

## Fibre Optic Lens Modelling for Optical Tomography

N. Ramli<sup>1</sup>, R.G. Green<sup>1</sup>, R. Abdul Rahim<sup>2</sup>, K. Evans<sup>1</sup> and B. Naylor<sup>1</sup>.

<sup>1</sup>School of Engineering, Sheffield Hallam University, Pond Street, Sheffield S1 1WB Email : r.g.green@shu.ac.uk

<sup>2</sup>Head of Department Control & Instrumentation Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, KB 791, 80990 Johor Bahru, Johor, Malaysia. Email : ruzairi@suria.fke.utm.my

**Abstract** *The paper describes an investigation into the preparation of fibre optic sensors for use in process tomography. Simple mathematical models are developed for fibres with polished and lensed terminations. The optimum radius to provide a lens for a specific application is determined. Lensed fibres are produced and their characteristic polar emission determined experimentally. The improvements in beam quality obtained using a combined light stop and aperture stop is presented.*

Keywords: Optical Fibres, lensed fibres, Process Tomography, Models

### 1. INTRODUCTION

Optical tomography involves projecting beams of light through a transparent medium from one boundary and detecting the level of light received at another boundary. Arrays of beams are used and each array is termed a projection. Several projections are required to minimise the probability of image aliasing which occurs when two particles intercept the same view.

The authors are investigating the use of optical fibres for process tomography. Fibres are used in pairs. The first, termed the transmitter, carries light from a bright source and transmits it into the cross-section being monitored. The second, termed the receiver, carries the light arriving at its surface after travelling across the conveyor to a PIN photo-diode. Here the received light intensity is converted into electrical energy. Several fibre pairs (typically thirty-two) are used, so pairs must have similar characteristics with minimum differences in intensity and emission angle. Thus fibre preparation must carefully controlled throughout.

This paper describes modelling of the optical fibre and the production of lensed fibres.

### 2. FIBRE OPTIC TERMINATION

For optical fibre sensors the way both ends are terminated is important. The termination effects the acceptance and emission angles of the light energy transmitted by the fibre. The following sections investigate two methods of terminating the fibre: a flat, polished surface normal to the optical axis of the fibre and a spherical lens surface. Three combinations of these ends are considered: (a) flat - flat, (b) flat -

lensed (c) lensed - lensed. rays and emitted rays for three methods of termination. The calculations are based on a 1 mm diameter multimode, plastic fibre, EH4001.

#### 2.1 Model for both ends of fibre flat

The flat ended fibre model is shown in figure 1. The emission angle,  $\beta$ , shows the maximum output divergence of the beam. A large divergent beam is undesirable, because it reduces the energy centred in the beam and can cause overlapping of adjacent transmitted beams at the receivers.

It is assumed that the cladding fibre is thin compared to the central fibre and can be ignored in the modelling. However, it is due to the cladding material, with lower refractive index [1], that total internal reflection, TIR, occurs inside the fibre.

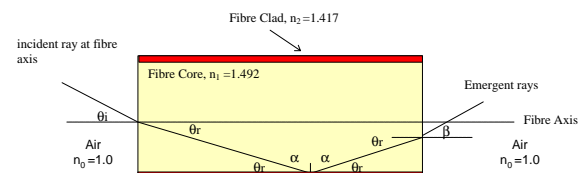


Figure 1: Flat ended model

By the use of Snell's law and symmetry it can be shown that the angle of the emergent ray has the same value as the angle of the incident ray (i.e.  $\beta = \theta_i$ ).

Thus for flat ended fibres, the divergent angle of the emergent beams can be reduced by restricting the light source for the incoming ray to a narrow angle which must be smaller than the acceptance angle of the fibre.

## 2.2 Combined flat and lens ended fibre model

In this model, one end of the fibre is flat and the other moulded to a curve of known radius (figure 2).

A similar analysis to that used in section 2.1 is carried out to determine the relationship between the emergent angle,  $\theta_o$ , and the angle of incident of the input ray as shown in figure 2.

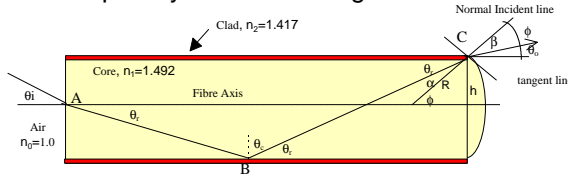


Figure 2: Combination plano-convex lens fibre model

The first refracted angle is  $\theta_r$ , which is the maximum angle that ensures the beam is totally internally reflected along the fibre. The angle between the horizontal and the emergent ray,  $\theta_o$ , termed the divergence angle at point C is obtained from:

$$\theta_r = \phi - \alpha \quad (1)$$

$$\theta_o = \phi - \beta \quad (2)$$

The radius of the fibre is  $h$  (0.5 mm) and assuming the lens has a radius of curvature  $R$ :

$$f = \sin^{-1}\left(\frac{1}{2R}\right) \quad (3)$$

and:

$$b = \sin^{-1}(n_1 \sin(f - q_r)) \quad (4)$$

Hence the relationship for the divergence angle is:

$$q_o = \sin^{-1}\left(\frac{1}{2R}\right) - \sin^{-1}\left(n_1 \sin\left(\sin^{-1}\left(\frac{1}{2R}\right) - \sin^{-1}\left(\frac{\sin^{-1} q_r}{n_1}\right)\right)\right) \quad (5)$$

