A diagnostic tool for microbends in fibre termination as a source of FRD

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ABSTRACT

Microbends in multimode optical fibers are shown to lead to focal ratio degradation which compromises fiber fed spectrograph design and performance. By propagating specific vortex mode patterns through multimode fibers containing a single controlled microbend the mechanisms for FRD can be understood. For example, we see both experimentally and through ray tracing analysis that a microbend can produce spiral patterns in the far-field. These patterns are potentially useful tools for diagnosing termination problems in fiber assemblies. For example, by analyzing the spiral patterns produced by a single microbend it is possible to determine the location of a microbend hidden in the fiber termination.

Keywords: spectrographs, microbends, optical fibers, focal ratio degradation, termination, vortex beams, radial velocity

1. INTRODUCTION

Optical fibers have long been used to feed astronomical spectrographs. A particular concern when using multimode optical fibers is focal ratio degradation (FRD) where the fiber output cone angle is greater than the input cone angle [1]. More generally, FRD corresponds to an increase in the system etendue hence compromising the design and performance of multimode fiber fed spectrographs. FRD arises from multiple factors [2] including scattering within the length [3] of the fiber to scattering from the fiber end surfaces [4]. Stresses and microbends in the end termination are known to be a major factor in producing FRD [5, 6, 7, 8], and much work has gone into trying to design termination strategies to minimize these effects [9].

Such defects within the fiber termination structure are usually hidden, so while their effects can be seen, the exact origin of the defects in fiber termination are often difficult to determine by direct measurement [10]. Thus a trial and error approach is often used to determine the best fiber termination hardware [11]. In this paper, a new method is presented which enables the location of a single point defect (microbend or stress defect) within the fiber termination structure to be determined for the first time thus aiding in characterizing and optimizing opto-mechanical design of multimode fiber termination to minimize end effects on FRD. The method is based on a careful analysis of the characteristic distortion patterns produced for specific fiber modes as a result of microbends near the terminal end of a multimode optical fiber.

One standard method for measuring FRD is to launch a collimated beam at an angle into the fiber under test which produces an annulus (ring) in the far-field (due to azimuthal scrambling) as shown in Figure 1 [3, 12, 13]. FRD is determined by the width of the output annulus. Where FRD is severe, it is not unusual to observe a more complex structured far-field pattern during such tests. For example, in some circumstances it is possible to observe a spiral pattern in the far-field. Here we show the geometric origins of the spiral far-field pattern, and use these to determine the location of the point defect responsible for their generation. The analysis that follows is based on ray-tracing modelling supported by experimental measurements of controlled microbends induced in a variety of multimode step-index optical fibers.
Figure 1. Standard configuration for ring test measurement for FRD. The fiber is illuminated with a collimated laser at an angle \( \theta_z \) to the fiber axis. Scrambling within the fiber produces a ring pattern in the far-field. FRD causes the width of the ring (\( \Delta \theta \)) to increase.

2. MODELLING BY RAY TRACING

Ray tracing can provide insights into complex phenomena for propagation in multimode optical fibers [14]. A ray trace model was developed to explore the effects of a single microbend on propagation within multimode optical fibers [15]. A ray trace approach is appropriate for fibers with 0.22 NA and core diameters from 50 \( \mu \)m to over 300 \( \mu \)m as the number of modes supported in the visible is in the thousands (1,700-70,000). The validity of this model is further established through the remarkable agreement between modelling and experimental measurements that follow.

To simplify the analysis, a single microbend was assumed (though, it will be seen that the analysis equally applies to any point-like deformation including stress defects). Multiple (sequential) defects are not considered here. Further, it is assumed that the microbend is near the output end of the fiber.

A microbend was modelled as a lateral shear displacement of the form \( \Delta x = (h/\pi) \arctan((z-z_0)/z_{scale}) \) corresponding to a smooth s-bend centered at \( z_0 \) with maximum displacement \( x_{max} \) (see Figure 2). By choosing an analytical form for \( \Delta x(z) \), the orientation of the fiber surface normal also has an analytical form, enabling precise determination of ray angles upon reflection. This type of deformation corresponds to a shear which preserves a circular fiber cross section further simplifying the ray propagation algorithm.

Figure 2. Ray tracing through a multimode fibre with a (large) microbend. Curvature along the z-axis changes the ray propagation angle \( \theta_z \).

The model was used to determine the far-field beam profiles for an input beam consisting of a bundle of rays with random incident positions but all having an equal propagation angle (14 degrees’ external angle) with respect to the fiber z axis. Typically, 5,000 rays were propagated to determine the far-field profile which is plotted for different microbend heights in Figure 3 below. The impact of a microbend on FRD can clearly be seen. For a fiber with a very small...
microbend \((h = 2 \, \mu m)\), the rays generate a narrow ring-pattern in the far-field as expected. For a much larger fiber deformation, the far-field diverges considerably corresponding to high FRD.

