# Wafer-Fused Optoelectronics for Switching

Ali Shakouri, Bin Liu, Boo-Gyoun Kim, Patrick Abraham, Andrew W. Jackson,
Arthur C. Gossard, *Senior Member, IEEE,* and John E. Bowers, *Fellow, IEEE*

***Abstract*—Wafer fusion technique for realization of compact waveguide switches and three-dimensional (3-D) photonic integrated circuits is investigated theoretically and experimentally. Calculations based on beam propagation method show that very short vertical directional couplers with coupling lengths from 40 to 220 $\mu$m and high extinction ratios from 20 to 32 dB can be realized. These extinction ratios can be further improved using a slight asymmetry in waveguide structure. The optical loss at the fused interface is investigated. Comparison of the transmission loss in InGaAsP-based ridge-loaded waveguide structures with and without a fused layer near the core region, reveals an excess loss of 1.1 dB/cm at 1.55 $\mu$m wavelength. Fused straight vertical directional couplers have been fabricated and characterized. Waveguides separated by 0.6 $\mu$m gap layer exhibit a coupling length of 62 $\mu$m and a switching voltage of about 2.2 V. Implications for GaAs-based fused couplers for 850 nm applications will also be discussed.**

***Index Terms*—Integrated optoelectronics, optical couplers, optical switches, optical waveguide components, wafer bonding.**

## I. INTRODUCTION

MAJOR requirements for optical packet switching elements are scalability, low-loss, and low crosstalk. In addition, these structures should be compatible for coupling with fiber ribbon cables and should incorporate integrated optical amplifiers to compensate for losses associated with fiber loop memories. We are investigating here the use of wafer fusion to give an extra degree of freedom in the fabrication of coupled waveguide structures. The technique of wafer fusion has been used to combine materials of very different lattice constants which could not be grown by heteroepitaxy [1]. This technique can also be used to combine planar waveguides fabricated on two different substrates into a three dimensional structure in which there is vertical coupling between arrays of single mode waveguides through the fused regions (Fig. 1) [2]. In addition, application of a bias at fused areas will allow a change of gain or index for switching purposes. Because of the differences between fused vertical couplers and conventional planar couplers [3]–[6], we have studied theoretically the coupling length and extinction ratio using three-dimensional (3-D) beam propagation method [7]. In order to gain insight into fundamental limitations in the performance of these *strongly* coupled structures, we have also used improved coupled mode theories where the nonorthogonality of the modes of individual waveguides is taken into account explicitly. From a fabrication point of view, realization of vertical couplers requires a detailed optical characterization of the loss and uniformity of the fused interface. In the following, after discussion of various design issues for fused vertical couplers, their fabrication and characterization are described.

## II. BEAM PROGAGATION METHOD ANALYSIS

In order to calculate the coupling length and the extinction ratio in these two-dimensional (2-D)-fused waveguide structures a 3-D finite difference beam propagation program is used. The fused vertical coupler (FVC) is shown in Fig. 2. A single-mode ridge-loaded waveguide structure based on InP substrate, with 0.5 $\mu$m InGaAsP ($\lambda_{\mathrm{gap}} = 1.3$ $\mu$m) core region, 0.1 $\mu$m cladding and 0.1 $\mu$m ridge height, is vertically coupled through a fused gap layer to an identical waveguide. The gap layer thickness is varied from 0.1 to 0.6 micron with its index ranging from InP to InGaAsP ($\lambda_{\mathrm{gap}} = 1.4$ $\mu$m).

Fig. 3(a) displays the coupling length for different parameters of the gap layer. As expected, increasing the gap layer index reduces the coupling length. In a coupled-mode picture, this can be explained by an increase in the overlap integral of the two modes of adjacent waveguides. On the other hand, the dependence of the coupling length on the gap layer thickness shows a mixed behavior. When the gap region has small indexes close to InP layer, increasing its thickness will decouple the two waveguides and thus increases the coupling length. However, when the index of the gap layer is large (close to 1.3 $\mu$m quartenary), the mode amplitude in this region is not anymore exponentially decaying, but sinusoidal. So a thicker gap layer will increase the overlap integral between modes of adjacent waveguides and thus reduces the coupling length. When the gap layer thickness is more than 0.3–0.4 $\mu$m, an analysis based on the supermodes of three coupled waveguide is more appropriate, but the appearance of undesirable modes in the gap layer will deteriorate the performance of the directional coupler.

