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SINGLE-MODE FUSED BICONICAL TAPER FIBRE COUPLERS

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INTRODUCTION

In many single-mode optical fibre sensors, in particular those based on fibre interferometers, a single-mode 4-port directional coupler is needed to transfer light from one fibre to another. Although the coupling can be achieved with discrete components, a more stable and robust system with a lower insertion loss can be obtained if a fibre coupler is used.

Single-mode fibre couplers are now being routinely made in our laboratories by the fused biconical-taper technique, (Kawasaki and Hill(1), Slonecker (2)) which was originally used to make multimode couplers. This method has the advantage of being both simple and quick, unlike polishing (Bergh et al (3), Digonnet and Shaw (4)) and etching techniques, (Sheem and Giallorenzi (5), Liao and Boyd (6)) which require a considerable amount of skill. In this paper the fabrication technique of fused biconical-taper couplers is described together with a detailed experimental analysis of the properties of such couplers. Preliminary results on the fabrication of 6-port fused-taper couplers are also discussed.

COUPLER DESCRIPTION

The experimental arrangement used for making fused-taper couplers is shown in Figure 1. The two single-mode fibres, which form the coupler, are fused together and tapered in an oxy/butane flame. The taper in the fibres causes the fundamental mode in each of the cores to spread out and interact with its neighbour, thus the power oscillates between the two fibres along the length of the coupler. The amount of power coupled between the fibres depends on the fibre NA and core radius, the degree to which the core sizes are reduced, their distance apart and the length of the fused section. These parameters can be adjusted by varying the taper ratio in the fibre, hence couplers with various coupling ratios can be produced.

Total power transfer between the two cores takes place over a length L given by (McIntyre and Snyder (7))

$$L = \frac{n_1 \; a \; \pi \; V^3 \; K_1^{\;2} \; (W)}{2NA \; U^2 \; K_0^{\;'} \; (WD)} \qquad (1)$$

where D is the ratio of the separation of the core centres to the core radius a, n_1 is the refractive index in the core, U, W are the eigenvalues in the core and cladding respectively and $K_{1,0}(\;)$ are modified Bessel functions. The V value, U, W and a are functions of the distance along the fibre taper, hence L will change along the length of the coupler.

The power in the throughput port P_t is monitored as the coupler is made and, as expected, the power is seen to oscillate as the tapering is increased. A typical result is shown in Figure 2 where the throughput power is seen to go through thirteen oscillations as the fibres are tapered. The power oscillates more rapidly as the tapering increases since there is then greater interaction between the fields in the neighbouring fibres. Although it is not necessary to taper the fibres beyond the first oscillation to achieve any desired coupling ratio, fibres pulled to give large taper ratios exhibit interesting properties, as will be shown in the next section.

In the tapered region of the coupler, a large proportion of the field propagates in the cladding, hence the characteristics of the coupler will be affected by the index profile of the cladding. We have found that couplers made with fibres having depressed claddings have a very high insertion loss, >10dB, whereas those made with matched or raised claddings have a low insertion loss, <1.5dB for equal power splitting, if the taper is not too sharp.

Measurements of the loss caused by a taper in different types of single-mode fibre show that depressed cladding fibres are very susceptible to taper loss. Typical measurements of the taper loss are shown in Figure 3 for three depressed cladding fibres, curves a, b, and c and for a matched cladding fibre, curve d. The output from the matched cladding fibre remains constant as the tapering increases until the fibre breaks. At this point the taper ratio T_R (= initial fibre diameter/ diameter at centre of taper) is 50. On the other hand the output from the depressed cladding fibres falls rapidly for a small taper ratio and remains negligible until the fibre breaks.

The fundamental mode in a depressed cladding fibre has a non-zero cut-off V-value (Sammut (8), Monerie (9)) below which the mode propagates as a leaky mode. The taper ratio corresponding to the cut off points of the fundamental mode of the fibres used in the measurements are shown in Figure 3. It is seen that these points coincide with the sudden decrease in the output power. Thus it can be concluded that the large taper loss of depressed cladding fibres is due to the loss of the leaky LP_{01} mode along the taper.

PROPERTIES OF FUSED TAPER COUPLERS

It can be seen from equation (1) that the amount of coupling between two fibres depends on many parameters, for example, the core radius, NA and wavelength. Several experiments have therefore been carried out in order to obtain a better understanding of the behaviour and operation of single-mode fused-taper couplers and the results are presented in this section. Firstly, the wavelength dependence of the coupled power was measured for couplers made with two types of fibre with various taper ratios. Secondly, the effect on the coupled power of the index of the medium surrounding the coupler was investigated. The results show that in addition to their use as a power splitting device, single-mode fused-taper couplers also have potential for use as wavelength divisional demultiplexing devices and as sensors.