![Figure 3. Far-field profiles for a 320 micron diameter step-index fiber with different microbend heights \(h\) of (a) 2 \(\mu m\); (b) 10 \(\mu m\) and (c) 60 \(\mu m\). The input beam was launched at an angle of 14° corresponding to f/2.]

3. GENERATION OF SPIRAL PATTERNS IN THE FAR-FIELD

It has been noted that in some circumstances, FRD measurements using the ring approach depicted in Figure 1 leads to a spiral pattern in the far field rather than a ring. Careful modelling and experiment have shown that this arises when the input beam does not illuminate the full core cross section of the fiber, rather the input beam enters the fiber at a single point close to the core-cladding interface and so couples only to modes corresponding to highly skew rays.

An example of the type of mode that can be so generated is a vortex mode corresponding to a Laguerre-Gaussian \(\text{LG}_{l0}\) mode with large mode index \(l\) (which also defines the vorticity, see for example [16]). Such a mode can be represented as a family of rays all propagating with the same \(\Theta_z\) but evenly distributed around the fiber core circumference as depicted in Figure 4 which show the rays propagating in a helical fashion down the fiber. Both the near-field and far-field in this case is a narrow ring profile. The impact of a microbend is to modify the ray propagation such that some rays propagate with higher vorticity (increased \(\Theta_z\)) and some with lower vorticity (decreased \(\Theta_z\)).

![Figure 4. Propagation of a set of highly skew rays corresponding to a particular vortex mode through a straight fiber (left) or a fiber with small (center) and large (right) microbends. Rays initially propagate vertically in helical paths, staying just inside the core-cladding interface. The helical paths are subsequently distorted by the microbend. In each case a single ray is highlighted to aid as a guide to the eye. Note the vertical axis is compressed by a factor of approximately ten in this figure.]

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Figure 5 shows the impact of different size microbends (heights $h$) on the propagation angles $\theta_z$ for a set of 4000 rays in a 320 $\mu$m step index multimode fiber. All rays were initially propagating with $\theta_z = 14^\circ$ (also corresponding to an external launch angle, f/2) and equally spaced around the circumference of the fiber core, corresponding to a vortex mode. The effect of the microbend is to change $\theta_z$ so that it increases for some rays (corresponding to FRD) and decreases for other rays in a systematic way. Note that except in the most extreme case, the rays are sufficiently skew as to follow the contours of the microbend such that the corresponding near-field profile always remains a ring.

![Figure 5](image.png)

Figure 5. Output angles for a large set of rays propagating with an input angle of 14º to the fiber axis as a function of microbend height $h$. Microbending causes some helical ray paths to become more axial ($\theta_{out}$ less than $\theta_{in}$) and some ray paths to become more tightly wound ($\theta_{out}$ larger than $\theta_{in}$).

The impact of the microbend is that after propagating through the microbend followed by a (typically short, mm up to several cm) length of remaining fiber, and exiting into free space, the rays will generate a spiral pattern in the far-field as shown in Figure 6.

The mechanism for creating a spiral far-field is as follows: Ray paths that are redirected by the microbend to become more axial (lower $\theta_z$) propagate on a helical path making fewer revolutions of the fiber between the microbend and the fiber end tip than those that propagate with higher $\theta_z$, which propagate on a path that is more tightly wrapped. The former rays propagate in the far-field to form the inner part of the beam pattern, and the latter the outer part. These two extremities are smoothly connected for form an arithmetic double spiral pattern that is homeomorphic with the original circle.

![Figure 6](image.png)

Figure 6. Modelled and experimentally measured spiral far-field patterns for a 209 micron fiber with microbend near the output tip.
The number of spiral windings produced increases with both the distance of the microbend from the fiber exit tip and the size of the microbend. An example set of modelled far-field spiral patterns in a 320 μm core diameter fiber together with a set of experimentally measured spirals is presented in Figures 7 and 8 below.

![Figure 7. Array of modelled far-field spiral patterns generated by a 320 μm diameter fiber with a single microbend height \( h \) and located distance \( d \) from the fiber exit tip as shown at right.](image)

![Figure 8. Experimentally measured spiral far-field patterns for a 320 micron Ceram Optec UV320/380/410P fiber containing a single microbend (of fixed height) at increasing distances from the fiber tip.](image)