In order to quantify the effect of higher order modes, power transfer between two waveguides was analyzed. The eigenmode of one of the uncoupled waveguides was taken for the input field, and power transfer to the other waveguide as a function of propagation distance was monitored by the beam propagation method (BPM) simulation. Fig. 3(b) displays the extinction ratio defined as the ratio of mode powers in the two waveguides after a coupling length. When the gap layer is thick and its index is high, the coupler has poor extinction ratios from 5 to 10 dB. In this case BPM simulation reveals 3–4

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A. Shakouri is with the Jack Baskin School of Engineering, University of California, Santa Cruz, CA 95064 USA (e-mail: ali@opto.ucsb.edu).

B. Liu, B. G. Kim, P. Abraham, A. W. Jackson, A. C. Gossard, and J. E. Bowers are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA.

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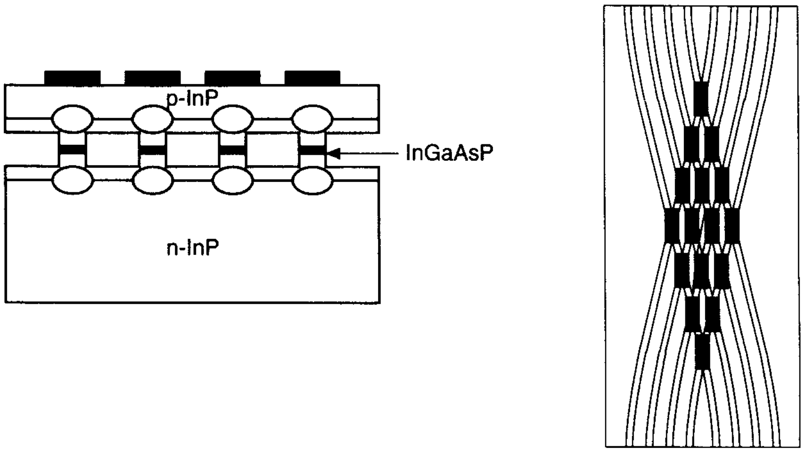


Fig. 1. InP crossbar switch based on coupling between independent arrays of waveguides on each substrate.

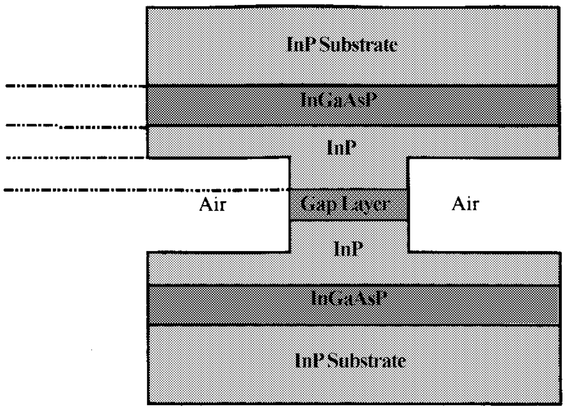
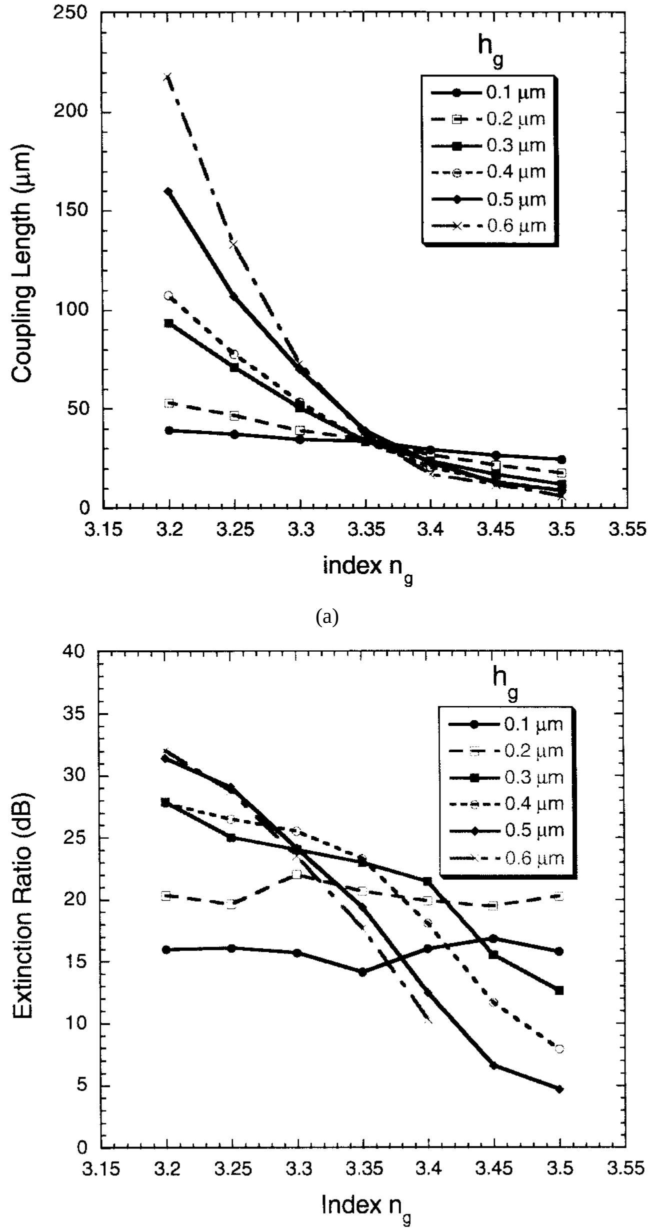


