore the modal noise characteristics of tapered fibres.

As outlined above, this work focuses on two main areas: transmission and modal noise in tapered graded-index fibres. In Section 2.1, we describe our setup for interrogating the NA-dependent coupling of incoherent white light into our tapered fibres. In Sections 2.2 and 2.3, we examine the impact that varying taper lengths has on the transmission properties of the fibres, using both simulated and experimental results. We explore the coupling of light into the cladding of our tapered fibres in Section 2.4. Lastly in Section 3, we present our modal noise experiments for custom GI and Thorlabs GI tapered fibre with macro-bending technique. The micro bending was used to quantify the impact of modal noise between 10 μm step-index untapered and tapered graded-index fibre.

2. Incoherent light transmission and effective numerical aperture in tapered graded-index fibre

Multimode graded-index (GI) optical fibres are used for signal transfer and are known for their low modal dispersion. Graded-index fibre

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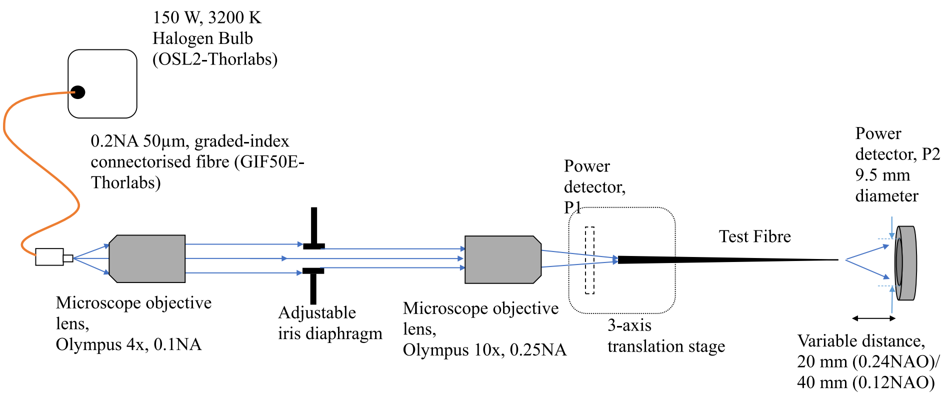

Fig. 1. The setup for incoherent light measurements of fibre transmission dependence on effective numerical aperture. The light source is coupled directly to 50 μm graded-index fibre with 0.2NA. The first objective lens (4×, 0.1NA) is used to collimate the light. The waist of collimated light can be varied by an adjustable iris diaphragm that is located before the second objective (10x, 0.25NA). The NA_{eff} of beam is defined by the second lens (10×, 0,25NA) and transmission is the ratio of measured power at positions P2 and P1.

has a slowly decreasing refractive index from the centre to the edge of the core (usually a parabolic profile). This property results in a smaller number of guided spatial modes than equivalent step-index profiles, as well as similar propagation velocities for each mode [14].

Coherent light transmission results [3] indicate that graded-index tapered fibre is an effective candidate for transferring light into a spectrograph instead of using more complicated fabrication processes for example Photonic Lanterns [4,5] or multicore fibre [15]. Incoherent light testing was not performed in the taper investigations of the previous work.

2.1. Transmission dependence on NA_{eff} setup

In general, the difficulty of coupling incoherent light spatially into a fibre in general arises because the radiance of the source cannot be changed according to the laws of thermodynamics [16–18]. In contrast light coupling into fibre is relatively easy with the coherent light sources. Only a single objective lens was used as the focuser for the 635 nm light source coupling. The focal length and NA of this lens determines the coupling. More optics are required to couple light optimally into the fibre core with incoherent light.

We designed a test setup to investigate the incoherent light transmission in tapers (illustrated in Fig. 1). We used a High-Intensity Fibre-Coupled Light source (Thorlabs: OSL2) coupled directly to a 50 μm graded-index multimode fibre (Thorlabs: GIF50E) as the source. Two microscope objective lenses (4× and 10×) were used as the collimator and focusor for the incoherent light coupling into the test fibre. An iris diaphragm was placed between the two objectives to vary the collimated beam size and therefore the numerical aperture. The effective numerical aperture (NA_{eff}) of this optical system is calculated using

$$NA_{\mathrm{eff}} = NA_{\mathrm{MOL}} \frac{d_{\mathrm{iris}}}{d_{\mathrm{MOL}}} \tag{1}$$

where NA_{MOL} is the full numerical aperture of the microscope objective lens, d_{iris} is the diameter of the iris diaphragm and d_{MOL} is the diameter of the exit pupil of the microscope objective lens. In this incoherent setup, the NA_{eff} is defined by the second objective lens (10×, 0.25NA)

Input power was measured after the second objective (position P1). The output power was measured at the exit point of the test fibre (position P2) at fixed distances of either 20 mm or 40 mm. The diameter of the detector's active aperture is 9.5 mm. Therefore when the output power at P2 is measured at a distance of 20 mm from the test fibre, this results in an output beam numerical aperture of 0.24 (denoted '0.24NAO'). When the output power at P2 is measured at a distance of 40 mm, this gives an output beam numerical aperture of 0.12 ('denoted 0.12NAO'). We are developing a fibre-fed high-resolution spectrograph EXOhSPEC [19] which has 0.1NA acceptance. Therefore, we measure NAO variability to predict the transmission for EXOhSPEC. At 0.24NAO all light from the fibre end is collected.

