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Development of a Multimode Fibre Simulation Tool for Characterising Attenuation as a Function of Launch Conditions and Handling

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An experimental system has been constructed at NPL which can control the launch conditions used to excite a multimode fibre and scan the transmitted near-field (TNF) leaving the far end. Simulation software is being developed at The University of Leeds based on experimental data from this system. Mode coupling, differential modal attenuation, and bending loss models are being used to simulate the attenuation of a parabolic-index fibre under various launch and handling conditions.

I) INTRODUCTION

It is well known that the attenuation of an optical signal as it propagates along a multimode fibre (MMF) is difficult to predict. The launch optics used to excite the fibre and connectors, splices and bends can have a significant effect on the measured attenuation of a multimode fibre system [1, 2, 3]. The many guided modes available to share the optical power all experience attenuating factors to different degrees, and the distribution of power over these modes depends critically on the launch conditions [4]. In addition, the initial Modal Power Distribution (MPD) excited at launch may be affected by the exchange of power between neighbouring modes due to imperfections in the fibre geometry. This *mode coupling* effect, together with *differential modal attenuation,* make it difficult to define a single attenuation value for a fibre which is applicable under every launch condition. Consequently, MMF has rarely been used in situations where the loss characteristics are critically important.

However, use of multimode fibre is growing due to a widening range of industrial users, one example being the avionics industry which is moving toward using comparatively short lengths of MMF in aircraft control systems, replacing heavier copper wire. The full potential of multimode technology in areas such as this cannot be fulfilled until users can have confidence in the performance of a fibre system under any imposed launch or external conditions. The aim of this work is to produce a model which can be used to characterise the launch and handling dependence of the attenuation of short (100s of m) lengths of multimode fibre. Such a tool can then be used to investigate a possible attenuation standard for such fibres.

II) THE MODAL POWER DISTRIBUTION (MPD)

For a fibre illuminated by a source with significant spectral linewidth but peak wavelength λ_0, such as an LED, the discrete solutions of Maxwell's equations at each wavelength overlap to form a *continuum* of guided modes [5]. Modes with the same compound mode number, m, but different radial and azimuthal mode numbers, have almost identical propagation constants in a parabolic-index fibre, and are easily coupled by the random imperfections found in real fibres. These *degenerate modes* may therefore be considered identical so that the modal power distribution in the fibre may be represented by a function of compound mode number only, P(m). Under these circumstances, P(m) may be used to calculate the radial intensity distribution, I(r), in the fibre, and vice versa [6].

III) EXPERIMENTAL LAUNCH AND NEAR - FIELD SCANNING SYSTEMS

A launch system has been constructed whereby a spot of radiation can be focused on to the end face of a multimode fibre (figure 1). The radius of the spot and the launch NA are set using two circular apertures A1 and A2. The output end of the fibre is mounted in a transmitted near-field (TNF) scanning system so that the MPD at the far end of the fibre can be calculated from the radial intensity distribution, I(r). Cut-back measurements on long lengths of fibre for overfilling and low-order launch conditions have been performed, as well as measurements on fibres with and without fixed radius bends for various launch types. The MPDs calculated from the near-field scans are used to refine mode coupling, differential modal attenuation and bending loss models.

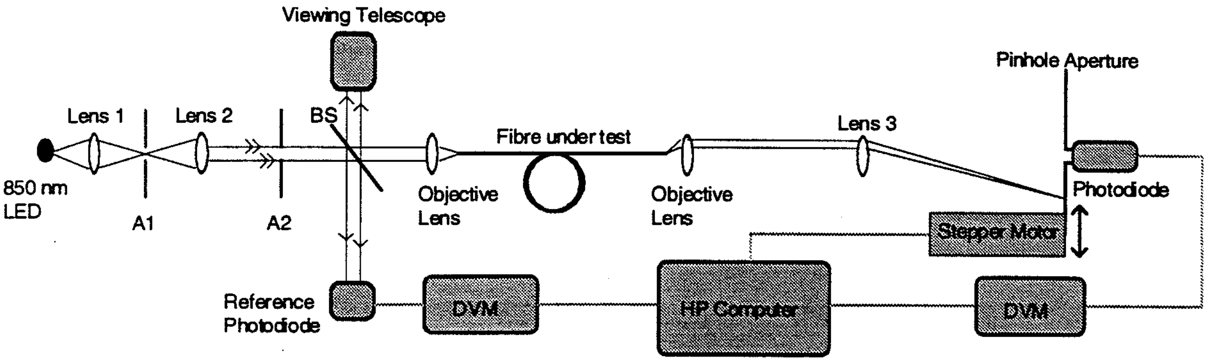

Figure 1. Optical systems for generating controlled launches and scanning the near-field leaving the fibre.