Fig. 2. The coupling region between two fused waveguides, and the parameters used for BPM simulations ($\lambda = 1.55$ $\mu$m, n(InP) = 3.17, n(InGaAsP) = 3.37).



(a)

(b)

Fig. 3. (a) The coupling length and (b) the extinction ratio as a function of gap layer index for different thicknesses of the gap layer.

supermodes in the coupling region. In addition to the expected symmetric and antisymmetric eigenmodes, there are modes of the gap layer and some leaky modes. But for a wide range of parameters (gap thickness from 0.2 to 0.6 $\mu$m, and gap index from 3.2 to 3.4), extinction ratios from 20 to 32 dB can be achieved. From Fig. 3(a) we see that this corresponds to coupling lengths of the order from 40 to 220 $\mu$m. Since the two waveguides are very close, it is almost impossible to excite only of the them and to measure the extinction ratio experimentally. In practice, the two ridge structures will be separated by curved regions and on/off ratio is limited by unwanted couplings at regions where the waveguides join together. The above analysis, however, shows the inherent limitation in extinction ratios.

In these symmetric ultra short couplers, the main problem to achieve low extinction ratio is nonorthogonality of the modes of individual waveguides [8], [9]. Using a slight asymmetry, one can improve extinction ratios to arbitrary small values. To see this, lets consider the one dimensional index profile of the coupling region of FVC in Fig. 2 with 0.2 $\mu$m InP gap layer. Fig. 4 shows calculations based on improved coupled mode theories, where corrections due to overlap integrals are incorporated [8]. BPM simulations agree very well with these results. When the gap layer thickness is 0.2 $\mu$m, the asymmetry

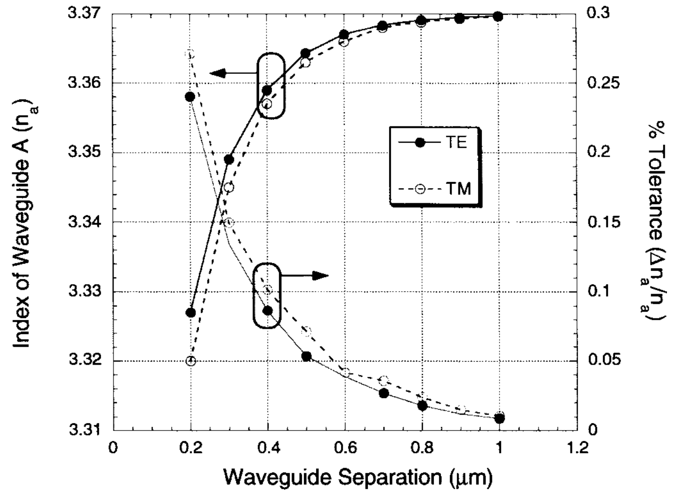


Fig. 4. Index of waveguide A for maximum extinction ratio and tolerance on that to achieve >30 dB extinction ratio as a function of waveguide separation.

