A Novel Vertical Directional Coupler Switch with Switching Operation-Induced, Extinction Ratio-Adjusted, and Extinction Ratio-Enhanced Sections

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We propose a novel very short (< 300 μm) vertical directional coupler switch with high extinction ratios larger than 30 dB. The device consists of a switching operation induced section (SOIS), an extinction ratio adjusted section (ERAS), and an extinction ratio enhanced section (ERES). These are achieved by changing the refractive index of one core. The switching operation is induced by changing the refractive index of one core in the SOIS. The improvement of extinction ratios larger than 30 dB for both the cross and bar states is made by controlling the asymmetry of the refractive indices of both cores in the ERES. Through the ERAS, different extinction ratios between the cross and bar states at the end of the SOIS are changed to the same value. For this reason, the optimum asymmetry of the refractive indices of the cores for the maximum extinction ratios and the lengths of ERES are the same for cross and bar states. Design guidelines for high extinction ratios with large tolerances are presented.

I. INTRODUCTION

High-speed optical switching components for high-bandwidth optical data streams play an important role in all-optical networks [1]. The major requirements for optical packet switching elements are high extinction ratios, low loss, low polarization dependence, and scalability. Fast switching speeds ranging from microseconds to nanoseconds are needed to apply an optical switch as a packet switching element [2]. The high speed switching operation can be induced by changing the refractive index using the electro-optic effect and carrier injection (or depletion) [3], [4]. Recently, a subpicosecond all-optical switching met- hod based on a simultaneous two-photon coherence change was proposed [5].

Ultra-short vertical directional couplers have a large tolerance [6], [7]. However, they have an inherent limitation in their cross state and bar state extinction ratios because of the non-orthogonality of individual waveguide modes. The extinction ratio of the cross state can be improved by using the slight asymmetry in the structure and that of the bar state using a combination of symmetric and asymmetric two-section structures [6], [7].

In the vertical directional coupler switch (VDCS) in [7], three P-i-N structures and three electrodes in a vertical direction were necessary to modify the refractive indices of the two cores and the inner cladding layer independently. This made the fabrication process and structure complex. Recently, we proposed a VDCS with a switching operation-induced section (SOIS) and an extinction ratio-enhanced section (ERES) [8].

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For the VDCS with an SOIS and an ERES induces the switching operation by changing the refractive indices of the two cores in the SOIS. Controlling the asymmetry of the refractive indices of the two cores in the ERES improves the extinction ratios larger than 30 dB for the cross and bar states. In this VDCS, two P-i-N structures and two electrodes in a vertical direction were necessary. However, changing the refractive index of one core and a single electrode in a vertical direction results in a simpler structure and fabrication process.

In this paper, we propose a novel very short (< 300 μm) VDCS with an SOIS, an extinction ratio adjusted section (ERAS), and an ERES. We change the refractive index of one core to obtain the switching operation and the improvement of the extinction ratios. The resulting single electrode and simple structure made the newly proposed VDCS with an SOIS, an ERAS, and an ERES possible. With the same amount of refractive index change in one core, we could make the device length of the proposed VDCS with an SOIS, an ERAS, and an ERES much shorter than that of the VDCS with only an SOIS and an ERES in [8]. In addition, we present design guidelines necessary for achieving high extinction ratios with large tolerances.

We use the transfer matrix method and improved coupled mode theory (ICMT) to analyze these structures and compare the results with those of the 2D finite difference beam propagation method (BPM).

This paper is organized as follows. Section II describe the proposed vertical directional coupler switch with an SOIS, an ERAS, and an ERES and its realization. Section III gives the design procedure and the examples for vertical directional coupler switches with an SOIS, an ERAS, and an ERES that have both cross and bar states with high extinction ratios larger than 30 dB. We also present design guidelines for achieving large tolerances in VDCSs. Finally, conclusions are given in section IV.