IV) SIMULATION RESULTS

Launch Model

In multimode fibres where the core radius is large compared to the wavelength of the incident radiation, propagation can be calculated using a geometrical optics approach. Under these conditions, fibre modes can be represented by ray paths through the fibre, and relationships can be found between mode numbers and ray-tracing variables. A launch model has been developed, based on geometrical optics, which calculates the modal power distribution, P(m), from the radius of the focused launch spot and the angular range of the incident radiation at the fibre end face. The MPD can then be used to generate the corresponding near-field, and examples are shown below in figure 2 for three different launch types. The 70/70 launch uses a launch spot which is 70% of the core radius and a launch NA which is 70% of the fibre NA. This launch is often used to produce a modal power distribution which approximates that which prevails in a typical multimode fibre after a few km of propagation, the so-called *equilibrium MPD*. The current reference test method for measuring the attenuation of multimode fibre specifies that the equilibrium MPD should be achieved before cut-back measurements are made.

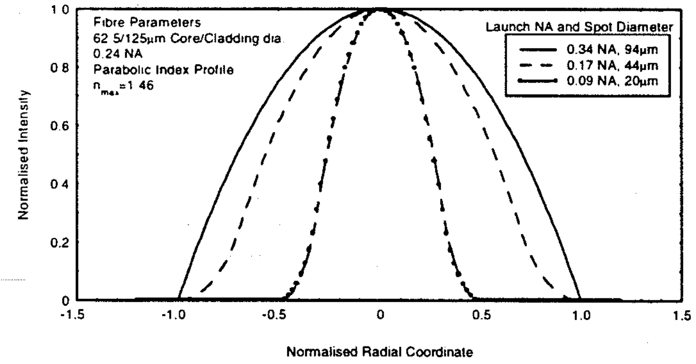

Figure 2. Simulated TNFs for low-order, "70/70" and overfilling launch conditions.

Mode Coupling and Differential Mode Attenuation

In good quality glass fibres, coupling of power from one mode to another tends to be restricted to modes very close together so that the coupling strength between modes m_1 and m_2 can be represented by a coupling function of the form [7]

$$C(m_1,m_2)=D(m_1,m_2)\exp\left(\frac{-(m_2-m_1)^2}{2\sigma^2_{m_1}}\right) \tag{1}$$

where
$D(m_1,m_2)$ is a factor which accounts for the relative degeneracies of modes m_1 and m_2, and
σ_{m_1} is a mode dependent term which defines the width of the coupling function.

Cut-back measurements using low and high-order launch conditions have been performed on a 2.2 km length of primary coated 62.5/125 μm graded-index fibre, and the results have been used to develop a mode coupling and loss model for a bare fibre. The MPD at 2 m along the fibre was calculated from a curve fitted to the TNF scan of the cut-back fibre. The fibre model was then refined by applying it to the MPD at 2 m to generate the predicted MPD after 2.2 km. This was then used to generate the predicted TNF after this distance. The model was modified until the predicted TNFs for the low- and high-order launches both matched their respective measured curves after simulated propagation over the same length of fibre. The required coupling and loss model was found to have only very slight mode coupling and a uniform attenuation coefficient for all modes.

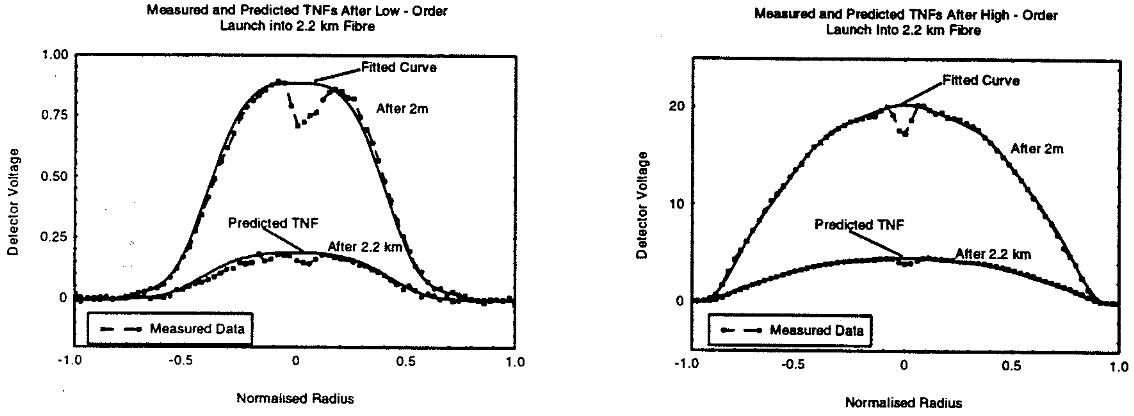

Figure 3. Experimental and predicted TNF curves for cut-back measurements using high- and low-order launches to excite a 2.2 km length of fibre. The MPD after 2 m was calculated from a curve fitted to the TNF measured at this length.

