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Volume 4, number 5 OPTICS COMMUNICATIONS January 1972

LAUNCHING INTO GLASS-FIBRE OPTICAL WAVEGUIDES

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Received 21 November 1971

Several novel and simple launching (and collection) mounts for use in the assessment of single-mode and multi-mode glass-fibre waveguides are described. The transmission efficiency for gaussian beams of 96% is limited only by Fresnel reflection loss at the entry face. Techniques for preparing the end of the fibre are outlined, a list of some suitable index-matching liquids and their properties is provided and two parameters, namely a smoothing factor S and a ray deviation θ, are proposed for assessing the optical quality of the launching system.

1. INTRODUCTION

In experiments on the propagation of light along cladded glass fibres of the type which are being developed for optical communication systems it has been shown that the dispersion [1] and the light distribution in the fibre [2] are markedly dependent on the launching conditions. If the end of the fibre is optically flat and perpendicular to its axis, efficient launching presents few problems but it is difficult to cut a fibre in this way and the ends rarely even approach such a degree of perfection. Optical polishing of the end is also difficult and tedious and, contrary to a recent report [3], we have for some time been using a very simple, quick and cheap method of mounting unpolished fibres. One version of the technique requires only a short piece of capillary tubing and a small thin plate of glass of ≈ 1 cm^2 or more in area (a microscope slide cover slip is suitable), together with a few drops of suitable index-matching liquid. The fibre and index-matching liquid (IML) are passed into the capillary until they come into contact with the glass plate sealed at the end. If the refractive index of the IML matches that of the core of the fibre any roughness or undulations in the latter are optically smoothed out and the core is effectively terminated by the inner surface of the glass plate (the outer surface if its refractive index is also matched to that of the core).

2. A VERSATILE FIBRE MOUNT

Although simple, this method has the disadvantage that care must be taken to exclude air bubbles when filling the capillary. An improved version, resulting in a robust permanent mount, can be made by the addition of a metal sleeve such as that illustrated in fig. 1. The capillary forms a close fit in the sleeve and is inserted sufficiently far that its end is close to the cover slip. At this end the inside of the metal sleeve is enlarged to provide a small reservoir of IML to which the cover slip is attached. The bore of the capillary may be adjusted for convenience but in our case is ≈ 250 μm so that a range of fibre diameters may be used. The fibre is pushed along the capillary until it makes contact with the cover slip and hence when fibres are changed or replaced no refocussing of the launching optics, but only lateral adjustment of the mount, is necessary. As shown in fig. 1, it is sometimes convenient, particularly with smaller bores, to flare the exposed end of the capillary using elementary glassblowing techniques, to facilitate insertion of the fibre. For launching a gaussian beam of small diameter, or into single-mode fibre, a high-power lens such as a ×45 objective is required and the fibre end must be within 1 mm of the lens. The cover slip must therefore be thin (≈ 100 μm). Even when its diameter is appreciably less than that of the capillary bore the fibre position is perfectly stable. A filling hole in the metal sleeve allows the mount to be flushed with cleaning fluid and refilled with fresh IML. Should it be necessary to have a long loop of unsupported fibre, any tendency for the fibre to pull out of the capillary can be greatly reduced by putting an upward bend in the latter, which also prevents leakage of IML.

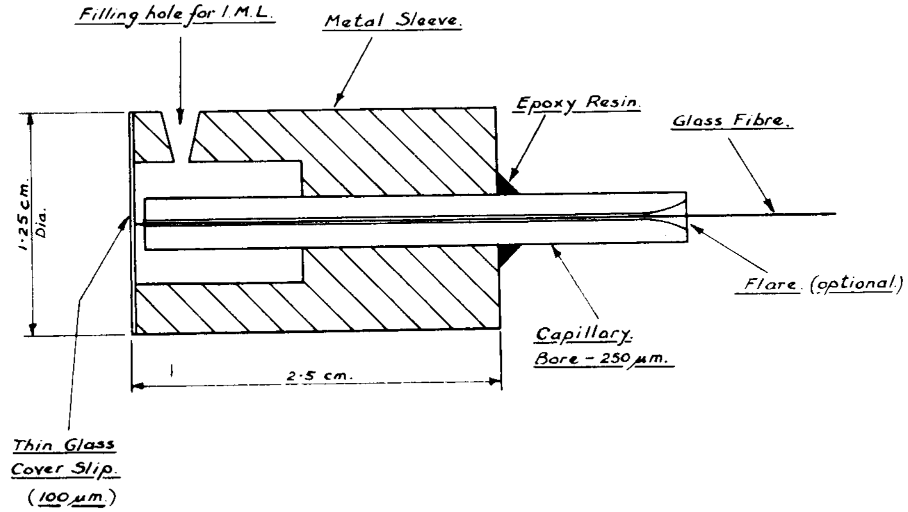

Fig. 1. The fibre mount.