II. VERTICAL DIRECTIONAL COUPLER SWITCHES WITH SOIS, ERAS, AND ERES

From our analysis of the two-section vertical directional couplers (VDCs) in [6], we achieved cross and bar states with high extinction ratios using two-section VDCs with symmetry in the first section and proper asymmetry in the second section and vice versa. The VDCS can be divided into two sections without difficult design considerations. The first section is the switching operation-induced section employing symmetry in the structure and the second section is the extinction ratio-enhanced section employing asymmetry in the structure.

Two methods are available for realizing the VDCS with an SOIS and an ERES. One method is to induce a switching operation in the SOIS and improve the extinction ratios for both cross and bar states by changing the refractive indices of the two cores [8]. The other is to obtain the switching operation and the improved extinction ratios by changing the refractive index of one core. This paper investigates VDCS realized by changing the refractive index of one core.

The phase mismatch between the two coupled modes gives rise to not only a reduction in the power swing but also a shortening of the coupling length. Using the phase mismatch in the proposed VDCS, the switching operation in the SOIS can be induced by changing the refractive index of one core. In the ERES, using the asymmetry of the refractive indices of the two cores results in high extinction ratios larger than 30 dB. In addition, changing the refractive index of one core allows the asymmetry to have high extinction ratios. Since changing the refractive index of one core induces the switching operation, the VDCS is designed so that the cross and bar states are achieved by the symmetry and asymmetry in the structure of the SOIS, respectively and vice versa. This results in a different coupling strength in the SOIS and different extinction ratios at the end of the SOIS for the cross and bar states. The input conditions and the asymmetry of the refractive indices of the two cores determine the extinction ratio at the end of a section. In addition, to have high extinction ratios, the refractive index of the core in the ERES in which the power is launched should be smaller than that of the other core. For this reason, for the cross state in the ERES, the optimum asymmetry for high extinction ratios larger than 30 dB is different from that for the bar state. Thus, the length of the cross state in the ERES is different from that of the bar state.

The symmetric structure converts different extinction ratios at the input to the same value after one coupling length. To solve the mismatch between the coupling length for the cross and bar states, an ERAS with a symmetric structure is added between the SOIS and ERES. By propagating the ERAS, different extinction ratios between the cross state and bar state at the end of the SOIS are changed to the same value. For this reason, the optimum asymmetry of the refractive indices of the cores and the lengths of the ERES are the same for the cross and bar states.

The switching operation and high extinction ratios for both cross and bar states rely on the asymmetric coupler which in turn relies on the control of the refractive index of a core. Using the electro-optic effect and carrier injection (or depletion) brings about the desired change. By manipulating the appropriate doping profile, material composition, or orientation we can control the change in the refractive index of different regions to produce the asymmetric structure. For example, Liu et al. recently demonstrated a push-pull operation for a vertical coupler switch with a single electrode [9]. Their operation took advan-

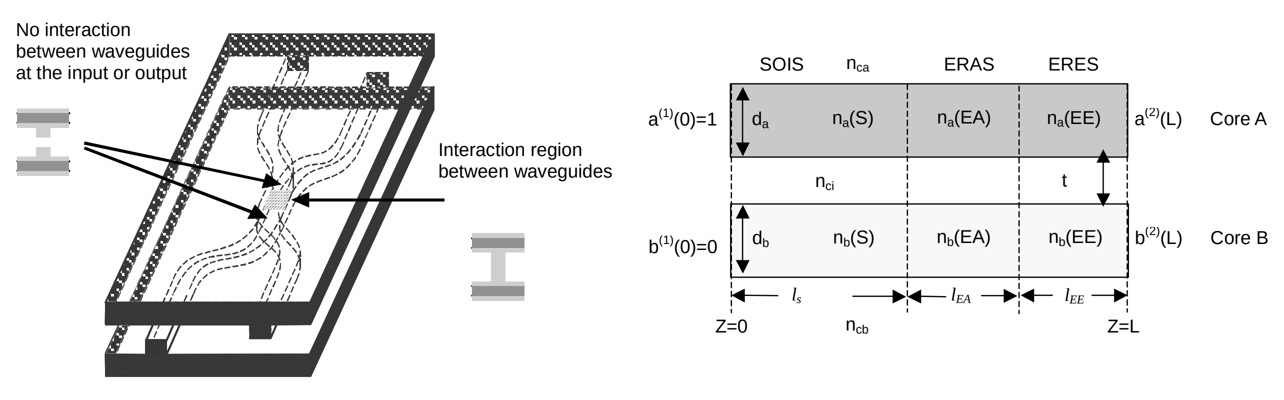

Fig. 1. (a) Schematic diagram of fused vertical coupler switches with separated input and output waveguides. (b) Schematic diagram of one dimensional index profile in the straight interaction regions of fused vertical coupler switches with switching operation induced section and extinction ratio enhanced section.