To determine the error in transmission measurement we repeated individual measurements five times and found the one sigma errors of transmission are contained within the plotting symbol (<1%). Reproducibility of the transmission measurement, i.e. complete removal and repeat measurement, is contained within 5%. The setup was situated in a clean laboratory held at a steady temperature in order to suppress impact from the environment such as dust contamination and air flow as well as temperature and pressure fluctuations. Particulate dust contamination alone can reduce the transmission of fibre more than 50% in a small core fibre (diameter $\leqslant$ 10 μm).

In this section, we compare transmission tests with coherent and incoherent light to investigate if the setup is valid. The coherent light setup is shown in Fig. 2. We used a 635 nm red laser source. The light beam was magnified 3.3× by a pair of achromatic (AC) doublet lenses with focal lengths 100 mm and 30 mm. The beam NA_{eff} can be changed with an adjustable iris diaphragm and was focused into the tapered test fibre input end by an Olympus microscope objective of 10×. Power input of the coherent light setup is located after the 10× objective lens. We collected light from the fibre end using a 9.5 mm-diameter detector. This was placed at two different distances to vary the collection NA when at 20 mm the NA was 0.24 (denoted '0.24NAO) and when at 40 mm the NA was 0.12 (denoted '0.12NAO).

We tested the coherent light transmission test setup with both untapered and tapered fibre with the same dimensions, 50 μm core diameter for untapered fibre and tapers with 5:1 taper ratio and 25 mm down taper length. The NA of tapered fibre (NA_{taper}) can be defined as

$$NA_{\mathrm{taper}} = R\, NA^{\dagger} = \frac{d_o}{d_i} NA^{\dagger}. \tag{2}$$

R is taper ratio or ratio between tapered end diameter (d_o) and untapered end diameter (d_i). $NA^{\dagger}$ is manufacturer NA or NA of fibre before tapering. Thus, NA_{taper} of Thorlabs SI, Thorlabs GI and custom GI tapered fibre are 0.044, 0.040 and 0.060, respectively. Note that the equation (2) is based on SI fibre geometrical approach i.e. a fibre with homogeneous step-index refractive index profile is used. This will not be accurate for the gradient profile such as in a GI fibre. The transmission of light through an untapered fibre is expected to start to decrease when the NA of the input light, in this case NA_{eff}, is greater than the NA of the fibre. Similarly, taking a geometric optics approach, for light entering a step-index fibre that has been tapered, it is expected that the transmission will start to fall if NA_{eff} (the NA of the input light) exceeds NA_{taper}. This trend was indeed seen in our previous work.

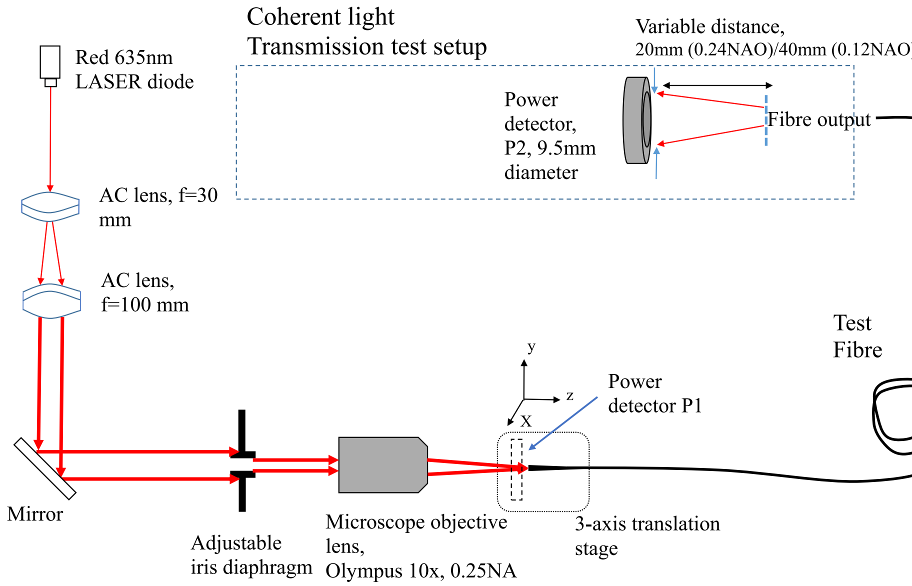

Fig. 2. A drawing of a coherent light (635 nm) fibre coupling setup for transmission dependent on NA_{eff} test. The 3.3× magnified collimated beam from a pair of AC doublet lenses (30 and 100 mm focal length) is focused into the test taper with a 10× Olympus objective lens. An adjustable iris diaphragm varies the input beam numerical aperture (NA_{eff}). The input end of fibre is mounted onto a three-axis translation stage.

Fig. 3 extends the results obtained previously and presents results of transmission dependence on NA_{eff} for both coherent light (635 nm red laser diode, denoted 'C') and incoherent light (denoted 'IC') for a Thorlabs GI taper. For untapered fibre, the trend is relatively flat due to the manufactured NA being relatively large ($NA^{\dagger} = 0.2$) for both coherent and incoherent light illumination. When the input beam exceeds the manufactured NA (beyond 0.2 NA_{eff}) a gradual reduction in transmission is seen as expected. When the same GI fibre is tapered, and the fibre diameter and core gradually decreases, there is a slow decrease in transmission after $\sim 0.1 NA_{eff}$, which is larger than $NA_{taper} = 0.04$. We believe this is because the graded-index fibre has a parabolic rather than step refractive index core profile and so has less intermodal dispersion and a smaller number of modes compared to a step-index fibre with similar attributes such as core radius and NA [14,20]. Hence, when GI fibre is tapered, the drop of transmission is seen at $NA_{eff} > NA_{taper}$. This was also seen in COMSOL simulations which used EM waveguide calculations that are presented in [3]. In addition, the overall transmission of incoherent light for both untapered and tapered fibre is less than the coherent light results. This is due to the smaller coupling efficiency of incoherent light into the fibre.