This shows the divergence angle will not equal the incoming incident angle but depends on the radius of the lens. It also implies that, within limits, the smaller the radius, the smaller the divergence angle becomes.

## 2.3 Lenses on both ends of fibre model

In this model both ends of the fibre possess a lens. For simplicity it is assumed both lenses have the same power, though there may be advantages in having different powers on each end. The lens at the input end will increase the acceptance angle of the incoming ray, thus increasing the power transmitted through the fibre. Again the main aim is to determine the relationship between the lens curvature and the divergence of the output beam.

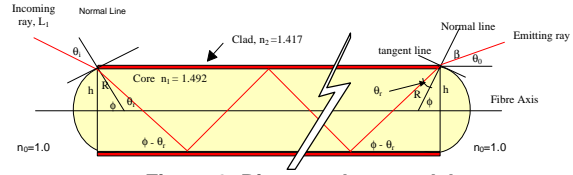


Figure 3 Biconvex lens model

The output beam must be the same as for the previous model. The only difference is that the incoming beam may subtend a larger angle at the first surface. Again, by symmetry, the angle of incidence at the second (output) surface is equal to the angle of refraction at the first surface by symmetry. Hence  $\theta_o = \theta_i$ . So a fibre lensed at both ends should have a wider acceptance angle for the incident light beam, which infers more power being transmitted from the normal non-collimated light source.

## 2.4 Optimum lens radius

The general relationship between divergence angle,  $\theta_o$ , and tip radius  $r$  is:-

$$\theta_o = \sin^{-1}\left(\frac{h}{r}\right) - \sin^{-1}\left(1.492 \sin\left(\sin^{-1}\left(\frac{h}{r}\right) - \theta_{i_{max}}\right)\right) \quad (6)$$

where  $h = 0.5$  mm and  $\theta_{i_{max}} = 28^\circ$ . Figures 4 and 5 show the relationship between  $\theta_o$  and  $r$ .

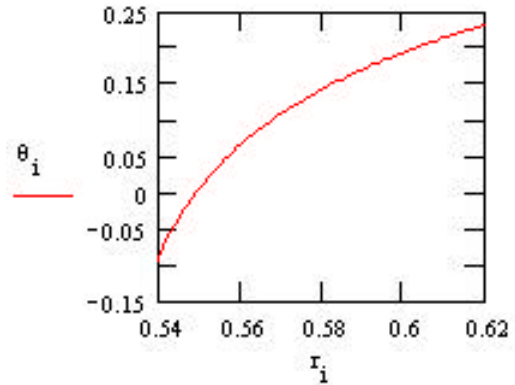


Figure 4 Divergence angle versus lens radius for small radii.

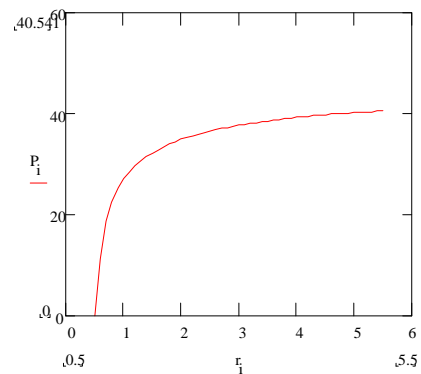


Figure 5 Divergence angle versus radius

The graph shows zero divergence angle when the tip radius is 0.54882 mm. This suggests

this is the ideal radius for optical fibres used with air as the conveying medium.

### 3 BEAM COLLIMATION USING A LIGHT STOP AND APERTURE STOP

Physical problems in producing the ideal lens radius and simplifications in the analysis mean that the emitted beam still diverges. Two mechanical devices termed a light stop and an aperture stop are employed to limit the spread of light from the fibre as it passes through the pipe [2]. These are shown in figure 5. The diameter of the physical aperture limits the angle subtended by the beam at the receiving fibre, however a small diameter hole limits the energy transmitted across the pipe and may also introduce diffraction factors [3]. Moving the aperture away from the end of the fibre also reduces the beam angle, permitting a larger diameter hole and reducing diffraction problems.