WAVELENGTH DEPENDENCE OF COUPLED POWER

The variation of the coupled power with wavelength has been measured for several couplers made from two different matched cladding fibres. The first fibre (A) had an NA of 0.15, the cut off of the second order LP_{11} mode was 650nm and the ratio of the fibre outer diameter to core diameter was ~30, whereas the second fibre (B) had an NA of 0.09, the LP_{11} cut off was 490nm and the ratio of outer diameter to core diameter was ~20.

The experimental results show that the power oscillates between the two output ports as the wavelength varies, with a period of oscillation which is determined by the fibre NA, core radius and taper ratio. For a given taper ratio, the output power of couplers made from fibre B oscillates more rapidly than those made from fibre A. The reason for this is that the ratio of the fibre outer diameter to the core diameter is smaller for fibre B than fibre A, hence the parameter D in equation (1) is smaller and the length L over which power is transferred is shorter.

The output power also oscillates more rapidly with wavelength for couplers made with a larger taper ratio since the larger reduction in the core diameter causes the field to spread out more. Hence there is greater interaction between the fields of the neighbouring cores.

Measurements of the ratio of the power in the two output ports as a function of wavelength are shown in Figures 4a and b for fibres A and B respectively. Both couplers had a large taper ratio. In both cases the period of the oscillation is virtually constant being ~260nm for fibre A and ~40nm for fibre B. The curves in Figure 4b show that the coupled power can be made to be very sensitive to wavelength. Thus it is possible to make a wavelength division demultiplexer by connecting together a series of couplers, each having a different taper ratio and which will therefore selectively couple out power at different wavelengths. Such a device has the advantage of being more stable than a wavelength division demultiplexer made from discrete components and should also have a low insertion loss. Further work on this device is being carried out and will be reported elsewhere.

DEPENDENCE OF COUPLED POWER ON REFRACTIVE INDEX

After fabrication of the fibre coupler it is necessary to provide a robust package for the device. In particular, the tapered region requires a protective coating. We have found that the coating can change the coupling ratio. This is because the refractive index of the coating is greater than that of the medium (i.e. air) in which the coupler was made. As a consequence the guiding properties of the fibres are changed and the degree of field spreading in the taper changes. The result is a change in coupling ratio which depends on both the refractive index of the coating and the taper ratio.

The sensitivity of the coupled power to the index of the surrounding medium has been measured for couplers with various values of taper ratio. The uncoated coupler was immersed in an oil having a refractive index less than that of the cladding (1.458) and the change in the coupled power was measured as the refractive index of the oil was reduced by heating.

Figure 5 shows the ratio of the coupled power P_C to the total power P_T as a function of index for two couplers having taper ratios of 10 (dotted curve) and 20 (solid curve). The change in coupled power can be very large and for the coupler with T_R=20 the power oscillates between the two output ports as the refractive index is changed. For smaller values of T_R the change in coupled power with index is less significant. For example, in a coupler having T_R~4 the coupled power changes by only 1.5% of its value in air over the range of refractive index 1.4 to 1.45.

The above effect should not pose any problems in coating couplers since any required coupling ratio can be produced for relatively small taper ratios. Any small change in the coupling ratio resulting from coating the fibre can then be compensated by making the bare coupler to have a somewhat different coupling ratio from that finally required. However, Figure 5 shows that couplers made with a large taper ratio are very sensitive to refractive index and thus to temperature. Hence a single-mode fibre coupler itself may form the basis for an interesting sensor with one output port monitoring the variation in either refractive index or temperature and the other output port providing a reference signal.

SIX PORT COUPLERS

Six port fibre couplers have also been fabricated using the fused biconical taper technique. The losses of these couplers are <1.5dB for various splitting ratios. Further results will be presented at the conference.

SUMMARY

Single-mode fibre couplers have been made by the fused biconical taper method having losses <1.5dB for various coupling ratios. It has been shown that low loss fused-taper couplers cannot be made with depressed cladding fibres because the fundamental mode is cut off for relatively small values of the taper ratio. Below cut off the leaky LP_{01} mode propagates but this mode has a high taper loss.

The dependence of the coupled power on wavelength and the refractive index of the medium surrounding the fibre has been measured for various couplers. The results show that the coupled power is very sensitive to wavelength and refractive index if the fibres are pulled to give a large taper ratio. Thus single-mode fused-taper couplers can be used to form the basis of wavelength division demultiplexers and temperature or refractive index sensors.