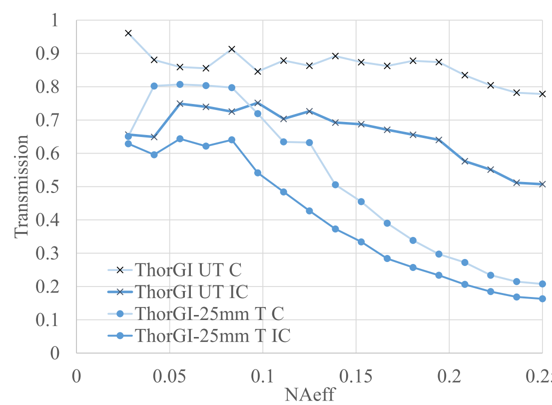

Fig. 3. Comparison of transmission related to effective numerical aperture results with coherent (C) and incoherent (IC) light. Test fibres are 50 μm Thorlabs GI untapered (UT) and 5:1 taper (T) from 50 μm Thorlabs GI fibre. Results with coherent light are in light blue thin lines and with incoherent light are in solid blue thick lines. Crosses are used to denote untapered experimental values. Filled circles are used to denote tapered experimental values. All results were collected the light with 0.24NAO. Experimental errors are contained within the plotting symbol.

2.2. COMSOL simulations and experiments of the impact of taper length on transmission in adiabatic step-index and graded-index tapered fibre

The taper length has a big effect on the transmission of the taper. To be able to fabricate an adiabatic taper there is a minimum taper length that depends on the core size and required taper ratio. Musa et al. [21] explored the optimum profile for tapered single mode fibre. Their results claimed that if the tapers have same tapered length and core diameter, longer tapered lengths (smaller taper angle) introduce less transmission loss, as well as less modes escaping to cladding. A similar conclusion was presented in [22] from a ray-tracing method of tapered simulations of graded-index polymer optical tapered fibre with 2 mm and 10 mm taper lengths. However, this statement is not always applicable because the transmission loss starts increasing again at a certain taper length.

We used COMSOL version 6.1 to model a taper ratio of 5:1 in graded-index and step-index tapers with taper lengths of 10, 25, 50, 75 and 100 mm. The COMSOL simulations and parameter descriptions can be found in Github.[1] COMSOL is well-known for EM waveguide problems. The simulation of beam input in COMSOL has a direct relationship with the number of mode selected to propagate through the waveguide, in this case, fibre optics. Each mode that propagates through fibre has an individual refractive index (n_i). The COMSOL transmission results are calculated from a summation of the power in the first 20 modes propagating in graded-index and step-index tapers with a source illumination of 635 nm. In order to imitate the experimentation of defining NA_{eff}, the number of modes launching into taper is selected to define NA_{eff}. The effective NA for an individual mode i (NA_i) can be defined as

$$NA_i = \sqrt{n_{core}^2 - n_i^2} \tag{3}$$

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

where n_{core} is the core refractive index and n_i is the effective refractive index of an individual mode i. For example, the 20th mode ($i = 20$) for GI Thorlabs taper with n_{core}=1.4708. The calculated $n_{i=20}$ by COMSOL is 1.4699, so NA_{20}= 0.050. In other words, NA_{eff} is 0.050 by defining 20 modes for input beam with the core refractive index = 1.4708. We used n_{core}=1.4708 based on the silica refractive index that can give NA fibre = 0.2 with the parabolic refractive index profile used in COMSOL parameters explained in Github.[2] We used the same n_{core} for step-index fibre simulation but with the step-index refractive index profile for the core and NA of fibre is 0.22. Thorlabs SI and custom GI, results of NA_{eff} of the 20th mode are 0.027 and 0.085, respectively. The reason to select 20 modes was the relative lack of importance of higher order modes and the practical consideration that each the calculation time was 10 min per mode using a Dell PowerEdge R740 Server.

The results in Fig. 4 show the relationship between transmission and tapered length. In both step-index and graded-index cases the tapered fibre transmission increases with shorter taper length. In contrast the graded-index taper has transmissions less than those of the step-index for all taper lengths modelled. Also the trend for the GI tapers shows a generally steeper decrease in transmission than the step index tapers as the taper length increases.

Experimental results of 5:1 taper ratio graded-index and step-index Thorlabs are presented along with the COMSOL results. A red laser 635 nm was used as a source. We tested with 25, 50 and 100 mm taper lengths. The experimental results shown in Fig. 4 were with 0.12 NA light collection at the detector. The COMSOL results agree reasonably well with the experimental results of graded-index tapers. COMSOL predicts slightly less transmission but the overall trends of transmission dependence on taper length are similar. The transmission improves as taper length reduces especially from 100 mm to 50 mm and with a small improvement from 50 mm to 25 mm. The GI model results suggested that at 15 mm the transmission can improve further with an increase in transmission by a factor of 2.4 compared to the 100 mm taper length. However, handling becomes a significant challenge for the 15 mm taper length fibre.

For the step-index tapered fibre, the COMSOL results suggest that for all lengths investigated the overall transmission should be greater than graded-index tapered fibres with comparable geometry. The experimental results, however do not agree with the COMSOL calculations as much lower transmission than GI tapers was seen. This is consistent with previous work [3]. The higher losses in the step index tapers is probably due to the destruction of the core/cladding interface during the tapering process for these fibres.