tage of the anisotropic electro-optic effect in zinc-blende semiconductors. In fact, an applied electric field perpendicular to the (001) surface gives a positive index change for TE polarized light propagating along the [110] direction and a negative index change for light propagating along the $[1\bar{1}0]$ direction. In this way, the asymmetry of the refractive indices of the two cores required for a switching operation and an improvement in the extinction ratio can be easily realized in the VDCS with a single electrode in the vertical direction. Also, the proposed device can be realized when one core has a P-i-N structure to control the refractive index using carrier depletion [4].

III. SIMULATION RESULTS AND DESIGN GUIDELINES

Figure 1(a) shows the VDCS with separated input and output waveguides. Since the two-dimensional index profile of the VDCS could be reduced to one dimension using an effective index method, the coupling length and the extinction ratio for the TE mode were calculated in a slab waveguide geometry to obtain the design guidelines. The results for the TM mode were similar to those of the TE mode. Figure 1(b) shows the schematic diagram of the one-dimensional index profile in the straight interaction region of the VDCS with the SOIS, ERAS, and ERES. The parameter values used in our analysis were $n_{ca} = n_{cb} = n_{ci} =$ 3.17, $n_b(S) = n_a(EA) = n_b(EA) = n_b(EE)$ =3.37, $d_a = d_b$ =0.5 μm, and t=0.6 μm, and the wavelength was 1.55 μm. We assumed that the refractive index change of the core was less than 0.5%. We analyzed the proposed VDCS by the ICMT and transfer matrix method in [7]. The extinction ratio of the cross and bar states of 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 power at the end of each section of waveguides A and B, respectively.

In order to achieve both cross and bar states at the same ends of the device, the coupling length of both the cross and bar states (or the multiples of the coupling length) must be the same and this length becomes the physical length of the device. For efficient adjustment of the extinction ratios in the ERAS, we chose the length of the SOIS to be the length of the bar state whose extinction ratio is around that of a symmetric coupler irrespective of the amount of asymmetry in the structure in the SOIS. Thus, the length of the SOIS is determined by $2m\, l_{c,\,bar}\,|_{n_a(S)|_{MIN\ or\ MAX}} = (2m-1)\, l_{c,\,cross}\,|_{n_a(S)=n_b(S)}$. The coupling length of the cross and bar states are denoted by $l_{c,\,cross}$ and $l_{c,\,bar}$, respectively. The refractive indices of the two cores in the SOIS are denoted by $n_{a,\,b}(S)$. Thus, the index difference, $\Delta n_a(S) = n_b(S) - n_a(S)\,|_{MIN\ or\ MAX}$, is the change in the refractive index for the switching operation and $n_a(S)\,|_{MIN\ or\ MAX}$ is the possible maximum or minimum refractive index of core A. We needed to design the VDCS in the region in which $\Delta n_a(S)$ was less than 0.015 because of the assumption of the refractive index change in the core. Based on the above relationship, we can determine the refractive indices of the two cores in the SOIS after choosing the length of the SOIS.

