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Cladding effects on silica directional couplers

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Abstract

Directional couplers are widely used as passive and active optical devices in fibre and integrated optics, and form the basis of components such as switches, modulators and wavelength filters. They consist of two closely-spaced parallel waveguides, whose separation is sufficiently small that power may be transferred between the modes propagating in the two guides through an interaction involving their evanescent fields. In this paper results are presented for a range of near infrared single mode silica directional couplers fabricated by electron beam irradiation. The effects of over cladding layers will be highlighted. Changes on coupling coefficient due to different cladding refractive indexes will also be examined. The coupled mode theory will be employed to fit the experimental results with prediction by theory. It is found that over cladding layer alters the transmission characteristics of silica directional couplers.

Keywords: *coupled mode theory, coupling coefficients, directional couplers, silica*

1. Introduction

Integrated optics has been an active field of research for the past two decades. During this time, considerable progress has been developed toward realizing high-performance optical devices using guided-wave technique [1-5]. One device that has received considerable attention because of its versatility in performing several important communications function is the directional couplers [6-8].

The directional coupler consists of two closely-spaced parallel waveguides, whose separation is sufficiently small that power may be transferred between the modes propagating in the two guides through an interaction involving their evanescent fields. In a conventional coupler, light exchanges sinusoidally between the two guides as it propagates. The required coupling coefficient is determined by the propagation constant difference between the two lowest order modes. However, all directional couplers have intrinsic wavelength dependence in their coupling ratio, which is very sensitive to parameters such as guide width, guide separation, refractive index difference and coupling length. Changes in these parameters can cause a large change in the power splitting ratio. The performance of optical waveguide directional couplers is commonly analyzed by solving a set of coupled-mode equations [9-12]. In this case of parallel-waveguide couplers, the coupling coefficients are constants and independent of the coordinate along the direction of wave propagation, and thus analytical solutions of such equations might be obtained [13]. In a practical coupler, however, the waveguide often have nonuniform spacing along the propagation direction, for example the fiber may be curved in an optical fiber coupler, resulting in a variable spacing between the two fibers. Consequently, the coupling coefficients will be functions of the position along the waveguide-coupling region. As the spacing between the waveguides varies slowly and gradually, the coupled-mode analysis based on weak guiding approximation would be a good approach [14-16].

2. Coupled Mode Theory

A method of analysis that can give analytic results for a directional coupler known as coupled mode theory. This is a perturbation approach that centers on the phase relationship and the mode overlap between the two-coupled guides. The theory is useful in providing a

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rational but oversimplified description of the field interaction and power transfer process, and can provide analytic solution in many cases of interest. In the coupled mode formulation, the total refractive index variation of the coupled system is considered as a combination of the index distributions of the two isolated guides, so we may write [11]:

$$n_T(x,y)=n_1(x,y)+n_2(x,y)-n_s(x,y) \tag{1}$$

where $n_T(x,y)$ is the total refractive index, $n_1(x,y)$ and $n_2(x,y)$ are the refractive index distributions of the two isolated guides, and $n_s(x,y)$ is the substrate index variation. An orthogonal coupled mode formulation is derived from a complex power theorem [12]. Suppose that each guide supports only one guide mode and the field of the coupler can be expressed in term of linear combination of the two-guide modes propagation in the same direction [13],

$$\psi(x,y,z)=A(z)\psi_1(x,y)e^{-j\beta_1 z}+B(z)\psi_2(x,y)e^{-j\beta_2 z} \tag{2}$$

where $\psi(x,y,z)$ is the field of the coupler, $\psi_1(x,y)$, $\psi_2(x,y)$ represent the two transfer field of guide 1 and 2 respectively, $A(z)$ and $B(z)$ are the amplitudes of the mode in guide 1 and 2 respectively. This approximation is valid when the two waveguides are not strongly coupled. The mode amplitudes *A* and *B* are determined by a coupled-mode equation, and is given by [11, 12]:

$$\begin{aligned}\frac{dA}{dz}&=-j[\Delta\beta_1 A+\mathrm{K}_{12}B]\\ \frac{dB}{dz}&=-j[\Delta\beta_2 B+\mathrm{K}_{21}A]\end{aligned} \tag{3}$$

where the additional transformation $A_1(z)=a_1(z)exp(j_oz)$; $A_2(z)=a_2(z)exp(j_oz)$ have been carried out, and the term $\Delta\beta_1=\beta_1-\beta_o$ and $\Delta\beta_2=\beta_2-\beta_o$ each represent a small difference in propagation constant from a reference value of ${}_o$ [5]. Here, we have neglected the additional self-coupling ${}_{11}$ and ${}_{22}$, since the conventional coupling coefficients ${}_{12}$ and ${}_{21}$ are normally much greater. The coupling coefficient ${}_{12}$ and ${}_{21}$ themselves are given by [10]:

$$\mathrm{K}_{ij}=\left(\frac{k_o^2}{2\beta_o}\right)\left\langle(n_T^2-n_1^2)E_i,E_j^*\right\rangle \tag{4}$$

here *i,j*=1,2. Figure 1 shows the variation of the coupling coefficient K_{12} with separation for coupled waveguides where typical values of n_1=1.465, n_2=1.458 and *h*=7 m have been assumed, these parameters are typical for silica-on-silicon waveguides. As can be seen, the coupling coefficient decays approximately exponentially as the inter waveguide gap increases. For two waveguide systems, the coupled mode solution of (3) can be shown to be [5]:

$$\begin{aligned}A(z)&=[\cos(\xi z)+j\frac{\delta}{\xi}\sin(\xi z)]\exp(-j\gamma z)\\ B(z)&=[-j\frac{\delta}{\xi}\sin(\xi z)]\exp(-j\gamma z)\end{aligned} \tag{5}$$

where the parameters ξ, δ, γ, are given by

$$\begin{aligned}\xi&=\sqrt{\delta^2+\mathrm{K}^2}\\ \delta&=\frac{(\Delta\beta_1-\Delta\beta_2)}{2}\\ \gamma&=\frac{(\Delta\beta_1+\Delta\beta_2)}{2}\end{aligned} \tag{6}$$

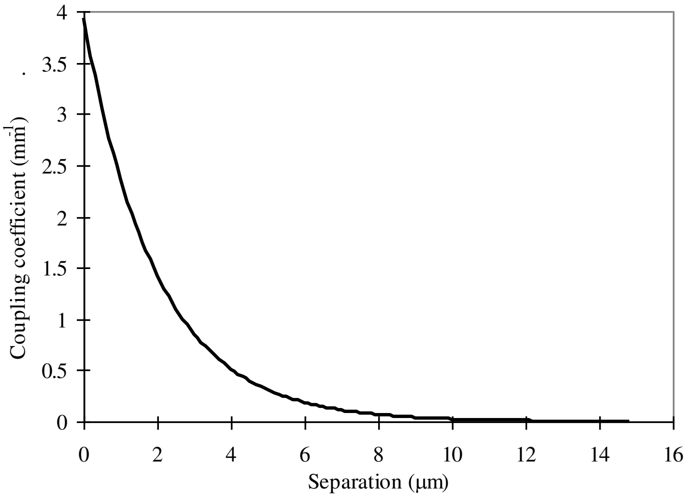


Figure 1. Variation of the coupling coefficient of a silica-based directional coupler with separation as predicted by (4)

Here $\mathrm{K}_{12} = \mathrm{K}_{21} = \mathrm{K}$ has been assumed. The power distributions in waveguide 1 and 2, denoted by $P_1(z)$ and $P_2(z)$, respectively, are then defined as:

$$
\begin{aligned}
P_1(z) &= |A(z)|^2 = 1 - \frac{\mathrm{K}^2}{\xi^2}\sin^2(\xi z) \\
P_2(z) &= |B(z)|^2 = \frac{\mathrm{K}^2}{\xi^2}\sin^2(\xi z)
\end{aligned}
\tag{7}
$$

as shown in (7), that the power transfers back and forth between the modes in the two guides as an oscillatory function of length, as shown in Figure 2. Complete power transfer from guide 1 to guide 2 occurs at the point $z = \frac{\pi}{2\mathrm{K}}$. It also occurs when $z = \frac{3\pi}{2\mathrm{K}}, \frac{5\pi}{2\mathrm{K}}$ and so on.