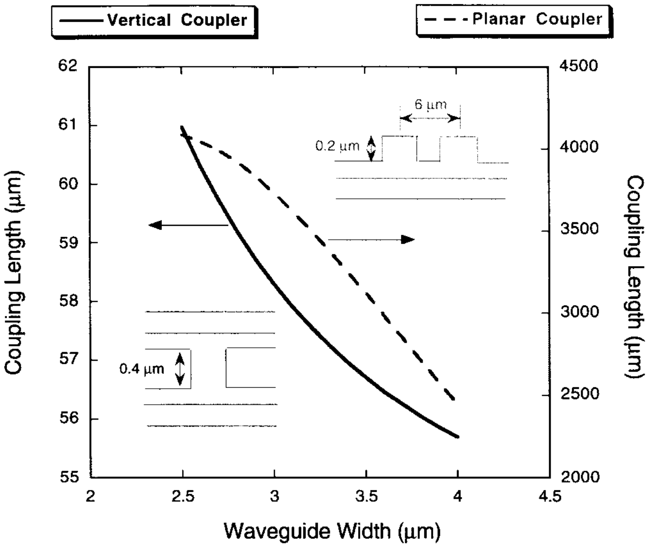


Fig. 5. Coupling length for the vertical coupler and conventional planar coupler as a function of waveguide width.

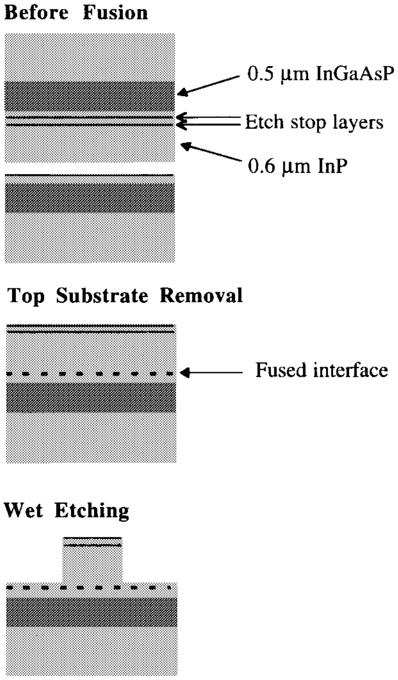


Fig. 6. Different steps of fabrication process for single-mode waveguide structure with a fused interface near core region.

in core waveguide index required to achieve the highest extinction ratio for TE (TM) mode is 0.003 (0.004). Having the core index within ±0.019 (±0.021%) of the optimum value for TE (TM) mode, one can achieve the extinction ratio larger than 30 dB (Fig. 4). As the separation between the two waveguides decreases, more asymmetry is needed but the tolerance to obtain an extinction ratio larger than 30 dB increases. This facilitates fabrication of passive asymmetric couplers or setting the voltage or current in active components. An intuitive picture is that a slight asymmetry can equalize the overlap integral of the single waveguide mode with the symmetric and antisymmetric supermodes of the coupler and thus increase the extinction ratio.

Vertical coupling through the ridge structure whose height is defined by etch-stopping techniques is much less sensitive to the ridge waveguide width and sidewall smoothness than the planar waveguide couplers. In fact, the difficulty in making reproducibly and uniformly very narrow gap (<1 $\mu$m) couplers have mitigated their development for ultra short switching devices. Fig. 5 shows the coupling length as a function of waveguide width for the case of a conventional ridge-loaded structure with 0.5 $\mu$m InGaAsP ($\lambda_{\text{gap}} = 1.3$ $\mu$m) core layer, 0.1 $\mu$m InP slab layer and 0.2 $\mu$m InP ridge. The center of the two waveguides are separated by 6 $\mu$m. It can be seen that a change of 1 $\mu$m in waveguide width will change the coupling length by 30–40%. When the same waveguides are coupled vertically, the coupling length is about two orders of magnitude smaller and at the same time less sensitive to waveguide width variation (4–5% change in coupling length for one micron change in waveguide width).

Another requirement for optical switches is polarization insensitivity. The fused vertical coupler shown in Fig. 2 has coupling length for TM polarized light at 1.55 $\mu$m wavelength which is 7–13% shorter than the TE one (for gap layer thicknesses between 0.1–0.6 $\mu$m). However, it is possible to make the switch polarization insensitive using the difference in materials dispersion, e.g., by combining GaAs and InP waveguides [10].