The light stop and the aperture stop is produced by inserting the transmitter end of the fibre into a tube, which reduces to a smaller diameter than the fibre with a smaller hole at its exit, figure 5.

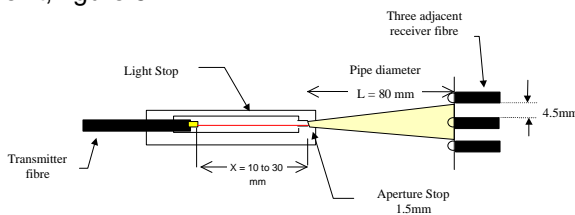


Figure 5: Block diagram of the aperture stop designed and application

### 4. PREPARATION OF THE OPTICAL FIBRE

This project requires at thirty-two sensor pairs (64 fibres) for concentration measurement at one cross-section. For velocity determination a total of one hundred and twenty eight fibres are necessary. All the fibres must meet a similar specification. This is attained by standardising the approach and the use of specially made fixtures designed to ensure good alignment of optical axes, lens principal axes and normality of the polished flat surfaces.

The fibres are cut to length and polished to provide a near optically flat surface. If required the polished surface is melted on a heated, curved surface to give the required lens shape.

Ten fibres (twenty ends) are mounted in a fixture consisting of a 50 mm thick block. The individual fibres are a close fit in holes in the block and the block provides support to the fibre. This support prevents the fibre bending when the end is being polished.

The polishing proceeds in stages starting with paper of 300 grit and continuing down to a polishing process with 5 micron paste. After a

final wash the fibres are ready to be used or to have lenses formed on them.

When the fibre is to have a lens formed on it the polished, flat end has 3 mm of the outer sheath stripped from it. The stripped end is positioned in the pre-heated, lens forming tool (figure 8) and a controlled pressure applied to the fibre.

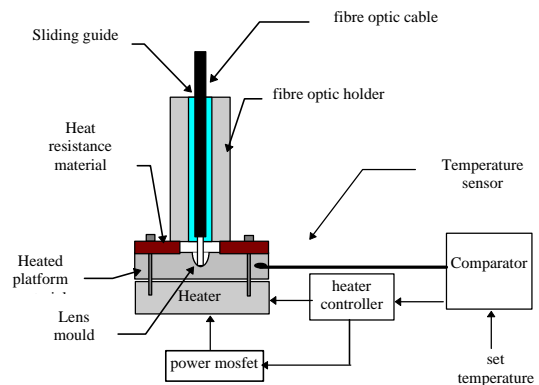


Figure 6 Lens making fixture

The tool ensures the optical axis of the fibre is aligned with the optical axis of the lens. The controlled movement of the fibre as the plastic melts, ensures close similarity in the size and shape of the lenses.

The heating platform enables the block temperature to be controlled over the temperature range 90 to 150°C and uses a feedback control loop to maintain the temperature within ± 0.4°C of the set value.

This lensing process is applied to the polished fibres as required. The finished fibres are then calibrated for alignment of the fibre and lens and for the beam divergence.

### 5. MEASUREMENT OF THE FIBRE EMISSION PATTERN

The performance of each fibre is checked to ensure that they have similar optical characteristics. There are two important measurements: (1) the alignment of the optical axes of fibre and the lens and (2) the angular divergence of the beam from the fibre. The latter is important to maximise the power in the centre of the beam.

#### 5.1 Measurement of emission pattern

The optical output forms a three dimensional cone with the peak intensity along the lens axis. So the measuring equipment is required to measure optical intensity in a plane normal to the optical axis of the fibre. This is achieved using a fixture which enables the fibre to be rotated about its optical axis relative to a fixed photo-diode measurement head, while ,at the same time,

permitting the fibre to be rotated in a horizontal plane relative to the sensor (figure 7).

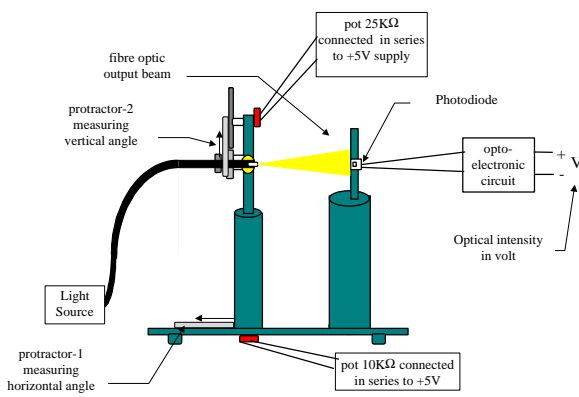


Figure 7 Measurement of emission pattern

Both angles and the output power reading are logged by a data acquisition system for further analysis and as a permanent record.