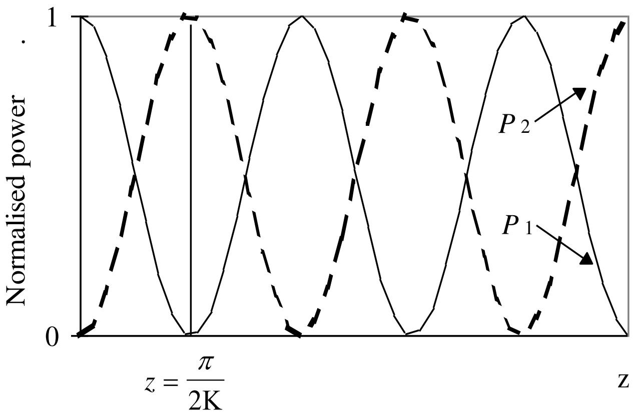


Figure 2. Variation of power in the two guides of a synchronous directional coupler with distance *z*

An important application of a directional coupler is an optical switch [15]-[17]. Suppose that a coupler is based on two identical waveguides and is chosen to have a length $L_c = \frac{\pi}{2K}$. In this case, energy launched into one waveguide will totally transfer to the other guide. This condition referred to as the coupled state. If now by some means we can introduce a finite difference between the two guides, the power will instead emerge from the first guide. This condition is referred to as the straight through state. By varying δ electrically we can switch the light energy from one waveguide to the other. This is the basic principle behind the directional coupler switch.

3. The Experimental Setup

The experimental setup for a single-point measurement of optical power transfer is shown in Figure 3. It consists of a laser with a wavelength of 1.523 m launched into a standard 8/125 m single mode fibre optics. A wavelength independent fused coupler used to provide a reference to allow changes in laser output [15]. A/2 plate was used to rotate the TE and TM mode polarisation, so that both modes could be launched. All the waveguides fabricated were single-moded. Two detectors and two lock-in amplifiers were used, and the transmitted intensity was normalised to the direct laser output.

