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Improved Extinction Ratios for Both Cross and Bar States Using Two-Section Ultra Short Vertical Directional Couplers

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We show that both cross and bar states with high extinction ratios larger than 30 dB can be achieved in ultra short vertical directional couplers with two sections. Various combinations of the refractive indices in the two sections are studied using the improved coupled mode theory and the beam propagation method. Design guidelines to achieve high extinction ratios with large tolerances are presented.

KEYWORDS: vertical directional coupler, extinction ratio, optical switch, asymmetric coupler, wafer fusion

1. Introduction

Compact directional couplers are critical components in photonic integrated circuits used in optical communication systems. Major requirements are low loss, scalability, low polarization dependence, and high extinction ratio.

Conventional directional couplers with laterally arranged waveguides cannot achieve very short coupling lengths because of technological limitations to produce uniformly very narrow gap layers.[1)] However, vertical directional couplers provide a short coupling length which can be less than 100 μm.[2)] The difficulty of separating the two vertically coupled waveguides into two distinct inputs and outputs limits the applications of these devices. Recently, a novel fused vertical coupler (FVC) with a very short coupling length of 62 μm was demonstrated.[3)] Since the technique of wafer fusion can be used to combine waveguides fabricated on two different substrates into three dimensional structures, the problem of waveguide separation can be solved. To use FVC in large switching fabrics, it should have high extinction ratios for both cross and bar states. Ultra short directional couplers have an inherent limitation in their extinction ratio due to nonorthogonality of individual waveguide modes.[4)]

It is reported that vertical directional couplers with 10–200 μm coupling length and with high extinction ratios larger than 30 dB for the cross state can be achieved in one-section vertical directional couplers.[5)] However, the extinction ratios larger than 30 dB for the bar state cannot be achieved in these structures. In order to use vertical directional couplers as optical switching elements, high extinction ratios for both bar and cross states are needed. In this paper, we show that one can achieve this using vertical directional couplers with two sections.

This paper is organized as follows. In §2, improved coupled mode theory (ICMT) and transfer matrix method are briefly described for the vertical directional couplers with two sections. In §3, ICMT and 2D finite beam propagation method (BPM) are used to analyze two-section vertical directional couplers. We will see how one can achieve high extinction ratios in the cross state at the end of section 1 using slight asymmetry in core waveguide indices and how one can get high extinction ratios in the bar state at the end of section 2 with a symmetric second section. The design guidelines and tolerances to achieve high extinction ratios larger than 30 dB are presented. Finally, an example of a fused vertical coupler switch that achieves high extinction ratios for both bar and cross states at the end of the device is presented. The conclusions will be given in §4.

2. Improved Coupled Mode Theory and Transfer Matrix Method in Vertical Directional Couplers with Multisection

The improved coupled mode equations in the ith segment of a two-section vertical directional coupler shown in Fig. 1 are given by[6)]

$$\frac{d}{dz}a^{(i)}(z) = -i\gamma_{(a)}^{(i)}a^{(i)}(z) - ik_{ab}^{(i)}b^{(i)}(z) \tag{1}$$

$$\frac{d}{dz}b^{(i)}(z) = -ik_{ba}^{(i)}a^{(i)}(z) - i\gamma_{(b)}^{(i)}b^{(i)}(z) \tag{2}$$