Macrobending

Bending an optical fibre with a radius of curvature of a few centimetres creates a critical radius, R_c, outside the fibre core at which the evanescent fields of the modes in the fibre are radiated away. For a given bend radius, the power lost from a particular mode will depend on what proportion of its total power is present at radii greater than R_c. Since this will depend on the modal eigenfield, bending loss from a fibre will depend on both the radius of curvature and the MPD.

An overfilling launch was used to excite a 12 m length of 62.5/125 μm graded-index fibre and the TNFs were measured with and without the fibre bent into 10 loops of fixed radius. The modal power distributions calculated for each TNF were then compared with the MPD calculated from the TNF with no bends in the fibre, giving the relative modal losses shown in figure 4a. Figure 4b shows the modal loss function calculated using a model for mode-dependent bending loss, based on an expression derived for a parabolic-index planar waveguide [8]. This bending loss model was then applied to the simulated MPDs corresponding to the low-order, 70/70, and overfilled launches used above. The resulting losses for single fibre loops with a range of bending radii are shown below in figure 4c.

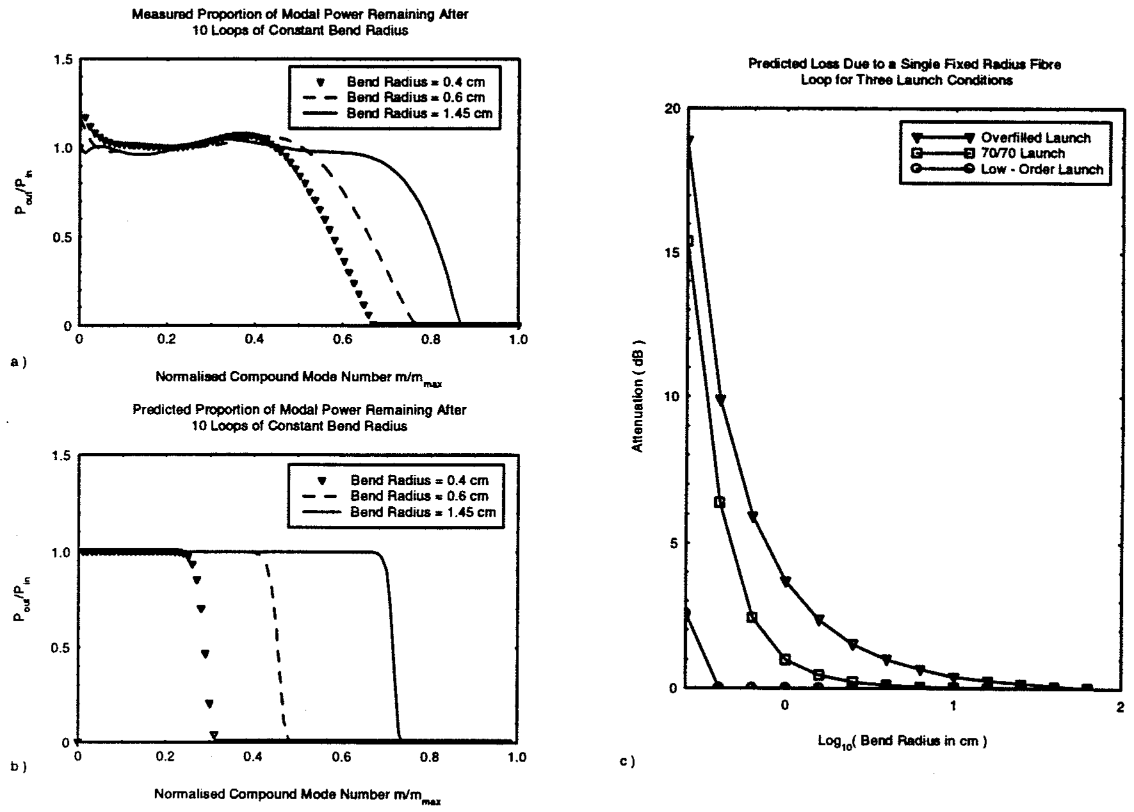

Figure 4. a) Bending loss as a function of compound mode number, calculated from experimental data; b) bending loss vs. mode number calculated from an expression for a graded-index planar waveguide; c) calculated loss due to bending for three different simulated launch conditions using the bending loss function illustrated in c).

CONCLUSIONS

A multimode fibre model has been developed which includes mode coupling, attenuation, and loss due to macrobending. Simulation results indicate that bending loss in particular is highly dependent on the modal power distribution in the fibre before the bend, which in turn is dependent on the initial launch conditions. Experimental data indicates that the bending loss function based on a graded-index planar waveguide produces a modal cut-off which is more sudden than is found in fibres. This is likely to be due to the presence of skew rays in the fibre which do not exist in planar waveguides, where all modes are meridional. A more appropriate model for mode-dependent bending loss in a graded-index fibre will be investigated, together with models for couplers and splices so that the launch dependence of loss from concatenated systems can be predicted.

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