JOINTING LOSS IN SINGLE-MODE FIBRES

Indexing terms: Optical couplers, Optical fibres

The jointing loss of single-mode fibres is mainly dependent on their numerical apertures, and is largely independent of normalised frequency and fibre diameter. The letter presents simple loss predictions as an aid for practical design work of single-mode fibre joints.

Introduction: As is well known, only the field spreading of the HE$_{11}$ mode in a fibre is an important parameter for fibre jointing. This field spreading can be expressed in terms of the spot size of the HE$_{11}$ mode.[1] Since the field distribution in a single-mode fibre is very similar to that of a Gaussian beam, the spot size can be assumed to be approximately equal to the width of the incident Gaussian beam which gives the maximum launching efficiency.[2,3] Strictly speaking, this spot size is a function of the core radius a, wavelength λ, normalised frequency $V = (2\pi a/\lambda)\,(n_1^2 - n_2^2)^{1/2}$, and numerical aperture $NA = (n_1^2 - n_2^2)^{1/2}$, where n_1, n_2 are the refractive indices of core, cladding, respectively. However the actual spot size (μm) in a fibre is approximately the same[4] for V values between 1·8 and 2·4. This implies that the dominant factor in jointing loss is the numerical aperture, and that V and a have only a small effect. We present here simple curves which may be used for the estimation of jointing loss. The different types of splice defect are given in terms of absolute values, and not normalised parameters.

Theoretical results: By introducing the equivalent Gaussian distribution, all jointing problems can be significantly simplified by replacing the HE$_{11}$ mode of the sending fibre by its transformed Gaussian field. The interesting conclusions which may be drawn from our extensive computations[2] of the efficiency with which a Gaussian beam can be launched into a single-mode fibre, and of the loss caused at joints by spatial angular misalignment, are that in practice the jointing loss is strongly dependent on numerical aperture only. This is because the spot size of the HE$_{11}$ mode for a given NA is almost the same for a wide range of V values.[4] In other words, as soon as the fibre numerical aperture is fixed, the mode spot does not depend on the fibre diameter, but is constant. However, this approximation becomes progressively less applicable for V values falling below 1·5, but gives in the worst case an accuracy of 3·5% for V values in the range 1·6–2·4.

We considered first the excitation of the HE$_{11}$ mode by a Gaussian shaped laser beam[3] for various types of misalignment. The fibre is later assumed to be the receiving fibre. Once the launching efficiency is known as a function of the input spot size of the Gaussian beam, the next step is to replace the Gaussian beam by the equivalent transformed single-mode fibre.[4] Finally the jointing loss can be obtained from the average of the launching efficiency over the range $V = 1{\cdot}6$–$2{\cdot}4$.

Theoretically calculated results are shown in Figs. 1*a* and *b*. The solid lines in Fig. 1*a* show the loss caused by a mismatch of mode spot sizes when the numerical aperture of the sending fibre (NA_S) differs from that for the receiving fibre (NA_R). It is evident that, in general, the effect of mismatch of NA does not necessarily yield high jointing losses. For instance, at $NA_R = 0{\cdot}10$, the jointing loss is less than 0·5 dB for NA_S in the range 0·7–1·4. For simplicity, the following three calculated results are shown for the case where the sending and receiving fibres have the same NA (i.e. $NA_S = NA_R$). The dotted and solid curves in Figs. 1*a* and *b*, respectively, show the loss due to the off-axis displacement and the angular misalignment. It is seen that, as the numerical aperture increases, the off-axis alignment tolerance becomes more restrictive, but the angular alignment tolerance is relaxed. This is due to the fact that the loss caused by off-axis misalignment is directly related to the field width at the fibre ends, but the loss caused by angular misalignment depends strongly on the acceptance angle of the fibre. From the practical point of view, the angular accuracy of 1° can be easily obtained, so that it should be less than 0·3 dB. The loss due to longitudinal fibre separation (dotted curves in Fig. 1*b*) is less than 0·5 dB for more than 10 μm separation. This can be easily achieved with normal mechanical tolerances in the jointing assembly. Thus it may be seen from these calculations and the achievable mechanical accuracy in a jointing jig, that the off-axis misalignment is the most important factor for the practical single-mode fibre joint.

Experimental results: Experimental verification of the theory has been carried out using a micromanipulator with piezoelectric drives. The active elements comprised piezoelectric transducers that expand when a voltage is applied, giving a resolution of 0·02 μm or less. The tips of the sending and receiving fibres, which were immersed in index-matching liquid, were fixed in V grooves on the micromanipulator. The V grooves had been aligned beforehand. Experiments on the jointing loss due to off-axis misalignments have been carried out.

The fibres used in the experiments were two types of phosphosilicate core fibre shown in Fig. 2 and a He/Ne laser was