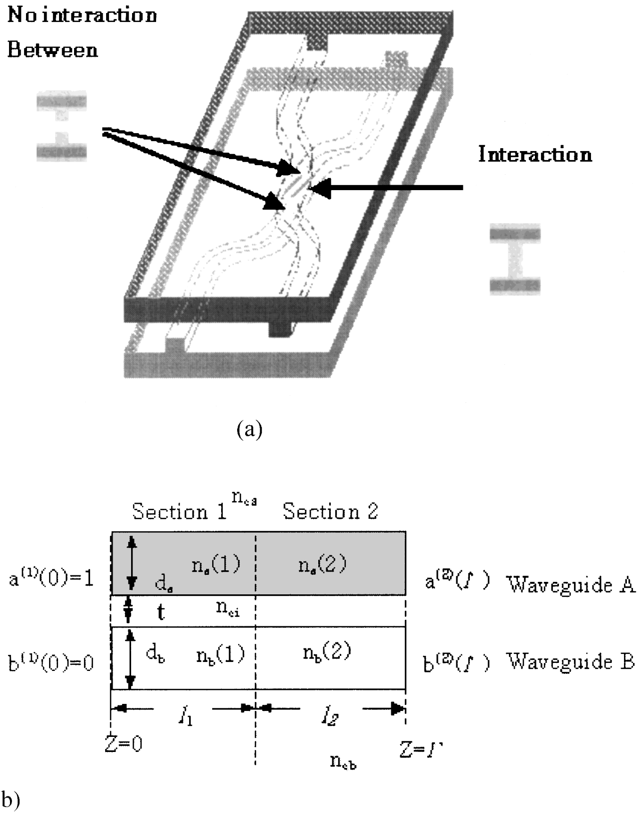

Fig. 1. (a) Fused vertical couplers with separated input and output waveguides. (b) Schematic diagram of one-dimensional index profile in the straight interaction regions of fused vertical couplers with two sections.

where

$$\gamma_{(a)}^{(i)} = \beta_a^{Oi)} + \frac{K_{aa}^{(i)} - C_{(i)}K_{ba}^{(i)}}{1 - C_{(i)}^2},$$

$$\gamma_{(b)}^{(i)} = \beta_b^{Oi)} + \frac{K_{bb}^{(i)} - C_{(i)}K_{ab}^{(i)}}{1 - C_{(i)}^2},$$

$$k_{ab}^{(i)} = \frac{K_{ab}^{(i)} - C_{(i)}K_{bb}^{(i)}}{1 - C_{(i)}^2},$$

$$k_{ba}^{(i)} = \frac{K_{ba}^{(i)} - C_{(i)}K_{aa}^{(i)}}{1 - C_{(i)}^2},$$

$$K_{ab}^{(i)} = \frac{\omega}{4}\iint \Delta\varepsilon_{(q)}^{(i)}\left[\boldsymbol{E}_{t,a}^{(i)} \cdot \boldsymbol{E}_{t,b}^{(i)} - \boldsymbol{E}_{z,a}^{(i)} \cdot \boldsymbol{E}_{z,b}^{(i)}\right] dxdy,$$

$$C_{(i)} = \frac{C_{ab}^{(i)} + C_{ba}^{(i)}}{2},$$

$$C_{ab}^{(i)} = \frac{1}{2}\iint \boldsymbol{E}_{t,b}^{(i)} \times \boldsymbol{H}_{t,a}^{(i)} \cdot \hat{z}dxdy,$$

$$C_{ba}^{(i)} = \frac{1}{2}\iint \boldsymbol{E}_{t,a}^{(i)} \times \boldsymbol{H}_{t,b}^{(i)} \cdot \hat{z}dxdy,$$

$\boldsymbol{E}_{t,a}^{(i)}$ and $\boldsymbol{H}_{t,a}^{(i)}$ and $\boldsymbol{E}_{t,b}^{(i)}$ and $\boldsymbol{H}_{t,b}^{(i)}$ are the transverse electric and magnetic fields of waveguides A and B in the ith section, respectively. And $a^{(i)}(z)$ and $b^{(i)}(z)$ are the mode amplitudes of waveguides A and B in the ith section, respectively.

The mode amplitudes at the end of section 2 of waveguides A and B, $a^{(2)}(L)$ and $b^{(2)}(L)$, can be expressed by the transfer matrix and are related to the mode amplitudes of waveguides A and B at the input of section 1, $a^{(1)}(0)$ and $b^{(1)}(0)$, as follows:

$$\begin{bmatrix} a^{(2)}(L) \\ b^{(2)}(L) \end{bmatrix} = T^{(2)}T^{(1)} \exp\left[-i\left(\phi^{(1)} + \phi^{(2)}\right)\right] \begin{bmatrix} a^{(1)}(0) \\ b^{(1)}(0) \end{bmatrix}. \tag{3}$$