2.3. Experimental results of the transmission dependence on NA_{eff} in tapered optical fibre with coherent light

This section discusses the experimental results on incoherent light transmission tests of tapered and untapered SI and GI fibre. Table 1 shows all test fibres in this work. 100 mm length tapers were fabricated by the University of Bath's adiabatic taper machine and others were fabricated using a Thorlabs Vytran Automated glass processing workstation (GPX3400). Fig. 5 shows transmission results using incoherent light illumination of graded- and step-index tapered fibres including 10 μm step-index, 50 μm graded-index and custom graded-index untapered (UT) fibre. The light is collected at 0.24NAO. We tested two different GI tapers: a custom fibre from Bath University (denoted 'CustGI'); and Thorlabs product GIF50E (denoted 'ThorGI'). The original NA and cladding sizes of the Bath custom GI and the Thorlabs GI fibre are 0.30NA/600 μm, and 0.20NA/125 μm, respectively. The step-index tapered fibre tested is a Thorlabs FG050LGA product (denoted 'ThorSI'). The untapered length of these test tapers were

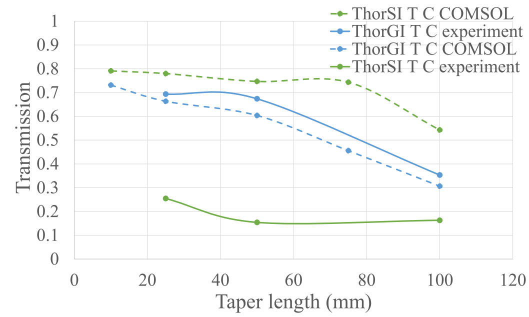

Fig. 4. COMSOL and experimental results of transmission in relation to taper length. COMSOL simulations (dash lines) of 5:1 graded-index and step-index taper have 15, 25, 50, 75 and 100 mm taper length. Original size of core before taper is 50 μm. Experimental results (solid lines) of tapers have 25, 50 and 100 mm taper length. The results are for coherent light (635 nm) illumination (denoted 'C'). NA output of experimental results were 0.12 in order to compare core light collection from COMSOL simulations. Experimental errors are contained within the plotting symbol.

relatively short (from 50 to 150 mm). Results are shown here for 25, 50 and 100 mm taper (length) fibres. Error propagation of transmission in experimentation in each NA_{eff} was very small (<0.01%). Thus error bars are insignificant compared to the trends seen in the data and so are omitted from the graph.

The experimental results are shown in Fig. 5. We found that for both the custom GI fibre and also Thor GI fibre the shorter taper lengths allow more light transmission through the fibre. These results indicate that shorter taper lengths allow more transmitted light. This also agrees with the COMSOL simulations of tapered fibres shown in Fig. 4. For a custom GI with $NA_{\text{eff}} = NA_{taper} = 0.06$ the transmission of the 25 mm taper is roughly 15% more than the transmission for the 100 mm taper. The Thorlabs GI fibres also show increased transmission at $NA_{\text{eff}} = NA_{taper} = 0.04$. Transmission in the 25 mm length taper is 30% more than the 100 mm length taper. Over the full range of NA the transmission of the 25 mm taper is higher than that of the 100 mm taper in the range 10%–40% for Thor GI tapers and 12%–30% for custom GI tapers. EXOhSPEC has 0.1NA acceptance, therefore, if we compare the transmission at $NA_{\text{eff}} = 0.1$, for the custom GI 25 mm taper it is about 75% and for the Thorlabs GI it is 55%.

The trends of the transmission of custom GI tapers are flatter than Thorlabs GI taper and gradually drop as NA_{eff} increases over the range investigated. There is some trend rises transmission when NA_{eff} increases for instance at NA_{eff} ~0.06. This is due to poor coupling when $NA_{\text{eff}} \leqslant 0.05$ The spot size of input beam at each NA_{eff} was calculated (also in Github[3]) and shows that the spot size will be larger than 10 μm when $NA_{\text{eff}} \leqslant 0.05$. In other words, coupling beam efficiency can significantly reduce at $NA_{\text{eff}} \leqslant 0.05$ as the taper core diameter is smaller than the spot size. The Thorlabs taper transmission trends drop more sharply as NA_{eff} increases compared to custom GI fibre. This is due to the original NA of the custom GI fibre (0.3 NA) being larger than Thorlabs GI taper (0.2 NA). It was observed by eye that the cladding light increased in custom GI fibre as the taper length got shorter. Thorlabs tapers however had slightly less light in the cladding. This motivated the investigation of whether the flatter curve in the custom GI taper was due to cladding rather than core light increasing the transmission. This investigation is discussed in Section 2.4.

2.4. Cladding light

Cladding light is a concern when using a tapered fibre link to a spectrograph as it broadens the spectral line width and hinders

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

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

Table 1
The list of test fibre in this work. NA† states for a manufacturer numerical aperture. Taper length, ratio and final core are physical dimension specified from Thorlabs and Bath machine.