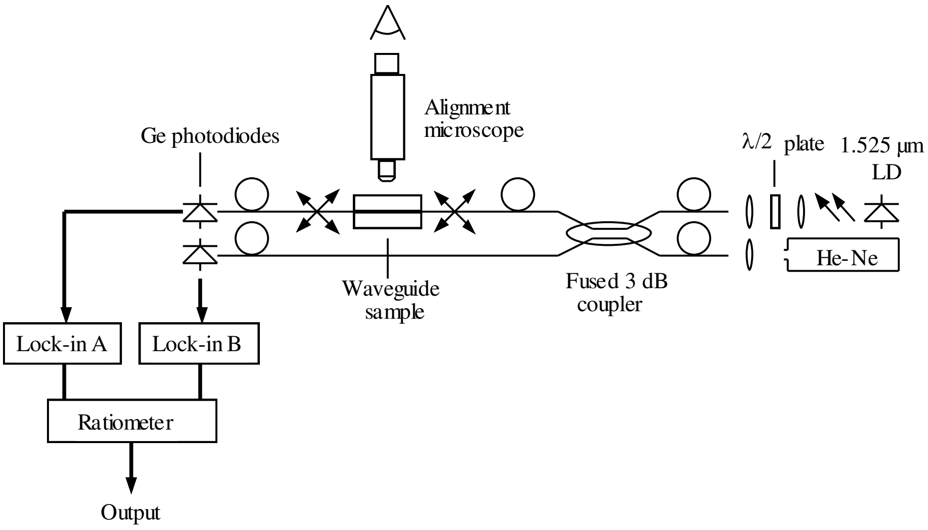


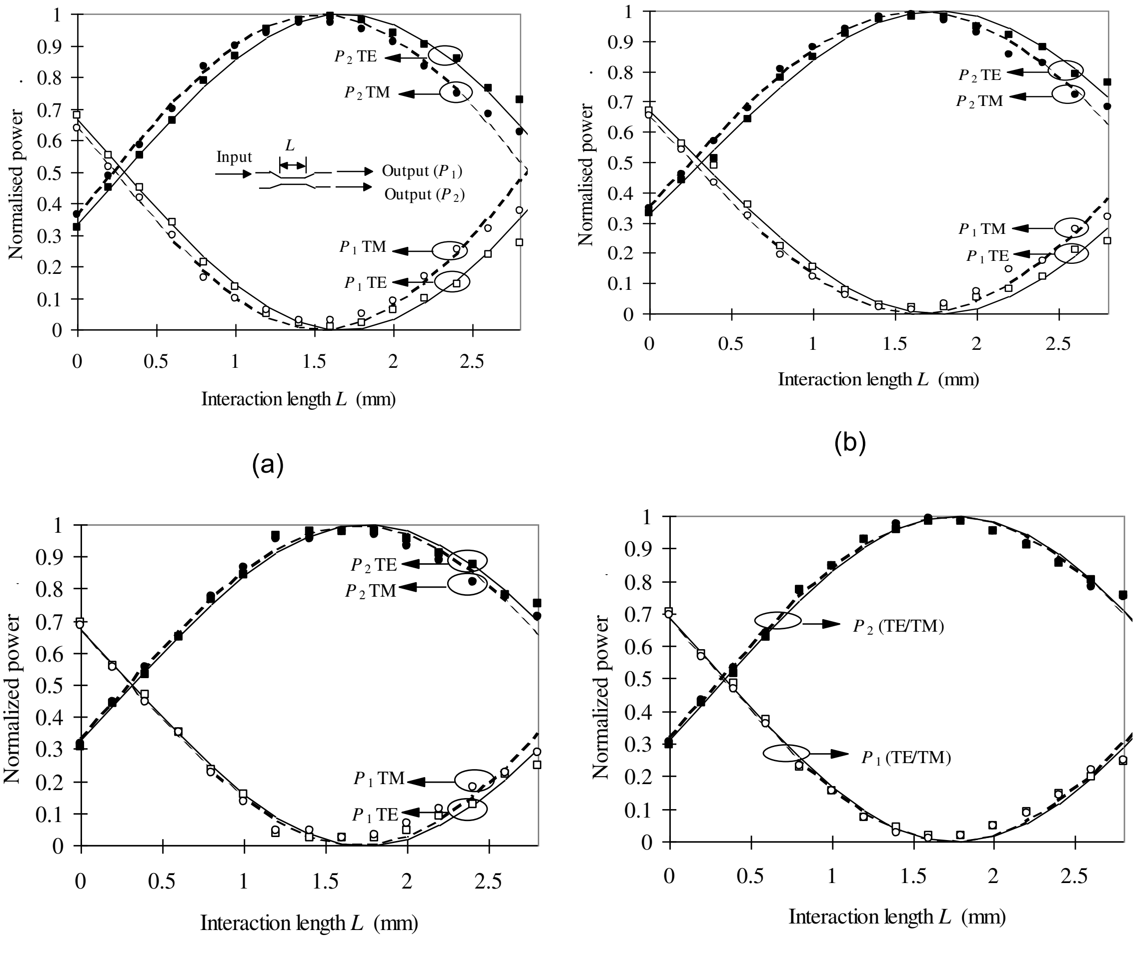
Figure 3. The experimental set-up used to measure power transfer in directional couplers, after reference [15]

The fibre-device-fibre power transfers were measured with manually optimised butt-coupling between the fibre and the devices. The exposed surface of the directional coupler was covered by a layer of oil with different refractive indexes.