where the transfer matrix in the ith section is given by

$$T^{(i)} = \begin{bmatrix} \cos\psi^{(i)}l^{(i)} + i\dfrac{\Delta^{(i)}}{\psi^{(i)}}\sin\psi^{(i)}l^{(i)} & -i\dfrac{k_{ab}^{(i)}}{\psi^{(i)}}\sin\psi^{(i)}l^{(i)} \\ -i\dfrac{k_{ba}^{(i)}}{\psi^{(i)}}\sin\psi^{(i)}l^{(i)} & \cos\psi^{(i)}l^{(i)} - i\dfrac{\Delta^{(i)}}{\psi^{(i)}}\sin\psi^{(i)}l^{(i)} \end{bmatrix}. \tag{4}$$

where

$$\Delta^{(i)} = \frac{\gamma_b^{(i)} - \gamma_a^{(i)}}{2},$$

$$\psi^{(i)} = \sqrt{\Delta^{(i)2} + k_{ab}^{(i)}k_{ba}^{(i)}},$$

and $l^{(i)}$ is the length of each section.

The output power at the end of each section for waveguides A and B, $P_a^{(i)}$ and $P_b^{(i)}$, are given by

$$P_a^{(i)} = \mathrm{Re}[(a^{(i)}(l^{(i)}) + C_{ab}^{(i)}b^{(i)}(l^{(i)}))(a^{*(i)}(l^{(i)}) + C_{ab}^{*(i)}b^{*(i)}(l^{(i)}))] \tag{5}$$

$$P_b^{(i)} = \mathrm{Re}[(C_{ba}^{(i)}a^{(i)}(l^{(i)}) + b^{(i)}(l^{(i)}))(C_{ba}^{*(i)}a^{*(i)}(l^{(i)}) + b^{*(i)}(l^{(i)}))]. \tag{6}$$

3. Results and Discussions

Figure 1(a) shows the FVC with separated input and output waveguides. Since the two waveguides are brought together with an air gap except the interaction region, this could minimize unwanted couplings for the separation of the output of the FVC. Since two-dimensional index profile of FVCs such as ridge waveguides can be reduced to one dimension using the effective index method, the schematic diagram of a one-dimensional index profile in the straight coupling region of vertical directional couplers with two sections is shown in Fig. 1(b). The parameter values used in our calculations are as follows. The refractive indices of three cladding layers are $n_{ca} = n_{cb} = n_{ci} = 3.17$, the thicknesses of both waveguides A and B are $d_a = d_b = 0.5\,\mu$m, the thickness of inner cladding layer is $t = 0.6\,\mu$m, and the wavelength is 1.55 μm, respectively. The results for TE mode are presented because the results of TM mode are similar to those of TE mode. The transfer matrix method and ICMT are used to analyze these structures and the results are compared with those of 2D finite difference BPM. Assuming that the power is incident into the waveguide A, without the loss of generality, the extinction ratio of cross and bar states of the section i is defined as $P_b^{(i)}/P_a^{(i)}$ and $P_a^{(i)}/P_b^{(i)}$, respectively, where $P_a^{(i)}$ and $P_b^{(i)}$ are the guided mode powers at the end of each section of waveguides A and B, respectively.

Figure 2 shows the extinction ratio of bar and cross states for TE mode at the coupling length and twice of coupling

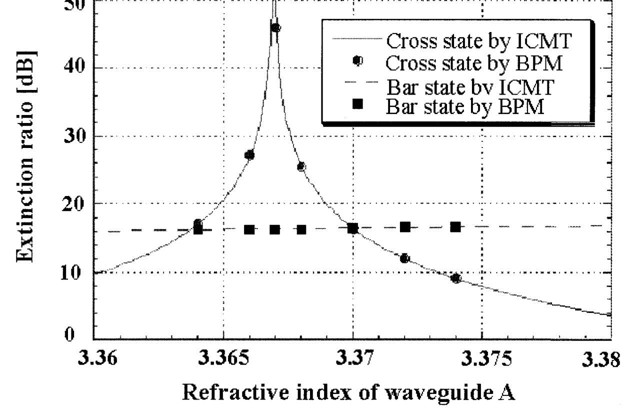

Fig. 2. The extinction ratio of bar and cross states for TE mode at the coupling length and twice of coupling length, respectively, as a function of the refractive index of waveguide A in one-section fused vertical couplers.

length, respectively, as a function of the refractive index of waveguide A in one-section fused vertical couplers. The refractive index of waveguide B, n_b, is 3.37. The coupling length is 51 μm when the refractive index of waveguide A is 3.367 giving the maximum extinction ratio. One can see that the extinction ratios larger than 30 dB for both cross and bar states cannot be achieved using symmetric one-section vertical couplers. Also, high extinction ratios only for the cross state can be achieved in asymmetric one-section vertical couplers.