## III. OPTICAL LOSS AT THE FUSED INTERFACE

The single mode waveguide structure was based on MOCVD grown material with 0.5 $\mu$m InGaAsP ($\lambda_{\text{gap}} = 1.3$ $\mu$m) guiding layer, 0.24 $\mu$m cladding layer which includes two 0.1 $\mu$m InP layers and two 0.02 $\mu$m InGaAsP ($\lambda_{\text{gap}} = 1.15$ $\mu$m) etching stop layers, and finally 0.6 $\mu$m InP ridge layer. For the purpose of comparison, we use the same wafer and single mode waveguide geometry with and without a fused interface near the core region. The control waveguide has 3 $\mu$m wide and 0.6 $\mu$m high ridges defined

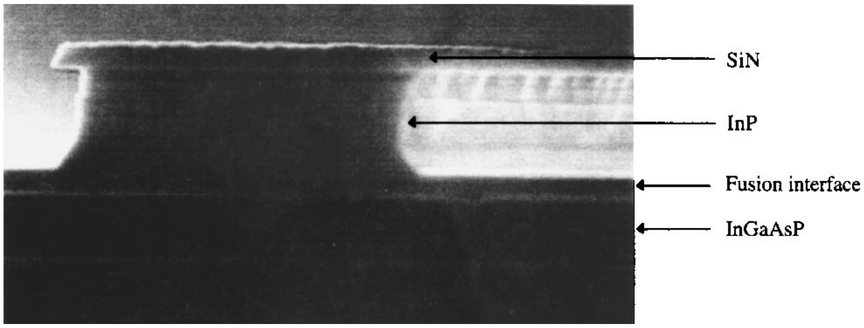


Fig. 7. The stain-etched SEM picture of the single-mode waveguide structure with fused interface.

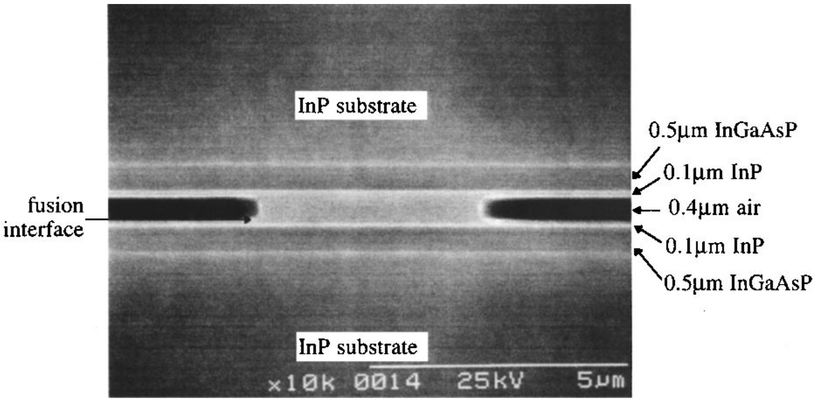


Fig. 8. The stain-etched SEM picture of a fused vertical coupler.

using wet-etching techniques. To fabricate the single mode fused waveguide, two 1 × 0.8 $cm^2$ samples are cut from the MOCVD grown wafer. First, the 0.6 $\mu$m InP layer and 0.1 $\mu$m cladding layer of one sample are removed using selective wet-etching (Fig. 6); then 10 $\mu$m wide, 0.6 $\mu$m deep channels with 160 $\mu$m spacing are opened in a second sample. The two samples are then fused at 630 °C in a hydrogen atmosphere for 30 min. Subsequently, InP substrate and 0.5 $\mu$m guiding layer of the top wafer is removed and 3 $\mu$m wide ridge waveguides are fabricated using wet etching. Fig. 7 shows a stain-etched SEM picture of finished device. The fused interface can not be seen in this picture. This is an indication of the high quality of the fused interface. The presence of the channels prior to fusion is crucial. Without these channels, we could see microscopic voids at the fused junction and many of the fabricated waveguides did not show clear eigenmodes.

Fabry–Perot resonance technique was used to measure the optical propagation loss [2]. The optical loss of the unfused waveguide is about 2.4 dB/cm, while the fused structure showed a loss of 3.5 dB/cm at 1.55 $\mu$m. Since the geometry and materials are identical, the 1.1 dB/cm excess loss should be attributed to the fused interface. BPM calculations indicate that the field strength at the center of the fused interface is 49% of the maximum field. The issue of waveguide uniformity for large scale monolithic integration is very important. The size of our fused wafers is about 1 × 0.8 $cm^2$. After thinning and cleaving, the size of the sample for measurement is about 6 × 6 $mm^2$. The yield of the fused waveguides is more than 90% which is almost same as unfused sample. The existence of channels in fused sample provides 150 $\mu$m wide multimode slab waveguides that contain a fused interface. We did not notice any "dark" spot in these multimode structures.

