FRD and scrambling properties of recent non-circular fibres

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ABSTRACT

Optical fibres with octagonal, square and rectangular core shapes have been proposed as alternative to the circular fibres to link the telescopes to spectrographs in order to increase the accuracy of radial velocity measurements. Theoretically they offer better scrambling properties than their circular counterparts. First commercial octagonal fibres provided good near field scrambling gains. Unfortunately the far field scrambling did not show important figures.

This article shows test results on new fibres from CeramOptec. The measurements show substantial improvements of the far field scrambling gains. In addition, evaluation of their focal ratio degradation (FRD) shows much better performances than previous fibres.

Keywords: Optical fibres, scrambling, FRD, radial velocity

1. INTRODUCTION

The focal ratio degradation (FRD) has been extensively reported in the technical literature. A description of the FRD and the way to reduce it may be found in this link[1]. Our contributions are reported in these papers[2,3].

The accuracy in the measurements of radial velocities is limited basically by changes in air pressure and temperature in the spectrograph, and by the fibre photometrical scrambling. The latter refers to the spurious shift of image of the fibre on the spectrograph detector (point spread function or PSF) when the image of the star moves with respect to the input fibre end.

The scrambling gain (SG) provided by optical fibres is currently defined as the ratio between the relative displacement of the star in front of the input fibre end and the shift of the point spread function (PSF) on the spectrograph detector: $SG = (d/D)/(f/F)$, where D is the fibre diameter, d the star shift, f the shift of the PSF and F the full width maximum of the PSF. The scrambling gain is driven basically by two factors, the near and far fields. The near field is the photometrical distribution of the light on the surface of the fibre output end. The far field is the angular distribution of the light of the output fibre beam, in other words it is the photometrical distribution on the spectrograph pupil. A way to increase the scrambling gain is to split the fibre and exchange the near and far fields by means of a lens relay. Another way is to apply mechanical stresses to the fibre in order to excite most of the fibre modes.

In previous papers[2,3], we have reported scrambling properties of several fibres and scrambler devices. In this article we summarize some FRD and scrambling results obtained with the following non-circular fibres: 300 x 150 µm rectangular, 200 and 67 µm octagonal.

2. RESULTS

2.1 Near and Far field

The first samples of non-circular fibres from CeramOptec were made with 2 claddings and a thick nylon jacket. The refraction index of the outer cladding is the same as the one of the core, but the refraction index of the nylon is smaller than the one of the second cladding. Therefore this configuration allows light transmission on the claddings when the input spot illuminate them. Figure 1 shows the near and far field of the end of the 300 x 150 µm fibre. The light spot shines also the external cladding. However, note the impressive photometrical flatness of the core.

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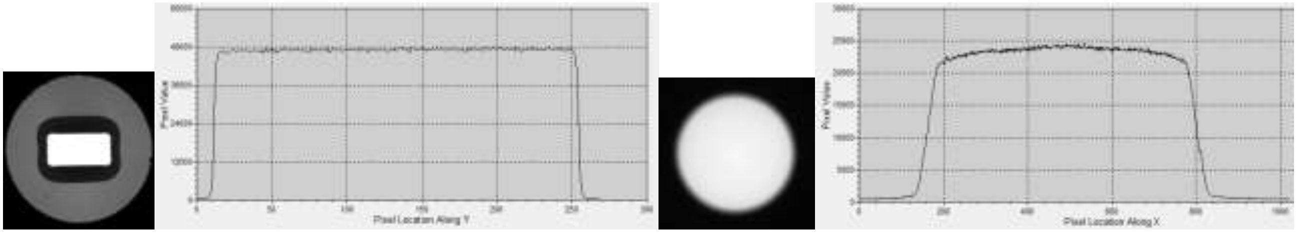

Figure 1. Fibre end of the 300 x 150 µm rectangular fibre. Part of the input spot illuminates the secondary cladding which allows light transmission. The graph on the left is a line profile of the core along the length of the rectangle. The next spot is the far field projection and the graph is a profile of a line crossing the centre. For all cases, the input aperture beam was F/2.5.