Figure 3 shows the extinction ratio of bar state (Θ) for TE mode at the end of section 2 as a function of the refractive index of waveguide A in that section, $n_a(2)$. Section 2 is 52 μm long and $n_b(1) = n_b(2) = 3.37$. The refractive index of waveguide A in section 1, $n_a(1)$, is chosen to be 3.367 to have a 66 dB extinction ratio for cross state ($\otimes$) at the end of section 1 ($l_1 = 51\,\mu$m). The tolerance of the refractive index of waveguide A which gives a extinction ratio larger than 30 dB for the cross state at the end of section 1, $\Delta n_a(1)|_{>30\,\mathrm{dB}}$, is 0.0012.[5] The solid line and circle represent the results of ICMT and BPM, respectively. The results calculated by ICMT agree very well to those by BPM. Similar to the case of the cross state at the end of section 1, the tolerance of the refractive index of waveguide A in section 2 which gives the extinction ratio larger than 30 dB for the bar state at the end of section 2, $\Delta n_a(2)|_{>30\,\mathrm{dB}}$, is 0.0012. The extinction ratio for the cross state can be maximized by the interference between the even and odd supermodes if there is slight asymmetry in two waveguides of vertical directional couplers with one section.[5] In this case the refractive index of waveguide B is slightly larger than that of waveguide A in which the power is launched. However, as can be seen in Fig. 3, the maximum extinction ratio of bar state is obtained when the refractive indices of both waveguides in section 2 are the same.

Table I shows the refractive index of waveguide A in section 2 with the maximum extinction ratio of bar state at the end of section 2 for various values of that in section 1 with the extinction ratio larger than 30 dB of cross state at the end of section 1. We can see that the difference between the former and the latter, $n_a(2)|_{\mathrm{max,dB}} - n_a(1)|_{>30\,\mathrm{dB}}$, is about 0.003 irrespective of the value of the refractive index of waveguide A in section 1. Since the amplitudes of optical field at the end of section 1 are inputs to section 2, the extinction ratio of bar state at the end of section 2 is influenced not only by the difference between the refractive indices of two waveguides in section 1 but also by the difference between the refractive index of waveguide A in section 1 and that of waveguide A or B in section 2.

Table I. The refractive index of waveguide A in section 2 with the maximum extinction ratio of bar state at the end of section 2 for various values of that in section 1 with the extinction ratio larger than 30 dB of cross state at the end of section 1.

Section 1		Section 2	
$n_a(1)$	Extinction ratio of $\otimes$	$n_a(2)$	Extinction ratio of Θ
3.3663	30 dB	3.3694	79 dB
3.3667	40 dB	3.3698	86 dB
3.3669	66 dB	3.3699	93 dB
3.3671	40 dB	3.3702	79 dB
3.3675	30 dB	3.3705	96 dB

Figure 4 shows the extinction ratio of the bar state (Θ) for TE mode at the end of section 2 of 103 μm as a function of the refractive index of waveguide B in section 2, $n_b(2)$, when $n_a(2) = 3.37$, and the same parameters in section 1 of Fig. 3. We can see that Fig. 3 is almost a mirror image of Fig. 2 with respect to the refractive index of waveguide of 3.37. In Figs. 3 and 4, we can see that the maximum extinction ratio of bar state occurs when the refractive indices of both waveguides in section 2 are equal to that of waveguide B in section 1 in which the power is not launched. Also, the extinction ratio of bar state decreases as the difference of refractive index be-