In other measurements, in which a microscope is used to view the fibre end during launching, and the fibre is vertical, we have used an oil-immersion microscope objective lens with equally satisfactory results.

A list of liquids we have found useful is given in table 1.

Table 1
Some index-matching liquids for use with optical fibres

No.	Index-matching liquid	refractive index n_D at 20°C	Comments
1	di-iodomethane	1.738	avoid contact with skin avoid heating
2	monobromo-naphthalene	1.658	avoid contact with skin and eyes; does not corrode epoxy resins; slight evaporation; light brown colouration
3	monochloro-naphthalene	1.633	poisonous by skin absorption
4	quinolene	1.625	harmful if in contact with skin; corrodes epoxy resins; slight evaporation and discolouration in atmosphere; avoid heating
5	cinnamaldehyde	1.617	deteriorates in air
6	benzylbenzoate	1.569	clear liquid with low evaporation
7	benzyl alcohol	1.539	avoid contact with skin
8	methyl salicylate	1.536	
9	oil of cloves	1.532	
10	liquid paraffin (heavy)	1.48	
11	liquid paraffin (light)	1.46	

3. LAUNCHING EFFICIENCY

In order to measure the launching efficiency we propagated a gaussian beam through a short length of fibre of 50μm core diameter, having such a mount at each end, and compared the output with that from the laser operating at 0.633 μm. Coupling between the laser and the fibre was provided by a lens of 16 mm nominal focal length and the transmission efficiency through the lens, both launching mounts and the fibre was 80%. The transmission losses of the lens and fibre were 8% and 4% respectively so that the loss in each mount was 4% which is equal, within experimental error, to the reflection loss at the outer surface of the cover slip. An even higher launching efficiency would be obtained if anti-reflection coatings are used but this would destroy the simplicity of the arrangement. The performance of the mount is thus excellent.

4. FIBRE PREPARATION

Even with a perfect refractive index match between IML and core it is necessary to prepare the fibre end with care. In particular there are two gross defects which affect the launching efficiency. Firstly, breaks can occur in which part of the cladding protrudes beyond the end of the core and partially blocks the converging cone of light being launched or the emergent cone of light diverging from the core. The effect can be observed by placing a white screen close to the output end of the fibre when the shadow of the protruding cladding can be seen if the fibre is illuminated from the other end. Secondly, small pieces of broken fibre or dust can adhere to the cut end of the fibre, possibly by electrostatic charges set up at fracture, again causing partial blocking of the transmitted light. Both effects reduce the launching (and collection) efficiency and in extreme cases, such as with narrow core fibres or small diameter beams ($\approx 5\mu$m), may block the light completely. More importantly they can also be the cause of severe scatter in experimental results, particularly in fibre loss measurements.

We find that a convenient way of cutting the fibre is to hold it under slight tension and apply a sharp edge. Simple visual inspection with a magnifying lens will reveal any gross deformities. The cut end should be cleaned by agitation in a solvent, which will also remove any small particles, and may then be inserted into the mount. The latter should be flushed regularly with the IML and in our case the 2 mm tapered filling hole in the metal holder is made a close fit to a syringe taper. With these precautions we find that if the same fibre is re-inserted repeatedly the launching efficiencies for nine out of ten insertions are within 1% of each other.

5. OPTICAL DISTORTIONS PRODUCED BY IMPERFECT MATCHING

In principle when the IML exactly matches the refractive index of the core, the fibre end is clean and there are no shrouding effects, then surface roughness and irregularities have no effect on light entering or emerging from the fibre. In practice the number of suitable index-matching liquids is limited and a convenient one of the correct refractive index may not be available. In this case it is often possible to obtain satisfactory results by mixing liquids having indices straddling the required value. However, even where this can be done perfect results are difficult to achieve because of the variation of refractive index of matching liquids with wavelength and temperature. It is necessary therefore to assess the degree of mismatch which can be tolerated in a given situation. The IML produces a finite optical smoothing effect, on the end surface of the fibre core, which depends on the difference in refractive index values and may be expressed as follows. Consider two points A_1, A_2 outside the surface of the core and two corresponding points B_1, B_2 inside the core such that the lines A_1B_1 and A_2B_2 are parallel to the fibre axis, as in fig. 2. When the surface of the core is rough or cut an incorrect angle to the axis the points on the surface cut by lines A_1B_1 and A_2B_2 are "stepped" by a linear distance δ. If n_c and n_m are the refractive indices of core and IML then the difference in optical path length for paraxial rays through these points is $(n_c - 1)\delta$ and $(n_c - n_m)\delta$ when the fibre is in air and index-matching liquid, respectively. A smoothing effect due to index matching may thus be defined as