Figure 2 shows the length of the SOIS as a function of the refractive index of core A for various multiples of the coupling length in the SOIS of the vertical directional coupler with the inner cladding layer having a thickness of 0.6 μm. The refractive index of core B was chosen to be 3.37. Thus, the length of

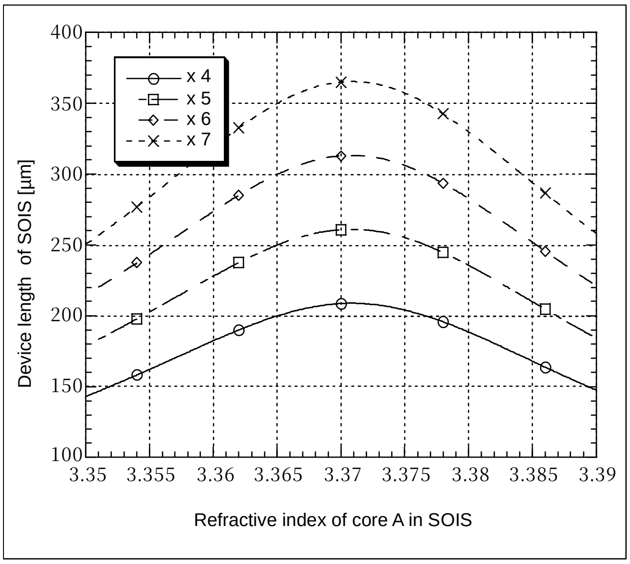

Fig. 2. Length of SOIS as a function of refractive index of core A for various multiples of coupling length in SOIS of a vertical directional coupler with the thickness of the inner cladding layer of 0.6 µm.

the SOIS for the cross state is $(2i-1)\,l_{c,\,cross}$ when the refractive index of core A is 3.37. The refractive index of core A for the bar state is determined by $(2i-1)\,l_{c,\,cross} = (2i)\,l_{c,\,bar}$. The refractive index difference between the cross and bar states is the refractive index change needed to induce the switching operation. That value should be less than 0.015- δ to fulfill the assumption of the refractive index change. The asymmetry of the refractive index of the core for the maximum extinction ratio is denoted by δ.

For example, we considered an SOIS with a length of 260 µm. In this case, the coupling lengths for the cross and bar states satisfy that $5l_c = 6\,l'_c$ =260 µm and the refractive index of core A in the SOIS for the cross and bar states are 3.37 and 3.3578 (or 3.3836), respectively. These figures are within the assumption of the refractive index change of the cores. Table 1 summarizes the parameter values. The switching characteristics of the bar state for $\Delta n_a(S)$ =3.3578 and 3.3836 are the same due to the function of ERAS. We consider the former case in the following calculations.

We consider two cases independently in which the power is launched into cores A and B due to the asymmetry of the SOIS for the switching operation. Figure 3 shows the extinction ratio of the cross and bar states as a function of the refractive index of core A in the ERES when the power is launched into core A. The refractive indices of core A in the SOIS for the bar and cross states are 3.3578 (or 3.3836) and 3.37, respectively. The lengths of the ERES for the bar and cross states are 51.9 µm and 51.2 µm at the refractive indices of 3.3729 and 3.3669 in core A, respectively, at which the maximum extinction ratio occurs. We chose the length of the ERAS to be one coupling length of the ERAS. This is enough to convert different extinction ratios at the input to the same extinction ratio. In the case of Fig. 3, the length of the ERAS is 52.16 µm. However, the optimum asymmetry of the refractive indices of the cores can be defined as the difference between that of core A for the maximum extinction ratio and that of core B. The refractive index difference between core B and core A for the maximum extinction ratio is 0.0029.

Table 1. Refractive index of core A in each section

Power Launch		$n_a(S)$	$n_a(EE)\|_{optimum}$
Core A	Bar	3.3578	3.3729
		3.3836	
	Cross	3.37	3.3669
Core B	Bar	3.3578	3.3669
		3.3836	
	Cross	3.37	3.3729

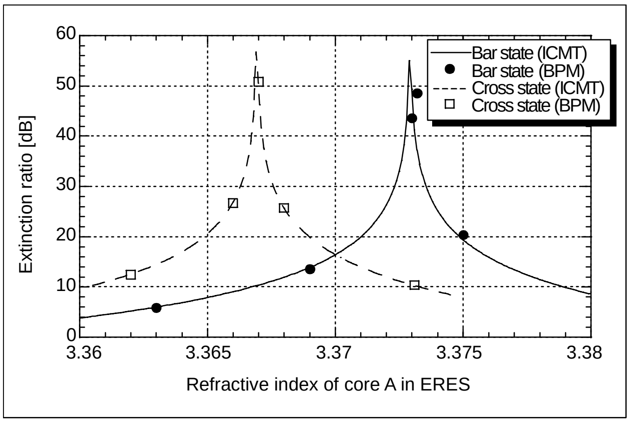

Fig. 3. The extinction ratio of cross and bar states as a function of the refractive index of core A in ERES when the power is launched into core A.