The far field is also very uniform and flat (right side of Figure 1). Figure 2 shows the near and flat fields of octagonal fibres. Above is a 200 µm core fibre with the old thick cladding and nylon jacket (cabled, 5 m). The photometrical uniformity of the core of the fibre end is remarkable. The plots below-left show the far field of the 67 µm fibre (bare fibre, 10 m). On the right side the flat field of the same fibre but the fibre has been gentle squeezed. The spurious pattern in the centre almost disappears.

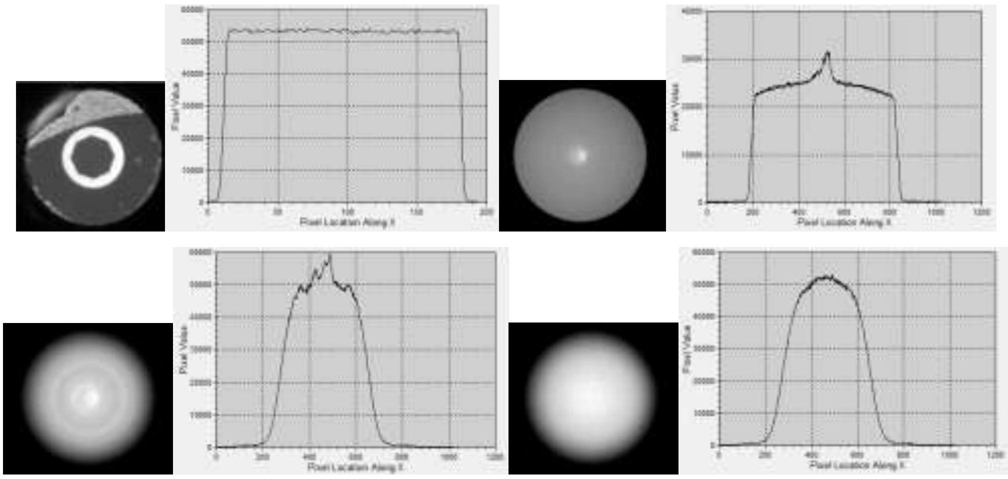

Figure 2. Above: near and far field of a 200 µm octagonal fibre (5 m). Below: far field only of the 67 µm octagonal fibre (10 m). The plot on the right and below graph shows the effect on the far field by a "gentle" squeeze of the fibre with a commercial "mode scrambler", Figure 7.

In spite the 200 µm fibre is enough long (5 m), the far field still shows a bright dot in the centre of the field. This effect has been observed before[3,4]. We have suspected a correlation with the thick secondary cladding. We noticed that this pattern highly changes with the fibre path and hand manipulations.

2.2 Focal Ratio Degradation

It is well know that the highest contribution to the FRD is the quality of the fibre termination: the glue stresses and the way the fibre is inserted into the protecting tube. Therefore, in order to compare FRD results with other authors, the fibres were prepared in a way to leave them as free as possible on the optical bench.

Figure 3 shows the FRD of the rectangular fibre 150 x 300 µm. The FRD is displayed as the relative transmission of the fibre as a function of the aperture of the exit beam. Each curve corresponds for a given input aperture (F/input). The 100% energy corresponds to the flux emerging at the numerical aperture of the fibre (0.22). The measurements do not take into account the internal transmission of the fibre, nor the Fresnel reflection losses at the surface ends of the fibre. On the left graph, the fibre is "free" but still kept in a loop of 70 cm diameter. Under these conditions, the relative efficiency at the output of the fibre is 88% for an F/4 input beam and the flux measured in a F/4 aperture at the output of the fibre. On the right plot, the fibre is submitted to a sinusoidal path to test its sensitivity to bends. Figure 7 left, shows the imposed path. In this case the FRD increases in such a way that the resulting efficiency at F/4 (input and output) reduces to 77 %.

Left plot of Figure 4 shows the FRD of the CeramOptec 200 µm octagonal fibre for a length of 5 m. The fibre was cabled and ended with SMA connectors. The FRD is substantially less than the one produced by circular fibres. For an input and output F/4 beam, the relative efficiency is almost 95 %. While for circular fibres, the efficiency typically drops between 60 to 85 %. The right plot of the same Figure 4 shows the FRD in a 67 µm octagonal fibre with a length of 10 m. The fibre ends were mounted in SMA connectors and glued with "very fast (2 min.)" two components epoxy glue.