## 6. RESULTS

Two tests were carried out on the completed fibres: (1) the eccentricity between the physical axis of the fibre and the optical axis of the transmitted beam was measured (section 6.1) and (2) the relationship between the emission angle and luminous intensity of the emissions from fibres with different terminations was investigated (section 6.2).

### 6.1 Fibre eccentricity

Each fibre was positioned in the test fixture with the fibre aligned with the photo-detector. The optical intensity was measured as the optical fibre was rotated through 360°. A typical set of results is shown in figure 12.

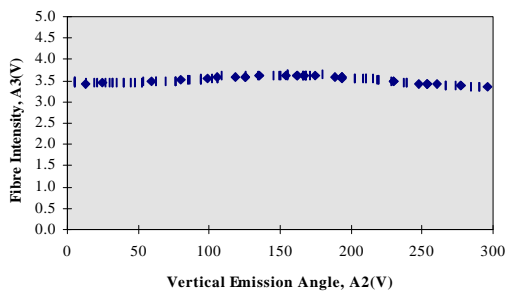


Figure 8: Emission pattern (fibres rotated 360°)

The figure shows the optical intensity is reasonably independent of the fibre orientation indicating the fibre end is normal to the optical axis of the fibre.

### 6.2 Polar diagram of light output intensity

For these tests the fibre was not rotated about its optical axis, but the fibre was rotated in a horizontal plane relative to the photo-detector. This enables a polar plot of the transmitted beam to be determined for 70° either side of the optical axis of the fibre. The measurements were repeated for various combinations of fibre terminations (Table 1).

Identification	Termination	Radius mm
PP	Polished	-----
M11	Lensed	1.59
M22	Lensed	1.98
M33	Lensed	3.17
M44	Lensed	4.76

Table 1. Types of terminations investigated

Results for these fibres are shown in figure 9.

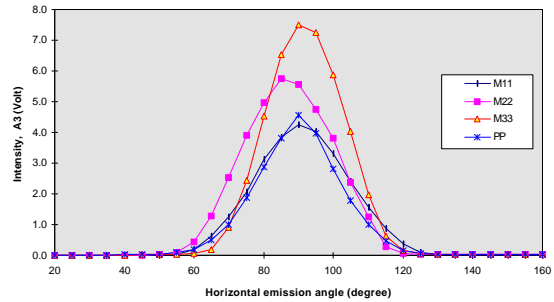


Figure 9 Polar plots for several fibre terminations

Measurement of the maximum value of the optical intensity provided by the individual fibres is plotted in figure 10. The X-axis scale is fairly arbitrary, however PP is considered to have infinite radius. Thus surface power increases with increasing X.

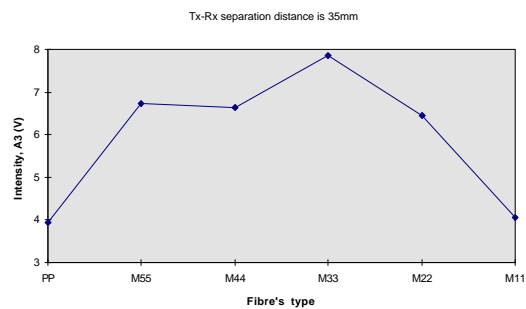


Figure 10. Peak optical intensity for different terminations

The results shown in figure 10 suggest that fibre M44 requires further investigation. A comparison of the optical intensity for the fibres shows that fibre M33 has the highest optical intensity and the polished fibre, PP, has the

lowest. These results justify the need to lens the fibres. Since fibre M33 transmits the most optical energy it be used for the new sensor array being built by the authors.

### 6.3 The light and aperture stops

For these tests a fixed aperture stop of 1.5 mm was decided upon. The aperture stop was positioned 80 mm from the photo-detector (the pipe flow diameter in the current work) and optimum position of the light stop determined by moving the exit tip of the fibre relative to the stop and determining the half power points in the slightly diverging beam normal to it's axis at 80 mm.

Without the stop the beam divergence is approximately 7.5 mm at the half power point. With the stops this is reduced to 2.5 mm at the half power point. However, the maximum power at the photo-sensor is also reduced to about 70% of the unstopped beam. This reduction in the maximum optical power is not expected to cause any problems as the signal to noise ratio at the receiver is still satisfactory.

## 7. DISCUSSIONS

A low cost approach to the production of optical lenses on plastic optical fibres has been described. The production system enables control of the lens power and ensures the optical fibres and the lens share a common principal axis.

The lens on the fibre is acceptably concentric with the axis of the fibre and the lenses help to collimate the beam. A fully collimated beam is unlikely to be achieved because the light source is not monochromatic and the lens surfaces are only simple curves. Further work is still required to optimise the lens curvature.

## REFERENCES

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