In the case of Fig. 3, the cross and bar states are achieved when the power is launched into core A and core B in the ERES, respectively. Since the ERAS has a symmetric structure, the extinction ratio for the cross state is a mirror image of that for the bar state with respect to a refractive index of 3.37 for core A.

Figure 4 shows the extinction ratio of the cross and bar states as a function of the refractive index of core A in the ERES when the power is launched into core B. The refractive indices of core A in the SOIS for the bar and cross states are 3.3578 (or 3.3836) and 3.37, respectively. The lengths of the ERES for the bar and cross states are 51.2 µm and 51.9 µm at a refractive index of 3.3669 and 3.3729 for core A, respectively, at which the maximum extinction ratio occurs. We can see that the extinction ratio for the cross state is a mirror image of that for the bar state with respect to a refractive index of 3.37 for core A. The refractive index difference between core B and core A for the maximum extinction ratio is 0.0029. The tolerance of the refractive index of core A in the ERES which gives extinction ratios larger than 30 dB is 0.0012 in both Figs. 3 and 4.

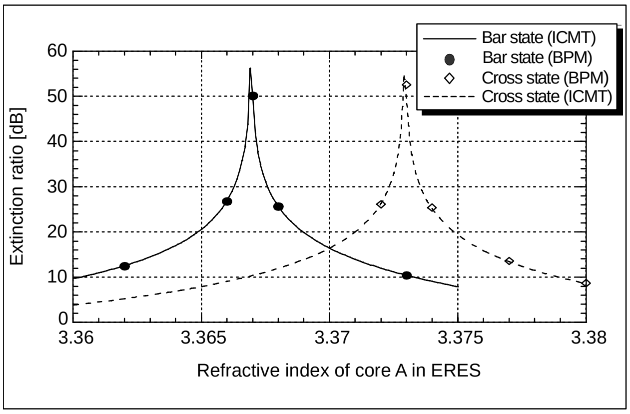

Fig. 4. The extinction ratio of cross and bar states as a function of the refractive index of core A in ERES when the power is launched into core B.

The results from Figs. 3 and 4 resulted in the design example of the VDCS with the SOIS, ERAS, and ERES shown in Fig.5. In the proposed switch using the asymmetry of the refractive indices of the cores for the switching operation and the improvement of the extinction ratio, as shown in the design example, the lengths of the ERES for the cross and bar states are slightly different. This reduces the tolerance for high extinction ratios larger than 30 dB. These different lengths come from the slightly different coupling strengths and the optimum asymmetry of the refractive indices. In other words, since the refractive index of one core is not changed, to achieve the optimum asymmetry of the refractive indices the refractive index of the other core for the cross and bar states must be different. This gives rise to the different coupling strength and the optimum asymmetry of the refractive indices for the cross and bar states.

This disadvantage could be overcome by employing the push-pull VDCS with a single electrode in a vertical direction. Figure 6 shows the design example of the push-pull VDCS with the SOIS, ERAS, and ERES. In the push-pull VDCS, when the electric field is applied in a vertical direction, it gives a positive and negative index change, respectively. As Fig. 6 shows, the lengths of the ERES for the bar and cross states are the same if we use the push-pull structure to achieve the asymmetry of refractive indices of the cores for the improvement of the extinction ratio. We can also achieve the asymmetry for the switching operation by using this. Thus, the VDCS with an SOIS, an ERAS, and an ERES can be realized by using the single electrode in a vertical direction.

