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A NEW IDEA FOR WAVELENGTH-INSENSITIVE FIBRE COUPLERS

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Introduction

Wavelength-insensitive single-mode optical fibre couplers are useful components in spectral measurements and will be important in future wavelength-multiplexed optical fibre networks.

In a normal single-mode fibre coupler, the power transfer between two fundamental modes of each fibre can be considered as interference between the first two normal modes in the composite waveguide[1]. Since the difference between the propagation constants of the normal modes is wavelength-insensitive, the power division between the coupling arm and the throughput arm is also sensitive to wavelength change.

In our new scheme, the propagation constants of the fundamental modes in each fibre are unequal and the difference between them, as well as the coupling coefficient, varies slowly along the coupler. Only the first mode in the composite waveguide is excited significantly, while the second mode is either negligibly excited or is cut-off[2].

Due to absence of interference, the power division between the two arms depends only on the power distribution of the first mode in the composite waveguide at the end of the coupler, which is wavelength-insensitive. If at the end of coupler the two coupled-fibres are identical, then a 3dB wavelength-independent coupler results.

Theory

Two parallel fibres are brought close to each other to cause coupling between the HE_{11} modes in both fibres as shown in Fig. 1, where A_1 and A_2 denote the amplitudes of HE_{11} modes in fibre 1 and 2 respectively. In the coupling region, the coupling between both modes can be described as[3]

$$\frac{dA_1}{dz} \; -j\beta_1 A_1 - jCA_2$$
$$\frac{dA_2}{dz} \; -j\beta_2 A_2 - jCA_1 \qquad (1)$$

where C, β_1 and β_2 are functions of z. We assume that these functions vary slowly with z, which may be realised in coupler design.

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We introduce local modes for the composite waveguide in the coupling region, the amplitudes of which, W_1 and W_2, relate to A_1 and A_2 as follows

$$A_1 = W_1 \cos\psi - W_2 \sin\psi$$
$$A_2 = W_1 \sin\psi + W_2 \cos\psi \qquad (2)$$

where

$$\psi = \frac{1}{2} \arctan \frac{2C}{\beta_1 - \beta_2} = \frac{1}{2} \arctan \frac{2C}{\Delta\beta} \qquad (2a)$$

Inserting (2) into (1), we have

$$\frac{dW_1}{dz} = -j_1 h_1 W_1 + \frac{d\psi}{dz} W_2$$
$$(3)$$
$$\frac{dW_2}{dz} = -j h_2 W_2 - \frac{d\psi}{dz} W_1$$

where

$$h_{1,2} = \frac{\beta_1 + \beta_2}{2} \pm \frac{\Delta\beta}{2} \sqrt{1 + \left(\frac{2C}{\Delta\beta}\right)^2} \qquad (4)$$

The coupling betwen the two local modes can be neglected, if the following condition is satisfied

$$\left| \frac{1}{h_1 - h_2} \frac{d\psi}{dz} \right| \ll 1 \qquad (5)$$

this is the criterion for slow variation. Then (3) can be approximated by two independent equations.

If at the input the fundamental mode with unit amplitude is incident only on fibre 1, then at $z=0$, we have $A_1=1$, $A_2=0$. From (2) it is simple to find that the terminal conditions for W_1 and W_2 are

$$W_1(0) = 1, \quad W_2(0) = 0 \qquad (6)$$

provided $C=0$ (or $|\Delta\beta| \gg C$) at $z=0$.

Since condition (5) is satisfied in the coupling region $0<z<L$, the magnitudes of W_1 and W_2 are almost the same as at the input. Thus at the output $z=L$, we have

$$|A_1(L)| = \cos\psi_0$$
$$(7)$$
$$|A_2(L)| = \sin\psi_0$$

where ψ_0 is determined by (2a) with $C(L)$ and $\beta_1(L)-\beta_2(L)$. If $\Delta\beta(L) = 0$ or $|\Delta\beta(L)| \ll C$, then $|\psi_0| = 45^\circ$ and

$$|A_1(L)|^2 = |A_2(L)|^2 = \frac{1}{2} \qquad (8)$$

which implies that a 3dB coupler is formed.