Type	NA†	Part number	Taper ratio	Taper length (mm)	Final core (μm)
Untapered fibre					
SI MM	0.10	FG010LDA	–	–	10
SI MM	0.22	FG050LGA	–	–	10
GI MM	0.20	GIF50E	–	–	50
Cust GI MM	0.30	custom fibre	–	–	50
Tapered fibre					
SI MM	0.22	FG050LGA	5:1	25	10
SI MM	0.22	FG050LGA	5:1	50	10
SI MM	0.22	FG050LGA	5:1	100	10
GI MM	0.20	GIF50E	5:1	25	10
GI MM	0.20	GIF50E	5:1	50	10
GI MM	0.20	GIF50E	5:1	100	10
Cust GI MM	0.30	custom fibre	5:1	25	10
Cust GI MM	0.30	custom fibre	5:1	50	10
Cust GI MM	0.30	custom fibre	5:1	100	10

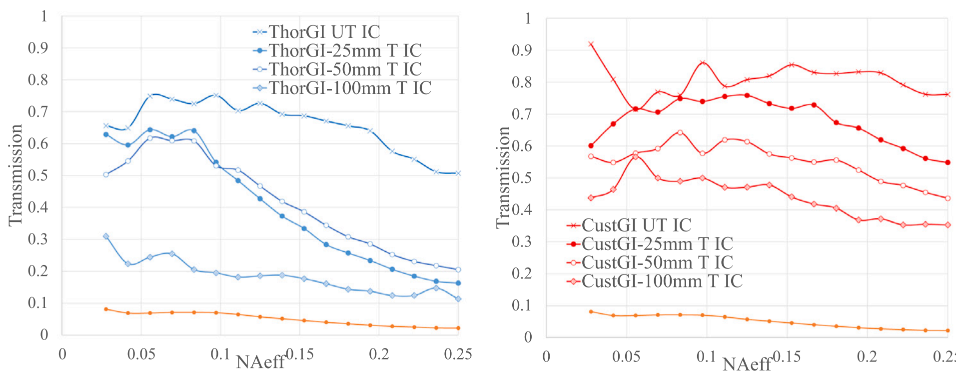

Fig. 5. Transmission versus NA_{eff} results for incoherent light (IC) source illumination. Comparison results between (left) Thorlabs GI taper ('ThorGI-') and (right) custom GI taper ('CustGI-') in 25 mm, 50 mm and 100 mm taper lengths are presented including 10 μm step-index ('Thor10SI UT'), 50 μm graded-index ('ThorGI UT') and custom GI ('CustGI UT') untapered fibre. All results have light collection at a detector at 0.24NA. Experimental errors are contained within the plotting symbol.

performance. Our previous work [3] claimed that the cladding light in 100 mm 5:1 graded-index taper fibre was not significant. Now that light can be seen leaking into the cladding with shorter taper lengths of 25 mm and 50 mm, this needs to be reconsidered. The 100 mm taper length should now be considered as relatively long. Also the measurement of cladding light in previous work was for only at a single NA_{eff} (0.10 NA_{eff}) and these conditions would have excluded cladding light to some degree. We therefore extended investigation of cladding light to include shorter tapers at various NA_{eff}, measuring the output light at 0.12 and 0.24NA.

We measured the effect of cladding light on taper output by comparing transmissions both with and without use of an index matching gel. The results for outputs of 0.12NAO and 0.24NAO are shown in Fig. 6. We tested Thorlabs GI and custom GI tapers with 25 mm taper length and 5:1 taper ratio. The original core diameter for both is 50 μm. The manufacturers NA of the Thorlabs GI and custom fibre are 0.20 and 0.30, respectively. The gel was applied to the fibre taper but left the tip of taper gel free (~1 mm) in order to not contaminate the output surface. The index matching gel has higher refractive index than the cladding. This means the gel diverts any light leaking into the cladding out of the taper, so it will not be measured at the taper output. The results shown in Fig. 6 indicate higher transmission in the custom GI taper compared to the Thorlabs GI fibre. It is clear that cladding light increases transmission through the taper at both 0.12NAO and 0.24NAO. For custom GI taper, the larger NA_{eff} contributed more light leaked into the cladding. For the Thorlabs GI taper results with and without gel show less transmission difference as NA_{eff} increases. The graphs with/without gel follow the same general trend as NA_{eff} increases. The results show that cladding light can increase the transmission through the taper in the range of 15%–30% as NA_{eff} varies. However, the custom GI fibre also generally has more cladding light than the Thorlabs fibre especially as NA_{eff} increases.

3. Modal noise in tapered optical fibres

Modal noise or mode patterns present at the output plane of a multimode can fluctuate giving rise to instability [12,13,23] in optical signals which impact optical systems using fibre optics. Modal noise can be induced by mechanical changes such as bending, movement, or change in temperature of the fibre [8,12,23]. Another main cause is non ideal illumination such as misaligned coupling between input beam to fibre or between two fibres [24] or the fibre output mismatched with a detector [12].

The modal noise investigation in this work focuses on macro- and micro- bending impact on fibre transmission. We designed the setup to measure transmission along with fibre bending at certain angles for the macro bending by comparing only custom GI and Thorlabs GI taper. Additionally, we quantified the modal noise impact in a 10 μm step-index untaper and equivalent core size (on tapered end) graded-index tapered fibre. The effect of bending the tapered fibre was measured with incoherent source.

3.1. Modal noise experimental results

Important factor that can cause signal distortion is mechanical displacement such as bending. We measured the effect of bending on tapered fibre transmission using two different methods, a single bend radius and multiple micro bends. We slightly modified the incoherent light transmission test setup (shown in Fig. 1) by adding the fibre