The difference between the proposed VCDS with an SOIS, an ERAS, and an ERES and the VDCS with only an SOIS and

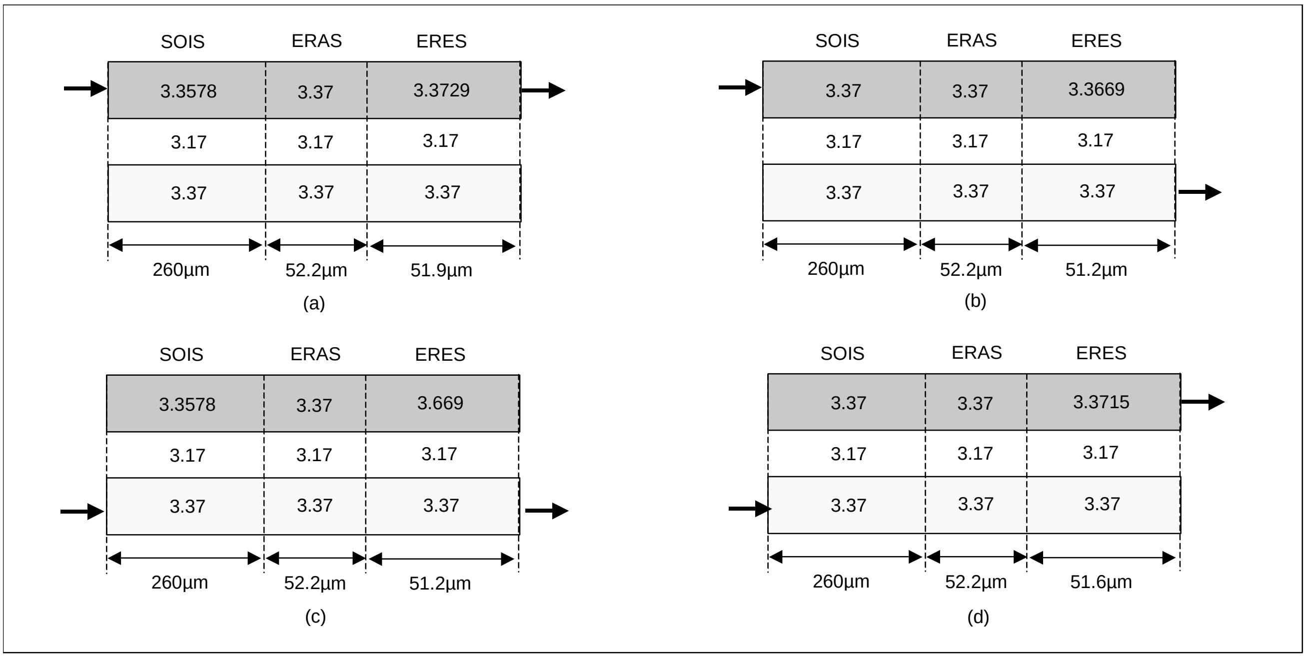

Fig. 5. A design example of a VDCS with SOIS, ERAS, and ERES. (a) and (b) are bar and cross states, respectively, when the power is launched into core A. (c) and (d) are bar and cross states, respectively, when the power is launched into core B.