At F/4 (input-output) the efficiency is similar to the 200 µm fibre (95%) but higher at faster beams, for example 97 % at F/3 (input and output). With these fibres, the working aperture inside the fibre can be therefore relaxed. This particular fibre is in use at the HARPS Nord instrument in La Palma[6].

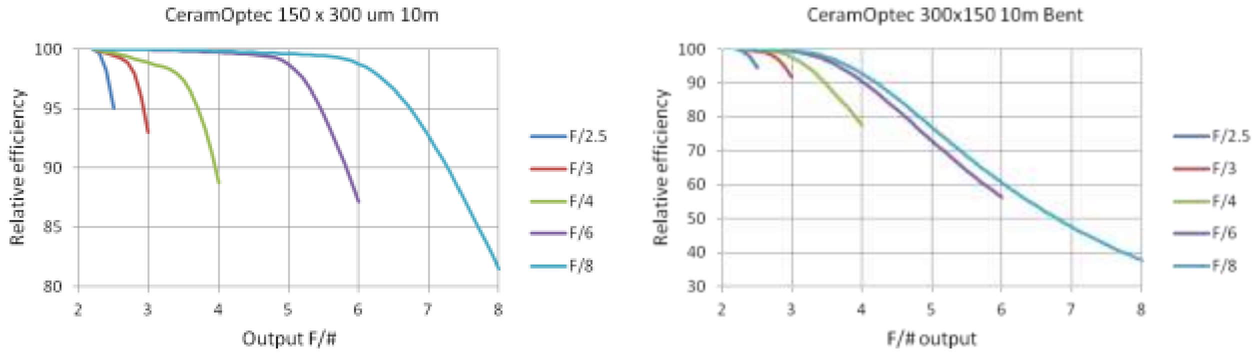

Figure 3. FRD produced by the 300 x 150 µm rectangular fibre over a length of 10 m. Left: The fibre was kept in a loop of 70 cm diameter. The fibre ends were just inserted to SMA connectors (metal ferrule). Right: the fibre is submitted to a sinusoidal path as shown in Figure 7.

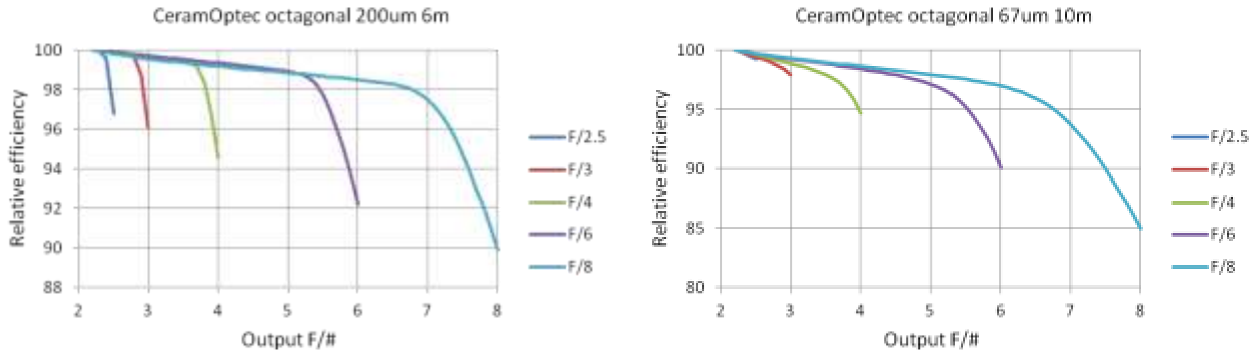

Figure 4. FRD produced by CeramOptec octagonal fibres. Left: a 200 µm core, 5 m long (cabled). Right: a 67 µm core, 10 m long (bare in a 30 cm diameter loop).

2.3 Near-field scrambling measurements

A practical way to estimate the degree of scrambling by optical fibres when the "star" moves in front of the input fibre end, is to measure the shift of the centre of mass of the image of a fibre output end projected on a CCD. In the Introduction we propose the simple equation $SG = (d/D)/(f/F)$. The projection optics of the image of the output fibre end onto the detector must be free of aberrations to avoid the contribution of the irregularities of the far field. In our optical bench we used high quality microscope objectives.