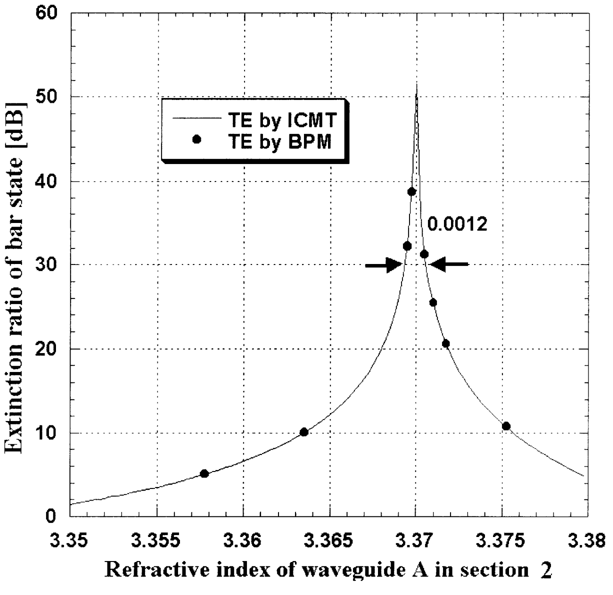

Fig. 3. The extinction ratio of the bar state (Θ) for TE mode at the end of section 2 of 103 μm as a function of the refractive index of waveguide A in section 2, $n_a(2)$, when $n_b(1) = n_b(2) = 3.37$. The refractive index of waveguide A in section 1, $n_a(1)$, is chosen to be 3.367 to have the extinction ratio of cross state ($\otimes$) of 66 dB at the end of section 1.

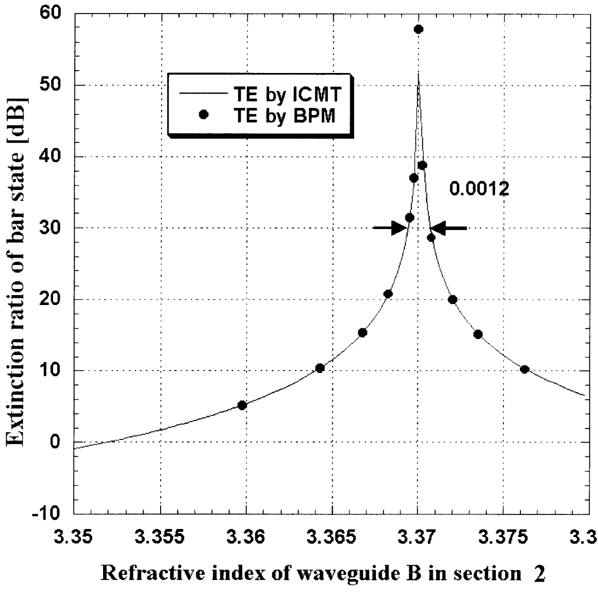

Fig. 4. The extinction ratio of the bar state (Θ) for TE mode at the end of section 2 of 103 μm as a function of the refractive index of waveguide B in section 2, $n_b(2)$, when $n_a(2) = 3.37$, and the same parameters in section 1 of Fig. 3.

tween both waveguides in section 2, $n_b(2) - n_a(2)$, increases.

In order to confirm the validity of the above results, we present the results of another case as follows. Figure 5 shows the extinction ratio of the cross state $(\otimes)$ for TE mode at the end of section 1 of $52\,\mu$m as a function of the refractive index of waveguide B in section 1 in which the power is not launched when the refractive index of waveguide A in section 1 is set to 3.37. The coupling length of $52\,\mu$m in this case is longer than that of section 1 (Fig. 2 of ref. 5) of Fig. 3. We can see that the maximum extinction ratio of cross state occurs at $n_b(1) = 3.373$. Similar to the case of Fig. 2 of ref. 5, the asymmetry defined by $n_b(1) - n_a(1)$ required to achieve the maximum extinction ratio of cross state is about 0.003 in section 1 and the tolerance of the refractive index of waveguide B in section 1 which gives the extinction ratio larger than 30 dB for cross state at the end of section 1, $\Delta n_b(1)|_{>30\,\mathrm{dB}}$, is 0.0012.