Therefore a wavelength-insensitive coupler can be realised, provided that: (1) $C=0$ or $C \ll |\Delta\beta|$ at $z=0$ and outside the coupling region; (2) $\Delta\beta(z)$ and $C(z)$ vary slowly so that equation (5) is satisfied in the region $0<z<L$.

Since the $C(z)$ and $\Delta\beta(z)$ functions are not specified stringently, it seems that these requirements are not difficult to fulfil.

Design

A possible scheme for a 3dB wavelength-insensitive coupler is shown in Fig. 2. Two single-mode D-fibres are fused together to form the coupler[4]. Before fusing, the lower fibre is heated and extended to form a taper with V value of 1.2-1.5 at the waist. The cross-sectional dimensions of the upper fibre of the coupler are constant and it has a V value of 2.2-2.4. The core diameter of the lower fibre is changed such that the smallest diameter of this fibre is located at the beginning of the coupler ($z=0$) and varies slowly along z until it reaches the same diameter as the upper fibre at the output end ($z=L$). These two fibres are then put into a capillary and fused together.

In the design, a step-index fibre with relative index change $\Delta = 0.3\%$ is used, and the core/flat distance of the D-fibre is about 1μm. It is simple to evaluate the coupling coefficient between the fundamental modes[1,3] at an operating wavelength of 633nm. It is found from the estimated result shown in Fig. 3 that the coupling changes slowly along z, while we require a much lower coupling coefficient at $z=0$. It is possible to solve this problem by rotating the lower fibre about 20°-30° at the waist. Since the distance between the two cores increases, the coupling is greatly reduced. A possible result is shown by the dashed line in Fig. 3. The $\Delta\beta(z)$ function can also be calculated if the change of the core diameter in the lower fibre is known. It has been estimated and is shown in Fig. 3.

Finally, the criterion for slow variation is used to evaluate the minimum length of the coupler to maintain wavelength independence. Using (2a) and (4) in (5), we have

$$\left|\frac{1}{h_1-h_2}\frac{d\psi}{dz}\right| = \left|\Delta\beta\frac{dC}{dz} - C\frac{d\Delta\beta}{dz}\right| [\Delta\beta^2+(2C)^2]^{-3/2} \qquad (9)$$

Since (9) has its maximum at $z=L$, we evaluate it at this point. If we take $C \approx 1$ 1/mm, eqn. (5) will be fulfilled if $L \geq 40$mm.

Conclusion

Wavelength-insensitive couplers have been shown as theoretically feasible. It should be possible to realise them in D-fibre couplers or polished single-mode couplers. The principle may also be used to construct wavelength-insensitive couplers in integrated optics.

Acknowledgements

The author wishes to thank Dr. C.D. Hussey, Dr. F.P. Payne, Dr. J.S. Wilkinson and Mr. M. Yataki for fruitful discussion in this work.

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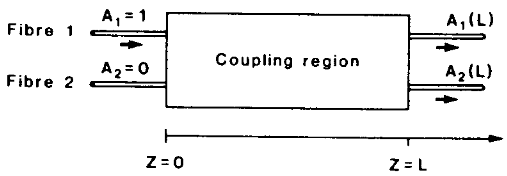

Fig. 1   An optical fibre coupler.

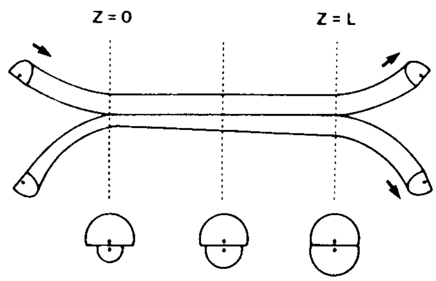

Fig. 2   A scheme of a 3dB wavelength insensitive D-fibre coupler.

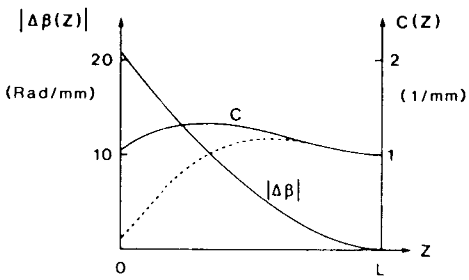

Fig. 3   Possible variations of C(z) and $\Delta\beta(z)$ along z.