4. Effects of Over Cladding Layers

In the experiments, all the couplers were made using electron beam irradiation method. Details of fabrication procedure can be found elsewhere [15-17]. The coupling length varying between 1 mm to 5 mm. The overall chip length was 3.4 cm. Parameters were chosen for a low loss coupling to a single-mode optical fiber, with a guide width of 7 m.

To observe the guiding characteristic of irradiated waveguides, we considered the effect of different cladding layers using silicone oils with indices in the range of 1.40-1.45. Two different waveguide separations were used. The first type (identified as sample BNR 2) had an inter-guide separation of 6 m and the second type (sample BNR 3) one of 7 m. Figures 4 (a), (b), (c), (d) show a range of measurements obtained with different cladding refractive indices for the BNR 2 sample. In each case, the variation of straight through and cross-coupled power at=1.523 m with interaction length is shown. The data points have been matched to the theoretical prediction of (7).



(a)

(b)

(c)

(d)

Figure 4. Measurements of cross-coupled and straight through power in a directional coupler (BNR 2) with oil cladding layers of index (a) 1.40, (b) 1.43, (c) 1.44, (d) 1.45. Points are experimental data; lines represent best theoretical fits to (7)

The effect of variation in the cladding layer index is to change the power transfer and polarization characteristic of directional couplers. For instance, at a cladding refractive index of 1.4, the TE and TM mode characteristics are very different. As the cladding index increases, the TE and TM characteristics become more and more similar, and at a refractive index of 1.45, polarization-independent operation is obtained. Clearly, the underlying reason for polarization dependence is the introduction of structural asymmetry by the use of a poorly matched cladding [18-22]. However, the effect is relatively small even for a cladding index as low as 1.40, because the guides are almost completely buried in silica [23]

An additional effect is a slow increase in the coupling length with the index of the cladding [24, 25]. Similar measurements were also performed using the other design of directional coupler (sample BNR 3), which has a larger inter-guide separation. A similar characteristic to that of BNR 2 also appeared as the cladding refractive index increases, as can be seen in Figure 5, which shows a comparison of the coupling coefficients of BNR 2 and BNR 3 as a function of the cladding refractive index.

The results show that the coupling coefficient of BNR 2 is higher than that of BNR 3. This effect is comparable to the prediction of (4), which suggests an exponential variation between the coupling coefficient and the waveguide separation.

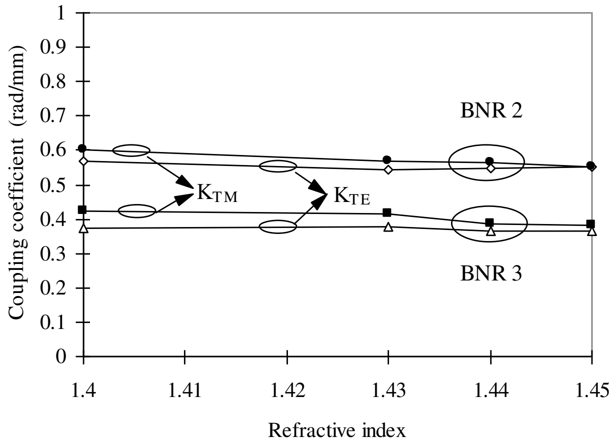


Figure 5. Variation of the coupling coefficient of two different directional couplers with the refractive index of the upper cladding layer

5. Conclusions

In conclusion, we have presented effects of different upper cladding layers on polarization and power output of directional couplers. Output characteristics of directional couplers are depend on upper cladding layers refractive index, the higher the cladding refractive index the lower the polarization splitting because the waveguides becomes a weakly guiding structures. Based on this phenomenon we can design the directional couplers to be polarization independent couplers as one of the important devices for switching purposes. Furthermore, the coupled mode theory can be used to fetch the coupling characteristic of directional coupler at different over cladding refractive index. It shows that the higher the distance between two waveguides the lower the coupling coefficient is which is consistent with the theoretical prediction.

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