Table 1 shows the scrambling gains for a number of cases. In the rectangular fibre case, the measurements were limited by the intrinsic precision of the optical setup. By far the rectangular fibre shows the best scrambling gain. Preliminary results on the 67 µm octagonal fibre with polyimide jacket show a relative low scrambling gain when the diameter of the light spot is close to the fibre core size. It is better when the spot remains inside the fibre core. In real life the star is always bigger than the fibre, so we have to take the worst case scenario. However, in order to compare and make our measurements compatible, we used a small spot to avoid "touching" the cladding of the nylon jacket and avoiding illumination of the cladding. When the fibre passes through a mode scrambler, the scrambling gain increase substantially: from 162 to 970. The FRD caused by the squeezing is of about 2% working at F/2.5 (input-output).

The thick 200 µm octagonal fibre showed a good near field scrambling gain provided that the "star" remains smaller than the core size. A sinusoidal bend still increases the gain but not as good as the bend applied for the 67 µm fibre.

The 200 µm fibre with optical scrambler provides an excellent scrambling gain (next Section).

Table 1. Near field scrambling gain for 4 fibre arrangements. SG is defined as the formula described in the Introduction. In the Free case the fibre is prepared with the minimum mechanical stresses and curled with the biggest loop. In the Bend case the 67 µm fibre is submitted to a mode scrambler (Figure 7) and the octagonal 200 µm fibre to a shape modulator.

Fibre	SG (free)	SG (bend)
Rectangular 300 x 100, 10 m	> 10 000*	
Octagonal 67µm, 10m	162 (63µm spot) 490 (25 µm spot)	970 (63µm spot)**
Octagonal 200µm, 6m	1450	1700
Optical scrambler with octagonal 200µm, 6	6100	

* Measurement limited by the precision of the setup
**2% losses by FRD at F/2.5, but much higher at slower beams

2.4 Far-field behavior

The photometrical stability of the far field influences the weight of the different aberrations present in the spectrograph design. The shape change of the point spread function (PSF) by the changes in the aberration pattern will modify the centre of mass and therefore will produce an error in the measurement of the radial velocities. The change of the PSF shape is particular for each aberration pattern and therefore of the optical design of the spectrograph. Some simple simulations with Zemax by adding annular masks at the pupil plane of the spectrograph provide an estimation of the scrambling needs to be applied. As a guideline for the acceptance of the fibre configuration to be employed in the spectrograph, we have imposed a limit of less than 10% changes in the ratio between two far field patters: one with the star in the centre of the fibre input end and the second far field patter when the star is displaced from the centre.

Figure 5 shows the ratios between far fields for three cases: "inside" or blue curve where the star moves from the centre of the rectangle fibre core to 80 µm along the length of the rectangle. "Edge" (red) when the spot "touches" the edge of the rectangle and "corner" when the spot goes to the corner of the rectangle without touching the edges.

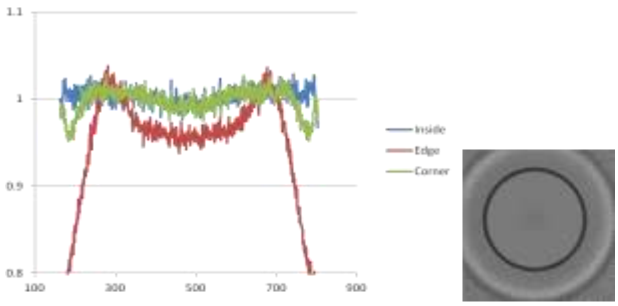

Figure 5.Ratio between far fields for the 300x150 µm fibre for an F/2.5 input beam. Left: Profiles of the ratio of far fields for different position of the input 50 µm spot on the fibre core. The spot has an 80µm diameter and moves x, y along the fibre rectangle core. All the plots (output beams) are cut to F/2.5. Inside: x 0, y 80. Edge: x 0, y 120. Corner: x20, y120. Right: picture of the ratio between far fields for the "corner" case.