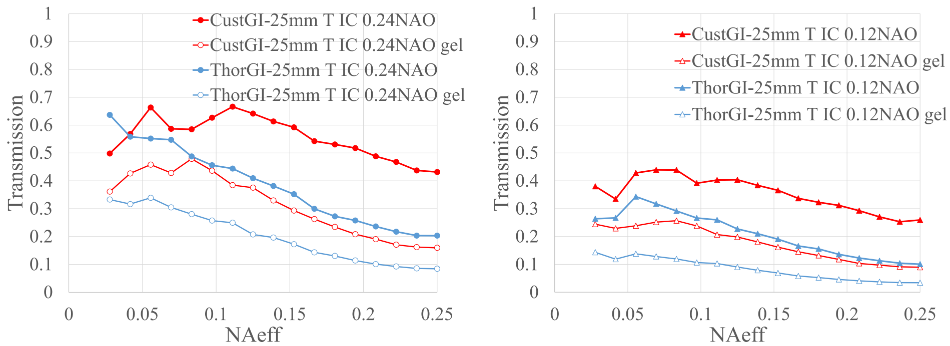

Fig. 6. Investigation of cladding light by difference transmission versus NA_{eff} with an incoherent light source illumination. Comparison results between custom GI (CustGI) and Thorlabs GI (ThorGI) taper with 25 mm taper length are presented. 0.24NAO results are presented on the left with circle marks. 0.12NAO results are presented on the right with triangle marks. Open circles ("o") and open triangles ("△") with thin lines are used to distinguish experimental values obtained using gel for 0.24NAO and 0.12NAO respectively, closed markings represent results without gel. Experimental errors are contained within the plotting symbol.

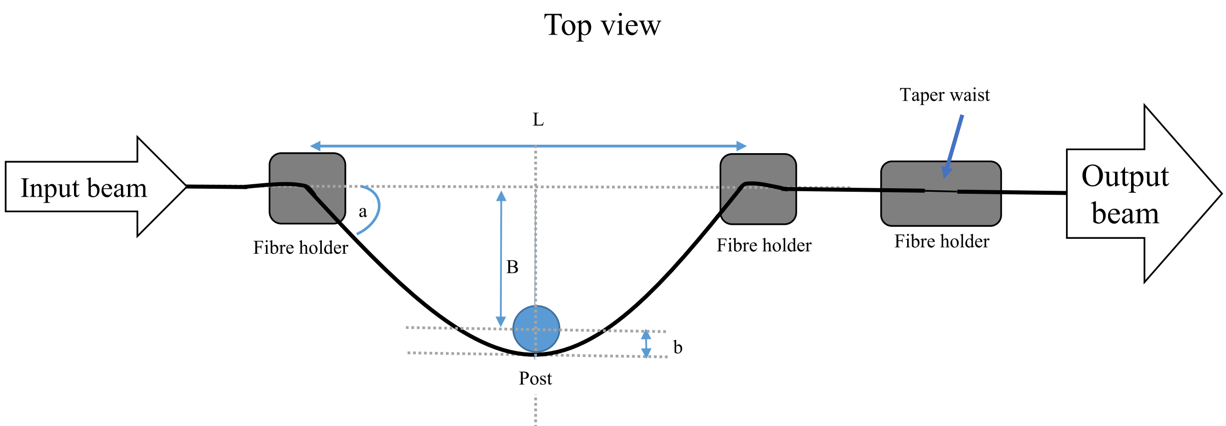

Fig. 7. Illustration of fibre bending technique from top view. Test fibre is held firmly on the holders. Taper waist is supported on the holder on the right of the second fibre holder. The post was attached to a 1-axis translation stage and was adjusted to a certain mm distance to create an angle a. The post radius, b is 3.3 mm. Total translation distance is B+b and L is 85 mm. Then the angle a can be $\sim \tan^{-1}\left(\frac{B+b}{L/2}\right)$.

holders and post attached to the translation at the end after the three-axis translation stage. In the single bend experiments we prepared the tapered fibre differently. Test samples have a 25 mm down taper, a 20 mm waist, and a 25 mm up taper. This is different to the transmission versus NA_{eff} tests described in the previous section where only a downtaper with ~10 mm waist was tested. For the single bend radius experiment the untapered input fibre is held firmly in two secured fibre rigs and a small post attached to a translation stage is lightly touched to the untapered fibre. The post (Thorlabs:PM4) was then moved with a micrometer (Thorlabs: PT1/M) in the lateral plane to bend the fibre (illustrated in Fig. 7). We measured power output at each 0.5 mm lateral move. The whole range of translation was from 0 to 5 mm, which was limited by the max fibre bend radius. Fig. 7 shows from the top view that the fibre was held firmly with a distance of 85 mm between two the holders. Assuming the post travels in a direction perpendicular to the test fibre, this will create a bending angle, a. The total translation distance is B+b. B is a distance of lateral move from non-bending position to bending position in mm by the translation stage and b is a radius of post used for bending. The diameter of the post was 6.6 mm so b is 3.3 mm. Thus, fibre's bending angle can be defined as

$$a = \tan^{-1}\left(\frac{B+b}{L/2}\right) \tag{4}$$

Proper beam launch conditions can optimise coupling efficiency. We categorised results by the beam input as under-filled, filled and overfilled in Table 2. Fig. 8 shows the effect of bending angle a on the transmission of incoherent light for both custom and Thorlabs GI tapered fibres. The incoherent white light source was collected at 0.12 NA (0.12NAO). The taper's effective numerical aperture is calculated from equation (2) and for the custom and Thorlabs graded-index tapers are 0.06 and 0.04, respectively. Two NA_{eff} were selected: 0.055 and 0.25 in order to compare different launch conditions which generate different mode propagation conditions along the multimode fibre. In other words, the 0.055NA_{eff} beam is under-filled for custom GI taper and over-filled for Thorlabs GI tapered fibre. We noticed that there was no significant change in Thorlabs GI taper with the macro bending so we only focus on the under-filled beam for the custom GI taper.

Table 2
Description of beam launch conditions for light coupling into fibre classified by a relationship of launched beam NA and NA of fibre. $NA^{\dagger}$ is manufacturer NA and NA_{taper} is taper NA as define by Eq. (2).