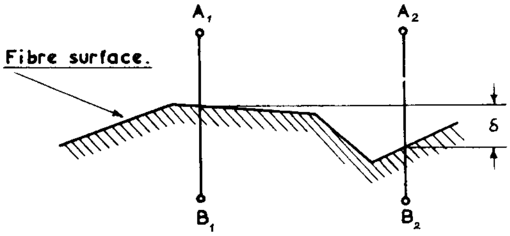

Fig. 2. Schematic section through fibre surface showing different optical paths travelled by paraxial rays A_1B_1 and A_2B_2.

$$S = \left|(n_c - 1)/(n_c - n_m)\right| .$$

With perfect matching $n_c = n_m$ so that $S = \infty$ and the fibre end becomes optically flat, or in practice as flat as the cover slip, but normally δ is finite and this is why it is necessary to make as good a break in the fibre as possible. The degree of smoothing required depends on the fibre surface conditions, on whether a wide or narrow beam is to be launched and on the particular experiment or application being undertaken. To take a typical example, if an index match within 1% is achieved with F7 core glass for which $n_c = 1.625$ then $S > 60$. It is obvious of course that matching must be effected at the temperature and wavelength of operation. The magnitude of the wavelength dependence is such that if F7 glass is matched by a mixture of monobromonaphthalene and benzylbenzoate at 633 nm then at 590 nm the smoothing factor has fallen to $S \approx 200$.

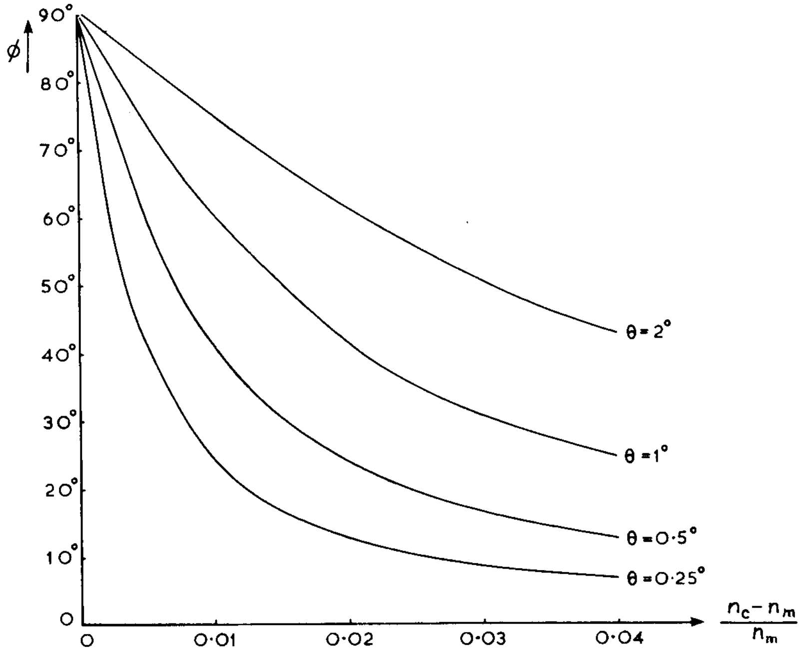

Fig. 3. Curves showing the maximum surface deviations ϕ which can be tolerated for fixed values of permitted ray or wavefront deviation θ as a function of normalised refractive index difference.

In order to achieve maximum bandwidth in a multimode fibre [1,2] and minimum launching loss in a single-mode fibre [4], it is necessary to launch a gaussian beam with the beam waist at the entry face. At the beam waist the wavefront is plane and the smoothing factor S is a measure of the amount by which the IML reduces the magnitude of the phase inhomogeneities across the wavefront which are introduced by surface roughness at the fibre end. An additional distortion caused by a rough end will arise because any portion of the surface at an angle ϕ to the ideal plane (perpendicular to the axis) will cause the wave vector of that portion of the wavefront passing through it (or, using a ray picture, the equivalent paraxial ray) to be tilted through an angle θ. As before in order to avoid increased dispersion or loss it is desirable to know the deviation θ produced by various combinations of normalised index mismatch $(n_c - n_m)/n_m$ and misalignment ϕ of the fibre surface. Curves showing the combinations of maximum permissible surface angle and index mismatch for fixed values of

$$\theta = \phi - \sin^{-1}[(n_m/n_c)\sin\phi]$$

are therefore given in fig. 3. These show that for a permitted deviation as small as 15 minutes of arc then surface distortions of 20° can be corrected by an index match of 1% while for $\theta = 2^\circ$ an index match of 4% is sufficient to correct for values of ϕ up to 45°.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to Science Research Council for supporting this work and for the award of a research studentship to one of the authors (JPD).

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