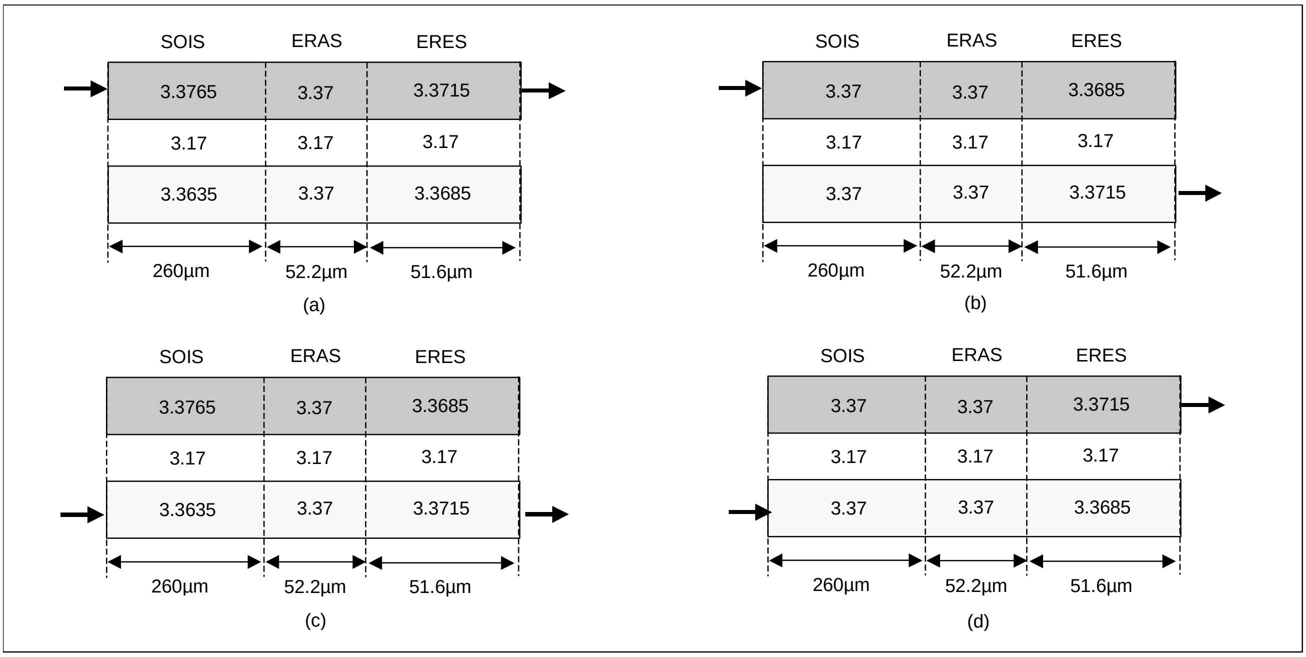

Fig. 6. A design example of a push-pull VDCS with SOIS, ERAS, and ERES. (a) and (b) are bar and cross states, respectively, when the power is launched into core A. (c) and (d) are bar and cross states, respectively, when the power is launched into core B.

an ERES in [8] is as follows. First, in the former the refractive index of one core is changed but in the latter those of two cores are changed for the switching operation and the improvement of the extinction ratios. Especially, in the former the asymmetry of the refractive indices of the cores in the SOIS is used to induce the switching operation. Second, in the former, the ERAS is added to adjust the extinction ratios. In the latter, the SOIS has symmetry in the structure for both the cross and bar states. In the former, the SOIS for the cross and bar states has symmetry and asymmetry in the structure, respectively and vice versa. This gives rise to the different extinction ratio for the cross and bar states at the end of the SOIS. However, the extinction ratio at the end of the ERAS in the former is almost equal to that at the end of the SOIS in the latter for both the cross and bar states because of the symmetry of the ERAS. Thus, the characteristics of the extinction ratio at the end of the ERES are the same for both devices. For this reason, we can obtain design guidelines for high extinction ratios larger than 30 dB by analyzing the extinction ratio in the ERES. The design guidelines for the VDCS with an SOIS, an ERAS, and an ERES are similar to those of the VDCS with an SOIS and an ERES.

Table 2 calculates and summarizes the tolerance and optimum asymmetry of the refractive indices of the cores in the ERES for various thicknesses of the inner cladding layer and the refractive indices of the cores in the SOIS. With this information we can determine design guidelines for high extinction ratios with a large tolerance of the refractive index of the core.

The refractive indices of cores A and B in the SOIS are denoted by $n_a(S)$ and $n_b(S)$, respectively. The refractive index change of core A in the SOIS required for the switching operation is denoted by $\Delta n_a(S)$. The optimum asymmetry in the ERES at which the maximum extinction ratio occurs is denoted by $n_{asy}(EE)_{optimum} = | n_a(EE) - n_b(EE) |$, and the tolerance of the refractive index of the core in the ERES that gives high extinction ratios larger than 30 dB is denoted by $\delta n_a(EE)|_{>30\ dB}$. Since the power confined in the core regions decreases as the refractive indices of the cores decrease (the strength of coupling between two cores increases), the tolerance of the refractive indices of the cores increases for the same thickness of the inner cladding layer as the refractive indices of cores decrease. However, the optimum asymmetry of the refractive indices of two cores to obtain the maximum extinction ratio increases as the refractive index of the core decreases (the strength of coupling between two cores increases). Compared with the tolerance and optimum asymmetry between the two cores in which the power is launched into cores A and B, those of the two cores are the same due to the adjustment of the extinction ratio through the ERAS.