	Beam input		
	Under-fill	Fill	Over-fill
Untapered fibres	$< 95\% NA^{\dagger}$	$95–100\% NA^{\dagger}$	$> 100\% NA^{\dagger}$
Tapered fibres	$< 95\% NA_{taper}$	$95–100\% NA^{taper}$	$> 100\% NA^{taper}$

The results show that bending effects are more significant in custom graded-index tapers and cause transmission reduction with bends in the range of bending angle of 8.5–14.3°. The custom GI taper transmission drops from a maximum value of 65% to less than 45% after 12.5°of bend for the under-filled beam condition (0.055NA_{eff}). Illuminating the taper input with an over-filled beam (0.25NA_{eff}) gives an overall fibre transmission that is less, as expected, 38% less than an under-filled beam at 0.05NA_{eff}. The transmission drops more rapidly as bending

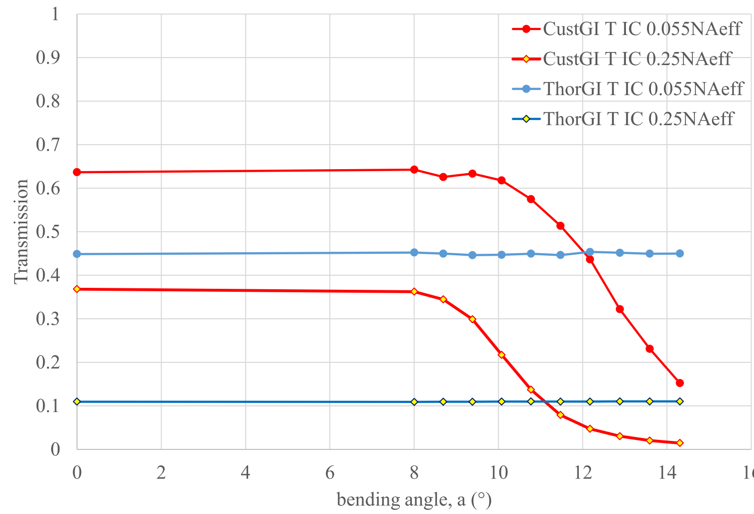

Fig. 8. Result of transmission variation related to a bending of custom GI and Thorlabs GI tapered fibres. The test fibres have a 25 mm taper length, 5:1 tapered fibre and 20 mm waist. The source was incoherent light. Two NA_{eff}: 0.055 and 0.25 were chosen to present the bending impact on transmission and results of transmission were collected with the detector position at 0.12NAO condition.

angle is increased than with the under-filled beam. This is due to the over-filled beam generating more modes propagating along the fibre [25] and even the fundamental mode may not transfer throughout the fibre. Some modes leak to the cladding. The over-filled beam is more sensitive to macro bending than the under-filled beam, which already has a smaller number of modes (primarily just the fundamental mode).

For the custom fibre, the impact on transmission of macro bending is very clear but all transmission trends are relatively flat in Thorlabs GI taper. This contradicts other results [26]. As the NA of the custom fibre (0.3) is bigger than the Thorlabs GI fibre NA (0.2), and the loss should be less even though core diameter of both fibre type is the same size. Moreover, 0.3 NA 'silica' GI fibre is considered a relatively large NA fibre [27]. Note that in the custom fibre the cladding size is 620 µm while Thorlabs's cladding diameter is 125 µm. Both fibres will experience the same strain for the same bending angle, however assuming that the Young's modulus is the same for both fibres, the custom fibre's larger cross section area will mean it experiences a force which is 24 times greater than the smaller diameter Thorlabs GI fibres. This large force will give rise to more modal variation in the larger diameter fibre.

To our knowledge there is no commercially available graded index fibre with core diameter less than 50 µm. The comparison between step-index and graded-index with small core diameter (10 µm) is performed with a 10 µm step-index fibre and a tapered graded-index fibre. Hence, we conducted another experiment in order to observe micro bending [28,29] impact the transmission. We prepared the samples in a similar way to the previous method but used a weight to press a consistent periodic bending pattern (teeth of comb) on an untapered part of the fibre. The fibre was bent periodically by 20 1-mm-width teeth with 1 mm gaps. The fibre was placed on top of a compliant surface so an estimate of the displacement could be made. We measured the power output before and after applying a fixed weight to the array of teeth at selected NA_{eff}. Three samples were tested: 25 mm Thorlabs graded-index tapered fibre, 10 µm step-index fibre and 50 µm graded-index fibre.

Table 3 and Fig. 9 show the power difference in terms of percentage power change as a function of NA_{eff}. A higher percentage of power change indicates more change in mode interference or more modal noise. These results indicate that the modal noise in a 10 µm step-index untapered fibre is more than in a 50 µm graded-index 5:1 tapered fibre and untapered graded-index fibre for all NA_{eff}. The smaller size 10 µm SI fibre allows only a small number of modes to propagate through the fibre which tends to be dominated by the fundamental mode. The 50 µm GI fibre allows more modes to propagate than the 10 µm SI fibre by a factor of more than 10 according to the mode number equations in [14]. The original mode number excited in the GI fibres is larger before bending compared to 10 µm SI. Therefore the modal noise changes are smaller in bigger core fibre [26]. For a taper, the mode propagation is already restricted by the taper so micro bending in an untapered section after the taper has small impact resulting in similar behaviour to 50 µm GI untapered fibre. The error bars for 50 µm GI untapered and tapered fibre overlap, so there is no significant difference in the modal noise between these two fibres. We note that the results at $NA_{eff} < 0.11$ suffer from background light, especially in the SI fibre. Thus we decided to present the results for NA_{eff} >0.10.