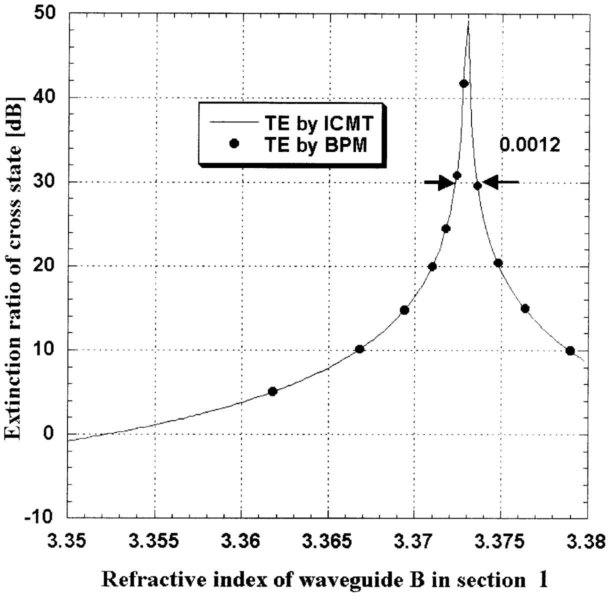

Fig. 5. The extinction ratio of the cross state $(\otimes)$ for TE mode at the end of section 1 of $52\,\mu$m as a function of the refractive index of waveguide B in section 1 in which power is not launched when the refractive index of waveguide A in section 1 is set to 3.37.

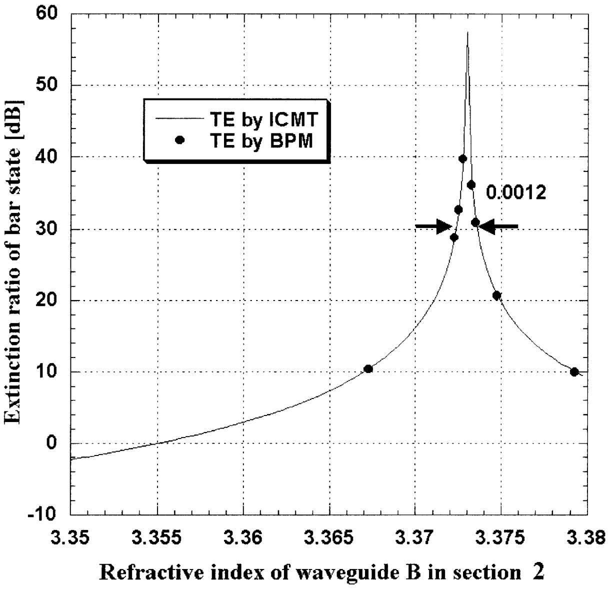

Fig. 6. The extinction ratio of the bar state (Θ) at the end of section 2 of $105\,\mu$m as a function of the refractive index of waveguide B in section 2 when $n_a(2) = 3.373$ and the parameter values of section 1 are equal to those which give the maximum extinction ratio of cross state in Fig. 5.

Figure 6 shows the extinction ratio of bar state (Θ) at the end of section 2 of $105\,\mu$m as a function of the refractive index of waveguide B in section 2 when $n_a(2) = 3.373$ and the parameter values of section 1 is chosen to give the maximum extinction ratio of cross state in Fig. 5. Similar to the case of Fig. 4, the maximum extinction ratio of bar state occurs when the refractive indices of both waveguides in section 2 are equal to that of waveguide B in section 1 in which the power is not launched. Also, the extinction ratio of bar states decreases as the difference of refractive index between both waveguides in section 2, $n_b(2) - n_a(2)$, increases and the tolerance of the refractive index of waveguide B in section 2 which gives the extinction ratio larger than 30 dB for bar state at the end of section 2, $\Delta n_b(2)|_{>30\,\mathrm{dB}}$, is 0.0012.