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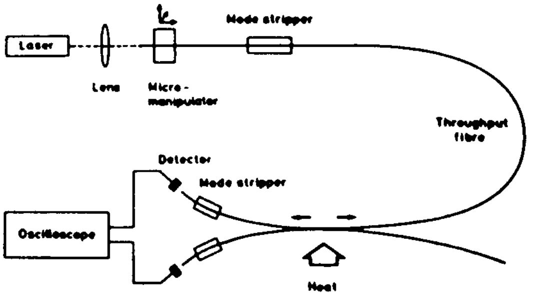

Figure 1 Experimental arrangement

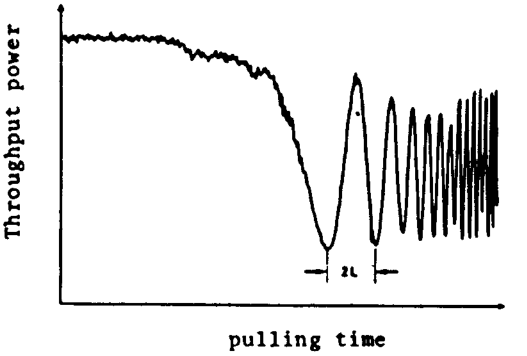

Figure 2 Power in throughput port as a function of pulling time

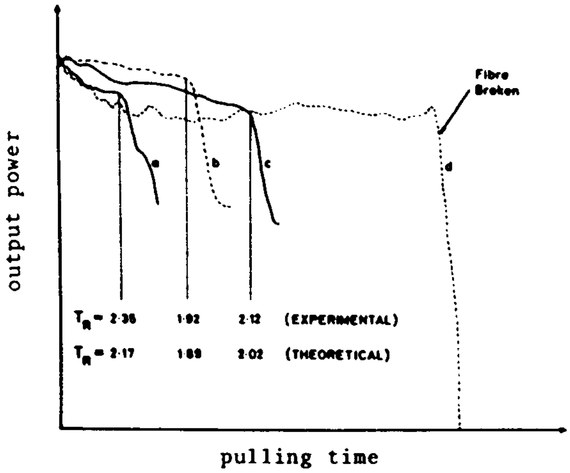

Figure 3 Output power of different fibres as a function of pulling time

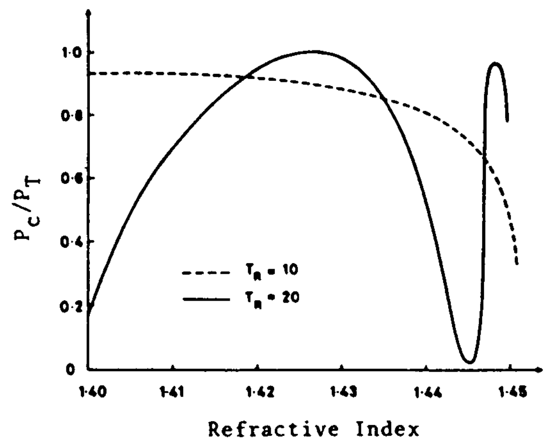

Figure 5 Variation of normalised coupled power P_c/P_t with refractive index

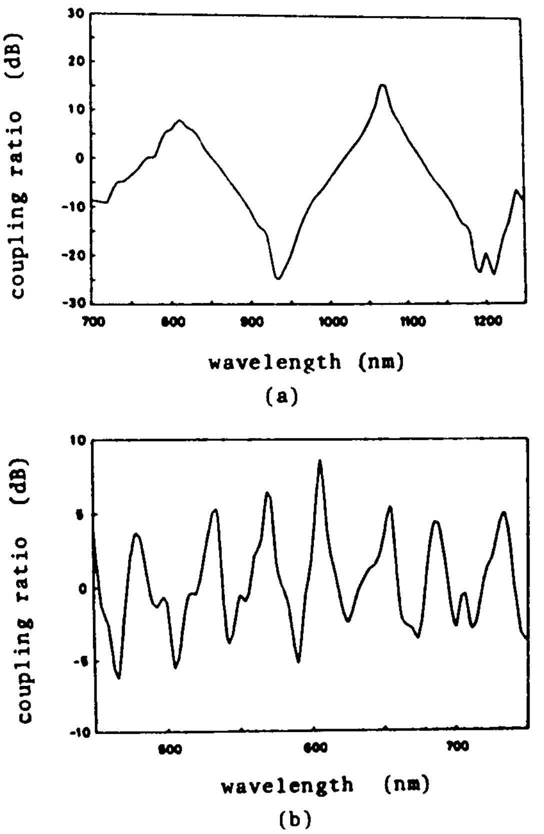

Figure 4 Wavelength dependence of power splitting ratio (10 log (P_c/P_t)) for fibres A and B