From the calculations of the tolerances of the refractive indices of the cores and the optimum asymmetry in the ERES for various thicknesses of the inner cladding layer and refractive indices of cores in the SOIS, we can summarize the results as follows:

1. The tolerance of the refractive index of the core increases

Table 2. Tolerance and the optimum asymmetry of refractive indices in ERES and the refractive index change of cores in SOIS required for switching operation for various thickness of the inner cladding layer. The cross and bar states are denoted by ⊗ and Θ, respectively.

$n_b(S)$	t [μm]	Length of SOIS [μm]	$n_a(S)$		$\Delta n_a(S)$	$\delta n_a(EE)\|_{>30dB}$		$n_{asy}(EE)_{optimum}$	
			Θ	⊗		Launch A (Θ) & Launch B (⊗)	Launch A (⊗) & Launch B (Θ)	Launch A (Θ) & Launch B (⊗)	Launch A (⊗) & Launch B (Θ)
3.37	0.4	288	3.3547 3.3882	3.37	0.0153 0.0182	0.0024	0.0029	0.0096	0.0107
	0.5	260	3.356 3.3862	3.37	0.014 0.0162	0.0017	0.0019	0.0053	0.0057
	0.6	260	3.3578 3.3836	3.37	0.0122 0.0136	0.0012	0.0012	0.0029	0.0031
3.43	0.4	275	3.4462 3.4163	3.43	0.0162 0.0137	0.0019	0.0021	0.0053	0.0056
	0.5	230	3.4171 3.4443	3.43	0.0129 0.0143	0.0013	0.0013	0.0026	0.0026
	0.6	207	3.3578 3.3836	3.43	0.0122 0.0136	0.0009	0.0009	0.0013	0.0013

while the optimum asymmetry of the refractive indices of the cores in the ERES at which the maximum extinction ratio occurs increases as the refractive index of the core decreases.

2. The optimum asymmetry increases as the thickness of the inner cladding layer decreases (the coupling strength between the two cores increases).

In summary, to achieve a large tolerance, the design of the VDCS with an SOIS, an ERAS, and an ERES should be as follows. The thickness of the inner cladding layer should be smaller (the refractive index of that layer larger) and the refractive indices of both cores should be smaller. However, since the optimum asymmetry increases as the coupling strength increases [7], there is a minimum thickness of the inner cladding layer. In other words, the optimum asymmetry is larger than the assumption of the refractive index change when the inner cladding layer thickness is less than the minimum thickness. The design guidelines of the VDCS with an SOIS, an ERAS, and an ERES are similar to those of the VDCS with an SOIS and an ERES in [8].

IV. CONCLUSIONS

We proposed a very short vertical directional coupler switch with switching operation-induced, extinction ratio-adjusted, and extinction ratio-enhanced sections. The switching operation and the improvement of extinction ratios larger than 30 dB in the VDCS were achieved by changing the refractive indices of one core in each section. The device can be realized with a single electrode in a vertical direction. The integration of N by N switch fabric on a single wafer could be realized because of the very short device length. Thus, the realizing the proposed switch is relatively easier than realizing the VDCS with an SOIS and an ERES in [8].

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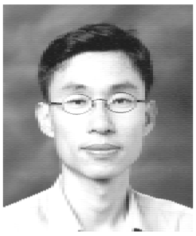

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Hyun Ha Hong, for photograph and biography, see this issue, p. 108.

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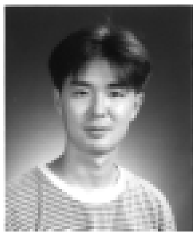
Hae Geun Kim, for photograph and biography, see this issue, p. 108.



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