We can summarize the results to achieve both cross and bar states with high extinction ratios larger than 30 dB at the end of section 1 and 2, respectively, in two-section ultra short vertical directional couplers as follows. When the thickness of inner cladding layer is $0.6\,\mu$m, the asymmetry defined by $n_b(1) - n_a(1)$ required to achieve the maximum extinction ratio of cross state at the end of section 1 is about 0.003 and the refractive index of waveguide B is larger than that of waveguide A in which the power is launched. Also, the tolerance of the refractive index of waveguides in section 1 which gives the extinction ratio larger than 30 dB for cross state at the end of section 1 is about ± 0.0006 from the value at which the maximum extinction ratio occurs.

The maximum extinction ratio of bar state at the end of section 2 occurs when the refractive indices of both waveguides in section 2 are equal to that of waveguide B in section 1 in which the power is not launched. As the difference of refractive indices of both waveguides in section 2 increases, the extinction ratio of bar state decreases. The extinction ratio larger than 30 dB for bar state can be obtained when the refractive index difference of both waveguides in section 2 is within ± 0.0006 from the value at which the maximum extinction ratio occurs.

Thus, the design guidelines to achieve both cross and bar states with high extinction ratios larger than 30 dB at the end of section 1 and section 2, respectively, in vertical directional couplers with two sections are as follows. Proper asymmetry in refractive index of two waveguides is needed only in section 1 and the refractive indices of both waveguides in section 2 are the same as that of the waveguide in section 1 in which the power is not launched. And the difference of refractive indices of both waveguides in section 2 should be small.

In a real device, it is very difficult to use the output of the cross state at the end of section 1 and that of the bar state at the end of section 2. Following the design guidelines described above, we present an example of a two-section vertical coupler switch that has good extinction ratios for both bar and cross states at the same end of the device. The material parameters, doping profile and contact layers should be chosen so that the application of a bias at the fused layer will modify the refractive index of inner cladding layer between the two waveguide as well as the core index of one of the waveguides.

The high extinction ratio of the cross state is achieved by controlling the asymmetry in refractive index of waveguides for $n_a(1) = n_a(2)$ and $n_b(1) = n_b(2)$. Also, one can achieve the high extinction ratio of bar state with the optimum asymmetry in refractive index of waveguides in section 1 for $n_b(1) = n_a(2) = n_b(2)$. That is, switching operation is achieved by changing the refractive index of inner cladding layers and high extinction ratios for both cross and bar states are achieved by the asymmetry of refractive indices of cores.

The example of a vertical directional coupler switch with high extinction ratios larger than 30 dB for both cross and bar states at the same end of the device is shown in Fig. 7. It is assumed that the possible change in refractive index of III–V compound semiconductors by carrier injection and/or electro-optic effect is less than 1%. Details of the design will be reported elsewhere. Figure 7 shows refractive indices of each layer, device lengths and extinction ratios for (a) cross state and (b) bar state at the end of the device so that the change in refractive index of inner cladding layers and that of waveguide cores for switching operation is 0.025. One can achieve both cross and bar states with high extinction ratios larger than 30 dB at the same end of ultra short vertical directional coupler switches.

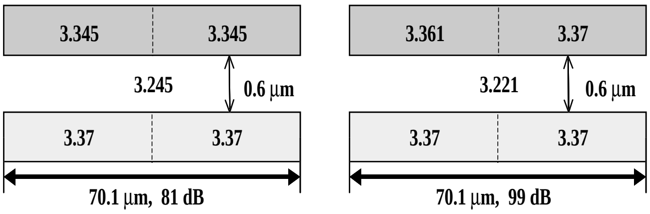

Fig. 7. The refractive indices of each layer, device lengths and extinction ratios for (a) cross state and (b) bar state when the change in refractive index of inner cladding layers and that of waveguides for switching operation is 0.025.

4. Conclusions

We have shown that both cross and bar states with high extinction ratios larger than 30 dB can be achieved in ultra short vertical directional couplers with two sections. With the proper asymmetry in the refractive index of two waveguides in section 1 and the refractive indices of both waveguides in section 2 equal to that of the waveguide in section 1 in which the power is not launched, both cross and bar states with high extinction ratios larger than 30 dB are achieved at the ends of section 1 and 2, respectively, in ultra short vertical directional couplers with two sections. As the difference of refractive indices of both waveguides in section 2 increases, the extinction ratio of the bar state decreases.

Acknowledgments

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