When the spot stays inside the rectangle, the far field variations are enough small to produce significant distortion of the PSF at the spectrograph detector. However, when the spot touches the edges of the rectangle window, the far field deformation increases rapidly at the border of the pupil. These changes may introduce undesirable deformation of the PSF.

A very interesting result is the change of “phase” of the far field illumination pattern when the star moves symmetrically with respect to the centre of the fibre core. Figure 6 shows the far field ratio plots for the 6 m of octagonal fibre with a core of 200 µm. In the red curve the input spot (50 µm diameter) travels from the centre to 60 µm. The blue curve shows the result when the spot goes from the centre to opposite direction (- 60 µm). A well symmetrical change in the illumination is produced. The pattern is highly reduced when the fibre is submitted to a sinusoidal path (Figure 7). We believe that his asymmetry may be caused by an asymmetrical excitation of the fibre modes. Indeed, when a squeeze is applied, all the modes are evenly excited.

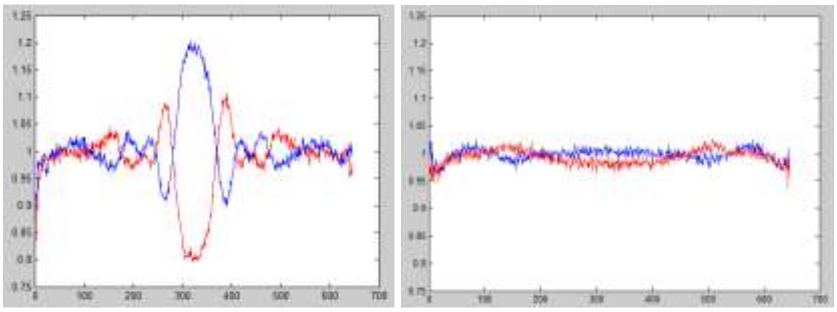

Figure 6. Ratio between far fields for the octagonal 200 µm 6 m mounted fibre for a F/2.5 input beam. Each curve is the ratio of the far field profiles when the ‘star’ moves from the centre to the edge. Red plot: a 50µm spot moves of 60 µm. Blue plot: the spot moves of -60 µm. Left picture: the fibre is free of bends. Right picture: the fibre is submitted to a sinusoidal bend (left of Figure below)

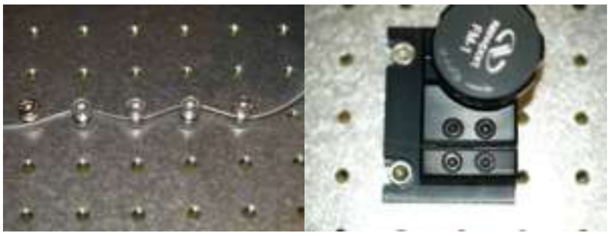

Figure 7.Mechanical squeezers to improve the scrambling of the fibres. Left: the period of the sinusoidal path is 50 mm, the amplitude is 6 mm (PV)

2.5 Optical and mechanical scramblers

As seen in the previous Section, a simple way to increase the photometrical scrambling of a fibre in both, near and far fields is to use a mechanical “mode scrambler” (Figure 7). By squeezing the fibre the higher order modes may be excited and therefore photometrical variations at the input fibre end should be smoothed at the fibre output end. The drawback of this technique is the increase of FRD. So a compromise between scrambling gain vs. efficiency may be reached to accept such a device. An alternative is the optical scrambler where the fibre is split in two and a relay lens is placed in between to exchange the far and near field between the two fibres. Examples of these devices are in regular use in Harps instruments[6,7]. In the latest reference, Harps Nord team reports only 10 % of throughput losses by the double scrambler with a near field scrambling gain higher than 1000.

A new interesting idea to improve the scrambling is to couple two non-circular fibres together[8]: one hexagonal with an octagonal or with square fibres. A coupling with a pentagonal fibre would be even better! Scrambling gains higher than 2000 with an octagonal-hexagonal 200 µm fibre configuration have been reported[8].