4. ANALYSIS AND DISCUSSION

The mechanisms that lead to the formation of a spiral are purely geometric. We can thus use the geometry of the spiral itself as a diagnostic to characterize the microbend in terms of its magnitude and location. The geometric analysis is shown in Figure 9 below.
Figure 9 shows a model for the propagation of a vortex beam in an optical fiber with a defect such as a microbend. An input beam is launched into the fiber from the left at a fixed angle \( \theta_i \), as is typical for FRD ring measurements. In this case however, the beam is focused to a point close to the core-cladding interface so as to generate a vortex beam with a particular handedness (consisting of highly skew rays only). On propagation through the fiber, the input beam diverges to form a ring (vortex mode) which can be described as a set of parallel rays, which propagate just within the core of the fiber. As such, the fiber can be unwrapped such that the core-cladding interface is represented as a plane, and guided rays propagate in straight lines on this plane. Any defect such as a microbend causes a distortion of the plane and the rays no longer propagate as straight lines through the defect zone, however the rays always follow the surface contour of the fiber. The initially parallel rays fan out after propagating through the defect and upon exiting the fiber, the rays propagate into the far-field to form a continuous straight line that is folded back upon itself in the unwrapped geometry. In transferring back to the 3d laboratory frame (lower half of Figure 9), we need to rewrap the fiber and also keep track of the light which has exited into free space. The continuous folded line in free space is therefore wrapped up (so that the two ends meet once again) and generates a spiral pattern consisting of a highly distorted continuous ring beam (a double spiral).

Using this diagram, we can also track backwards from a measured spiral to determine the size and location of the defect. The minimum and maximum angles (\( \theta_{\text{out,min}} \), \( \theta_{\text{out,max}} \)) can be measured directly from the pattern. The total spiral rotation angle \( \phi \) can also be determined from the spiral. Here it is important to accurately count the whole revolutions (units of \( 2\pi \)) as well as measuring the remaining fractional revolution angle (radians). Also note that the spiral is a deformed ring structure, so that for example in the \( h = 250 \mu m, d = 7.5 \text{ mm} \) spiral pattern in Figure 7, \( \phi \approx 2\pi \). Together, these measurements define two angles and the length of one side of a triangle in the unwrapped space, from which all the dimensions of the triangle can be determined. The distance \( d \) between the microbend and the fiber exit tip is given by:

\[
d = \frac{2a(\phi + \pi)}{\tan(\theta_{\max}) - \tan(\theta_{\min})}
\]

where \( \theta_{\min} \) and \( \theta_{\max} \) are the internal angles corresponding to \( \theta_{\text{out,min}} \) and \( \theta_{\text{out,max}} \), \( a \) is the fiber core radius, and the spiral rotation angle \( \phi \) is measured in radians. The extra factor of \( \pi \) comes from the typical azimuthal separation in the
generation of maximum vs minimum $\theta_z$ as can be seen in Figure 5. The uncertainty this introduces can also be seen as the location of the crossing point for the fan of rays just after the microbend defect shown in figure 9.

To minimize uncertainties in practically determining the location of a hidden microbend, the input coupling angle should be adjusted to give the clearest possible spiral. Generally, larger input angles $\theta_z$ lead to greater mode purity and hence a cleaner spiral. To minimize the effects of interference, it is best to use a spectrally incoherent source but with high beam quality (eg a white light supercontinuum laser or laser plasma white light source).

Importantly, while this analysis has been performed for a microbend, stress defects in fiber termination are also well known to introduce FRD. Tests in our laboratory have shown that such defects can also lead to spiral far-field patterns derived from a propagating vortex mode. The specific details of the fan out process illustrated in Figure 4 is different, but the geometric analysis shown in Figure 9 will still apply, but possibly with a different correction factor ($\pi$ in Equation 1). While this approach is applicable to circular or elliptical fibers, it is unlikely to apply to other fiber geometries such as octagonal and rectangular fibers [17]. However, the same issues in developing better fiber termination which can be aided by using this characterization method would be expected to apply equally to non-circular fibers.

The method described in this paper applies to a single point defect. Multiple defects at the output end of the fiber will lead to a more complex structure which is not so easily analyzed. However, an important observation from this work is that is when launching into the fiber to specifically preferentially excite vortex modes, if the output far-field beam shows any substantial asymmetric structure such as a spiral or a more complex pattern, such a pattern is a clear indication of problems in the fiber end termination which will be a major source of FRD. Further, stress induced defects and microbends will likely have the greatest effect on the outer portion of the core which is most effectively sampled by a vortex beam as such beams specifically propagate in this region of the fiber core cross-section. Hence in general, analyzing the propagation of vortex modes is a useful test for fiber defects in the termination region.

5. CONCLUSION

Defects such as microbends near the output end of a multimode optical fiber have been shown to lead to a spiral far-field pattern when the input coupling conditions preferentially excite vortex modes in the fiber. By careful analysis of the resulting spiral far-field pattern it is possible to determine the location of a single defect which may otherwise be hidden from view within the fiber termination. Just the presence of an asymmetric far-field pattern (eg spiral or a more complex pattern) is itself a clear indication that there are problems with the fiber termination at the output end of the fiber. Coupling to vortex modes is thus a powerful test for diagnosing problems in fiber termination which can aid in refining design of terminators to minimize FRD.

REFERENCES


