plates were distributed along the scan direction as shown in the Figure, and have the dimensions indicated. It can be seen from the plot that each deformation has been resolved clearly, and the table shows that the thickness of each plate has been measured to an accuracy of better than ±0.14 mm. This result is very encouraging, in view of the fact that data sampling was carried out for convenience at equal time intervals and assumed a constant dish rotation speed. Evidence of the magnitude of error arising from this assumption is seen in the regions well away from the deformation, where variations as large as 3° (±0.13 mm) have occurred.

Fig. 2 Configuration of deformations and results of profile measurement

Inspection of surface annuli at other radii can in principle be achieved by mechanical rotation of the small antenna. Suitable compensation for the differential path length change with radius is carried out in arriving at the best-fit focal length for the reflector. However, to avoid mechanical scanning, a synthetic-aperture technique using a linear sampling array is currently under consideration, and allows all necessary data to be recorded from one rotation of the antenna under test.

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References

POLARISATION ANALYSIS OF STRONGLY FUSED AND WEAKLY FUSED TAPERED COUPLERS

Indexing terms: Optical fibres, Optical connectors and couplers

The polarisation properties of both strongly fused and weakly fused single-mode tapered fibre couplers have been analysed. A comparison with experimental results shows excellent agreement with our analysis.

Introduction Our recent understanding of the behaviour of tapers in single-mode fibres has allowed us to analyse in a very simple manner the behaviour of the fused tapered coupler. In Reference 1 we studied the coupling behaviour of
the well fused tapered coupler, while (and we quote the relevant results here) the coupling behaviour of the weakly fused coupler is equally straightforward to analyse. Both types are of interest, since in practice a fused coupler can be either well fused or weakly fused (see Figs. 1a and b and Reference 3).

![Fig. 1 Photographs of cleaved cross-section of (a) strongly fused coupler and (b) weakly fused coupler](image)

Our main aim here is to show how the polarisation effects of both types of coupler can be accommodated within our overall model.

The polarisation behaviour of the fused coupler has been recently investigated experimentally, and it has been shown that couplers with long interaction lengths can act as polarisation beam splitters. The behaviour of the power splitting ratio for unpolarised light as a function of wavelength for such couplers shows several characteristic features. The power splitting ratio oscillates rapidly as a function of wavelength with a channel spacing \( \Delta \lambda \). This rapid oscillation is itself modulated with a slower period \( \Delta \lambda \) giving a response of a modulated comb filter. The modulation arises as a result of the \( x \)- and \( y \)-polarisations having slightly different coupling strengths \( C_x \) and \( C_y \) in the fused section of the coupler. If the fused region is long enough, it is possible for complete dephasing between the two polarisations to occur, and one polarisation will exhibit complete power transfer at the output of the coupler. This will correspond to the observed nulls in the modulation period.

Potentially, there are many applications which can exploit these properties of long couplers. They include polarisation beam splitters, spectral filters, modulators and switches. The successful design of such components requires a detailed knowledge of the coupling mechanisms within the coupler. In this letter we present the results of a detailed analysis of the coupling strengths of polarised light in both strongly and weakly fused couplers. We show that our analysis is in excellent agreement with recent measurements made on very long weakly fused couplers.

Analysis: In Reference 1 we showed that the fused coupler can be successfully analysed by assuming that power exchanges occur as a result of the interference between the lowest-order symmetric and antisymmetric modes of the waveguide formed by the whole of the cross-section of the fused region. Typical dimensions of the fused region are 5 \( \mu \text{m} \times 10 \mu\text{m} \). The corresponding \( V \)-value is in the range 15–50, depending on whether the coupler is potted (potting index 1–42) or is in air. Such high \( V \)-values allow an accurate asymptotic analysis of the coupling strengths. The well fused guide is modelled by an equivalent rectangular guide (Fig. 2a) and the weakly fused coupler is modelled by two touching cylinders, corresponding to the fibre claddings (Fig. 2b). The fibre cores are of negligible cross-section in the fused taper and are ignored.