On our side, we have evaluated the increase of scrambling by the 200 µm fibre when equipped with an optical scrambler made with a single lens. Figure 8 shows the concept of interchange between the far and near fields. We made a prototype with a GRIN lens with a focal distance of only 0.45 mm glued between the fibre ends. For a 200 µm core fibre, the projection of the pupil on the second fibre generates a working aperture of 450 / 200 = F/2.25. Our test bench could only deliver beams opened to F/2.5, so the coupling was not optimal and therefore a loose of efficiency. However for an F/2.5 output beam we measured a total efficiency of 70 % by the whole assembly.

The near field scrambling gain was noticeable improved from 1450 (free fibre or 1700 for a bent fibre, Table 1) to 6100. On the other hand, the far field showed strong circular patterns, but they proved to be highly stable when the "star" moves in front of the fibre input end. Graph of right side of Figure 9 shows an amplified ratio of far fields when a 50 µm spot travels from the centre to 60 µm.

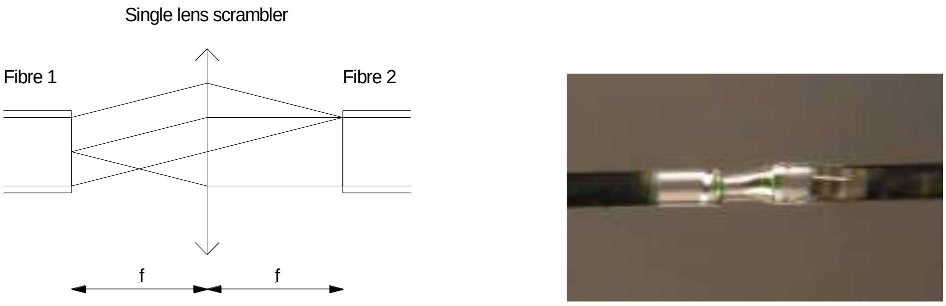

Figure 8.Left: Optical scrambler with only one lens between the fibre ends. The pupil (at infinity) of the left fibre is projected on the input end of the right fibre. The image of the end of the fibre 1 is sent to infinity with respect to the fibre 2. Right: photo of the prototype made with a GRIN lens (f = 0.45 mm) glued between the two fibre ends.

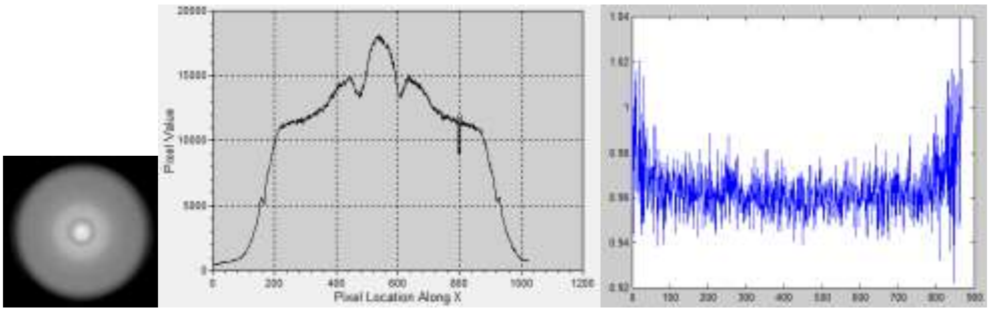

Figure 9. Left: Photo of the far field generated by the octagonal 200 µm fibre assembled with an optical scrambler. Input beam: F/2.5. Fibre mounted in a 6 m cable and ended with SMA connectors. Centre: line profile of the far field crossing the centre. Right: Ratio between far fields where a 50µm spot has moved from the centre to 60 µm. The entire spot stayed always inside the fibre core.

With these improvements and considering the whole efficiency of the fibre array of 70% including FRD, transmission and reflection losses, the optical scrambler with octagonal fibres is very attractive to couple telescopes to high accuracy radial velocities spectrographs.

3. CONCLUSION

Our tests on the available non circular fibres have shown superior FRD and far/near field scrambling properties than circular fibres.

The use of an optical scrambler to exchange the far and near fields improves considerably the scrambling gain. Since the FRD generated by the non circular fibres is smaller than the one for the circular fibres, the throughput of optical scrambler is higher than 80%.

Following our FRD and scrambling tests on non-circular fibres, we agree also that a fibre link composed with octagonal fibre and optical scrambler is at present the best option to stabilize the spectrograph PSF and increase the radial velocity accuracy.

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