4. Conclusions

We have measured how the incoherent light transmission of graded-index tapered fibre is affected by the numerical aperture of the input light. We also looked at the optimal coupling conditions for incoherent light into small to medium size fibre cores (0.1–0.2 NA). The methods we explored confirmed the importance of matching light source NA with the acceptance NA of the test fibre. If this is not done losses will occur. With coherent light, the beam size coupling was easier to manipulate because of the highly collimated beam. However, incoherent light coupling into the fibre is difficult especially if the light source dimensions and NA are unmatched with the test fibre.

We focused mainly on 50 µm core diameter, graded-index fibre. We tested two types of graded-index fibre: Thorlabs GIF50E and a custom fibre manufactured by University of Bath. The taper ratio was 5:1 and taper lengths were 25, 50 and 100 mm. We simulated step- and graded-index taper using COMSOL with the same dimensions as the test fibres. We found that as long as the fibre was tapered adiabatically, the transmission will improve with shorter length tapers. The experimental results agree with simulations except for the step-index taper. We believe this is due to the taper core and cladding interface being disturbed by the tapering process. The effect of cladding light was also measured by comparing the light transmission through a tapered fibre before and after using index matching gel to suppress the cladding light. Comparing Thorlabs GI to custom GI transmission results, transmission is higher in custom fibre but so also is the presence of cladding light. Properly matching NA_{eff} with taper NA will give the optimum light output with the least cladding light.

Table 3
Table of percentage of power change (% Δ power) for the modal noise test in three fibres: 10 µm SI untapered, 50 µm GI untapered and 25 mm Thorlabs GI 5:1 tapered fibre. Incoherent light was used as the source at a range of NA_{eff}: 0.111; 0.167 and 0.25. NA of fibre defined the beam condition. Under-filled, filled and over-filled are defined as for the macro bending experimentation as set out in Table 2.

Fibre	$NA^{\dagger}/NA_{taper}$	%Δ power		
		0.111 NA_{eff}	0.167 NA_{eff}	0.250 NA_{eff}
10 µm SI	0.10	3.947 over-filled	5.045 over-filled	5.834 over-filled
50 µm GI	0.20	0.107 under-filled	0.082 under-filled	1.635 over-filled
25 mm Thor GI taper	0.04	0.524 over-filled	0.303 over-filled	0.718 over-filled

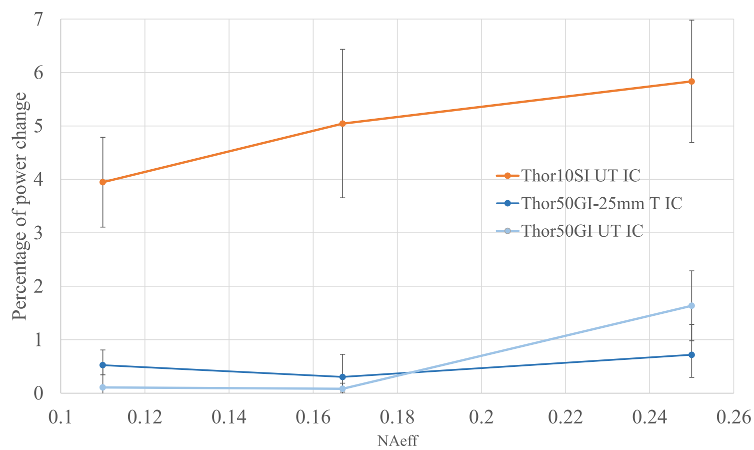

Fig. 9. The percentage of difference in output power as a function of NA_{eff} is shown for periodic fibre bending. The source is incoherent light (IC). Test fibres are 10 µm step-index untapered (Thor10SI UT), 50 µm graded-index untapered (Thor50GI UT) and 25 mm Thorlabs graded-index tapered fibre (Thor50GI-25 mm T). The results are shown at NA_{eff} = 0.111, 0.167 and 0.25.

In addition, we investigated the modal noise in multimode untapered and tapered fibre. We tested the fibre modal noise with both coherent and incoherent light. We investigated the effect of misalignment of a coherent source into tapered GI fibre and found that the mode number increases and transmission decreases when the input beam is more misaligned. We also tested fibre 'bending loss' using two different methods. The first method created a variable bending angle in the test fibre. We found the custom fibre with a larger diameter and manufacturer NA is more sensitive to bending than Thorlabs GI fibre, giving higher losses for the same bending angle >8.5°. In the second method, we created 'micro bending' by pressing a periodic bending pattern on top of the fibre with a weight. The test fibres were a 10 µm step-index fibre, a 50 µm graded-index fibre and tapered grade-index fibre (Thorlabs:GIF50E). The indicator of modal noise in this micro bending test was the percentage of power change that occurs at the output before and then after the micro bending weight was applied. We found that the modal noise depends on the input beam NA for incoherent light illumination. We found the 50 µm graded-index untapered fibre has less modal noise in general than the 10 µm step-index untapered fibre. There is no significant modal noise difference between untapered and tapered Thorlabs GI fibre. Thus, the Thorlabs tapered fibre is a good candidate for an astronomical mode field changer.

In conclusion, GI tapered fibre transmission performance is a promising candidate for a fibre link system that requires converting optics, as it has low modal noise and good transmission especially with shorter length tapers fabricated under adiabatic conditions. Also, cladding light can be suppressed if the coupling light is carefully selected to match the tapered fibre NA and index matching gel is applied.

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Data access

Data supporting this publication can be obtained from https://github.com/Piyamas-Ch or requested by emailing p.choochalerm2@herts.ac.uk under a Creative Commons Attribution license (https://creativecommons.org/licenses/by/4.0/).

CRediT authorship contribution statement

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

Declaration of competing interest

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Data availability

I have shared link to my data and simulation files in the manuscript

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