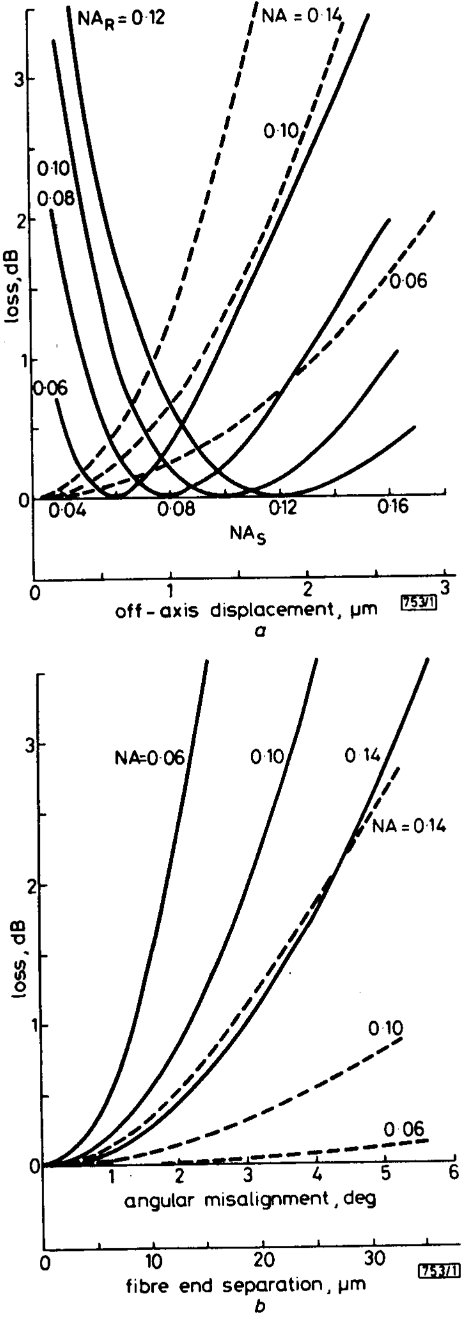

Fig. 1 *Jointing loss of single-mode fibres for various misalignments*

a Solid-curves–mismatching of mode spot sizes (i.e. two fibres are centrally aligned, but have different NA); dotted curves–off-axis displacement. The suffixes S, R denote sending and receiving fibre, respectively

b Solid curves–angular misalignment; dotted curves–fibre separation

Reprinted from ELECTRONICS LETTERS 2nd February 1978 Vol 14 No.3 pp. 54–55

used as the excitation source. Fig. 2 shows the jointing efficiency as a function of the off-axis misalignments for various combinations of the fibres, together with the theoretical curves. It is seen that the experimental values are in good agreement with theory. As the results have been normalised, it is worth mentioning that the minimum losses were (*a*) 0·27 dB, (*b*) 0·60 dB, and (*c*) 1·62 dB. In cases (*a*) and (*b*) the numerical apertures of the sending and receiving fibres were the same, but they did not show zero jointing loss. This may have arisen from scattering at the fibre ends, small angular displacement and so on.

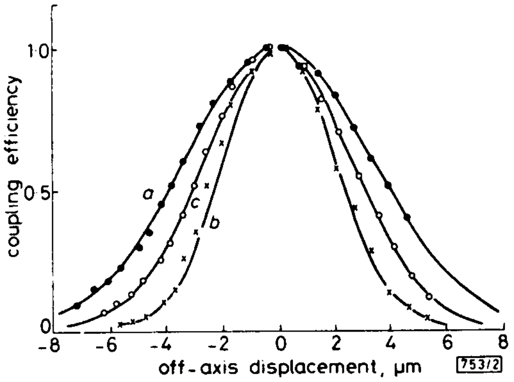

Fig. 2 *Normalised jointing efficiency for off-axis misalignment*

Two fibres have characteristics (determined by the far-field radiation method[6]) as follows:

Fibre 1 $a = 4{\cdot}30\,\mu m$, $V = 2{\cdot}41$, $NA = 0{\cdot}056$

Fibre 2 $a = 2{\cdot}15\,\mu m$, $V = 2{\cdot}18$, $NA = 0{\cdot}102$

Three experiments are shown, together with their theoretical curves as follows:

	Sending fibre	Receiving fibre
a	1	1
b	2	2
c	2	1

Discussion and conclusions: The losses due to different types of splice defect have been shown to depend on only one fibre parameter, namely the numerical aperture; the fibre diameter and the normalised frequency have only a small effect. Off-axis misalignment is probably the most important factor in low-loss fibre jointing and may arise from misalignment in the jointing jig or from eccentricity or noncircularity of the core. As *NA* decreases it becomes progressively less critical, but at the same time the mode spot size increases, making the fibre more susceptible to loss by bends and microbends. In addition, the stress effect caused by a tight coating, the presence of elastic bending strain and other effects are so sensitive to *NA*, at low values, that additional transmission losses may occur. Therefore the choice of *NA* must be a compromise between these various factors. We now believe from our many investigations on propagation in single-mode fibres (for example, Reference 5) and on fibre jointing that a fibre *NA* of about 0·10 is preferable.

Acknowledgment: The authors would like to thank D. N. Payne for supplying the micromanipulator with piezoelectric transducer and useful comments, S. R. Norman for fabricating the fibre and the Pirelli General Cable Company for a research fellowship.

W. A. GAMBLING
H. MATSUMURA
A. G. COWLEY

Department of Electronics
University of Southampton
Southampton SO9 5NH, UK

9th December 1977

References

1 PETERMANN, K.: 'Microbending loss in monomode fibres', *Electron. Lett.*, 1976, **12**, pp. 107–109
2 MATSUMURA, H.: 'Jointing loss in single-mode fibres'. ESU Report, July 1976
3 MARCUSE, D.: 'Loss analysis of single-mode fibre splices', *Bell Syst. Tech. J.*, 1977, **56**, pp. 703–718
4 GAMBLING, W. A., and MATSUMURA, H.: 'Simple characterisation factor for practical single-mode fibres', *Electron. Lett.*, 1977, **13**, pp. 691–693
5 GAMBLING, W. A., and MATSUMURA, H.: 'Propagation characteristics of curved optical fibres'. Post-deadline paper presented at IOOC Conference, Tokyo, July 1977
6 GAMBLING, W. A., PAYNE, D. N., MATSUMURA, H., and DYOTT, R. B.: 'Determination of core diameter and refractive index difference of single-mode fibres by observation of far-field pattern', *IEE J. Microwave Opt. & Acoust.*, 1976, **1**, pp. 13–17

0013-5194/78/0753-0054 $1.50/0