![Fig. 2 Model used to analyse coupling region of (a) strongly fused coupler and (b) weakly fused coupler](image)

If unpolarised light enters one of the input ports, then the power in an output port is described by

\[
P = \frac{1}{2} \left[ 1 + \cos \left( C_x + C_y \right) \right] \cos \left( C_x - C_y \right) \cdot L \]

(1)

where \( C_x \) and \( C_y \) are the coupling strengths of the \( x \)- and \( y \)-polarisations and \( L \) is the length of the fused interaction region. To leading order in \( V \) the following equations for \( C_x \) and \( C_y \) have been derived:

(a) Strongly fused coupler:

\[
C_x + C_y = \frac{3 \pi \lambda}{32 n_2 a^2} \left[ \frac{1}{\left( 1 + \frac{1}{V} \right)^2} + \frac{1}{\left( n_2^2 - n_1^2 \right)^2} \right] \]

(2)

\[
C_x - C_y = \frac{3 \pi \lambda}{16 n_2 a^2} \frac{1}{V} \left( 1 - \frac{n_1^2}{n_2^2} \right) \]

(3)

(b) Weakly fused coupler:

\[
C_x + C_y = \frac{2^{10} / \pi^4 \left( n_2^2 - n_1^2 \right)^{1/2}}{n_2 a \sqrt{n_2^2 / V}} \]

(4)

\[
C_x - C_y = \frac{2^{10} / \pi^4 \left( n_2^2 - n_1^2 \right)^{1/2}}{n_2^2 a \sqrt{n_2^2 / V}} \]

(5)

These formulas allow the response of the coupler to be analysed for any input state of polarisation. They also display, in a very simple manner, the dependence on wavelength, refractive index and coupler size.

Discussion: From eqns. 2–5 it is straightforward to compute the channel spacing \( \Delta \lambda \) and the modulation period \( \delta \lambda \). The ratio of these two quantities has a particularly simple form, and is given by

\[
\frac{\Delta \lambda}{\delta \lambda} = G \cdot \frac{V}{\left[ 1 - (n_1^2 / n_2^2) \right] } \]

(6)

where \( G = 1/2 \) for the weakly fused case and \( 1/4 \) for the strongly fused case. Eqn. 6 predicts that the modulation period should decrease with increasing wavelength and that \( \delta \lambda / \Delta \lambda \) should be proportional to \( 1/(\text{wavelength}) \). The experimental confirmation of this behaviour is contained in the measurements of very long fused couplers made in our laboratory, the results of which were presented in Reference 4. In Fig. 3 we have plotted \( \delta \lambda / \Delta \lambda \) against \( 1/\lambda \) for one of these couplers with a 300 mm-long interaction region. The points lie close to a straight line, as predicted by eqn. 6. The fact that this graph does not pass through the origin is a consequence of our neglecting higher-order \( 1/V \) terms, which result in a constant being added to the right-hand side of eqn. 6. The cross-section of these couplers

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was examined by cleaving and photographing. Fig. 1b represents a typical result, and it is clear that these couplers were weakly fused. The gradient of a best straight-line fit to Fig. 3 allows the coupler cross-section to be determined using eqn. 6 and G appropriate to the weakly fused case. We find that a = 3 \mu m, in excellent agreement with the measured cross-section of our couplers.

In conclusion, we have presented the results of a detailed analysis of the coupling of x- and y-polarised light in strong and weakly fused couplers. Our results are in very good agreement with measurements made previously in weakly fused couplers.

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References
4 YATAKI, M. S., PAYNE, D. N., and VARNIMAN, M. P.: 'All-fibre wave-length filters using concatenated fused-tapered couplers', ibid., 1985, 21, pp. 248–249
5 BRICHER, T., and BAKER, V.: 'All-fibre polarisation splitter/combiner', ibid., 1985, 21, pp. 251–252

Fig. 3 Experimental results for variation of modulation period/channel spacing against 1/(wavelength) for a weakly fused coupler with a 300 nm-long interaction region
Experimen-tal points are taken from previously reported measurements performed at our laboratory

Fig. 1 General geometry of horn antenna

Fig. 2 Simple plane-wave model to derive surface impedances

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