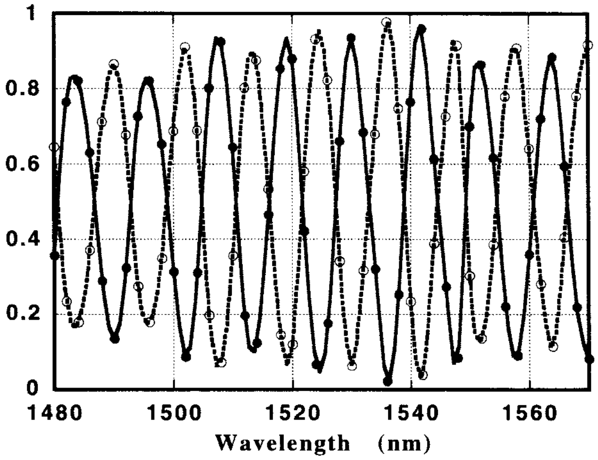


Fig. 9. Measured intensity of the upper and lower waveguides as a function of wavelength.

We have also investigated mass transport at the fused interface by comparing samples with different effective fused areas. In conventional fused structures, after fabrication of narrow channels on one of the wafers prior to fusion, typically over 90% of the surface of the samples is in contact during the fusion process. We studied samples where the fusion was only over the surface on the top of waveguides (3–6 $\mu$m thickness, separated by 125 $\mu$m, and about 1 cm long). In this case only 4% of the surface of the two wafers is in contact during fusion. We did not notice any substantial degradation or nonuniformity in the ridge waveguide structure.

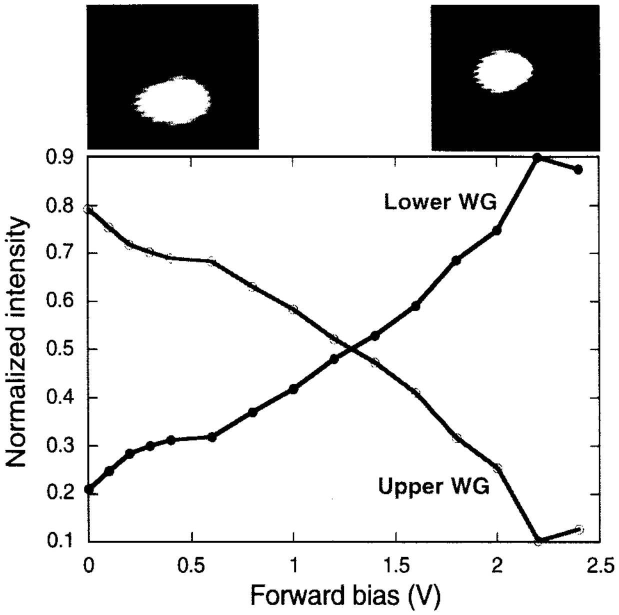


Fig. 10. Measured bias dependence of the output light intensity in upper and lower waveguides for a 3.5 mm fused vertical switch. The top pictures are photographs of the near field pattern at the output of the coupler at 0 and 2.2 V.

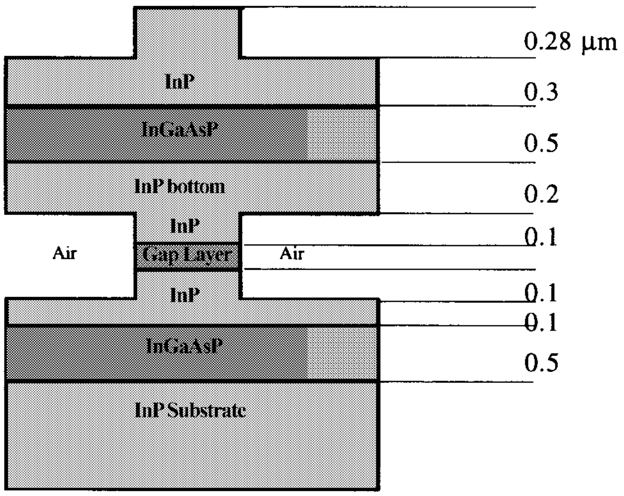
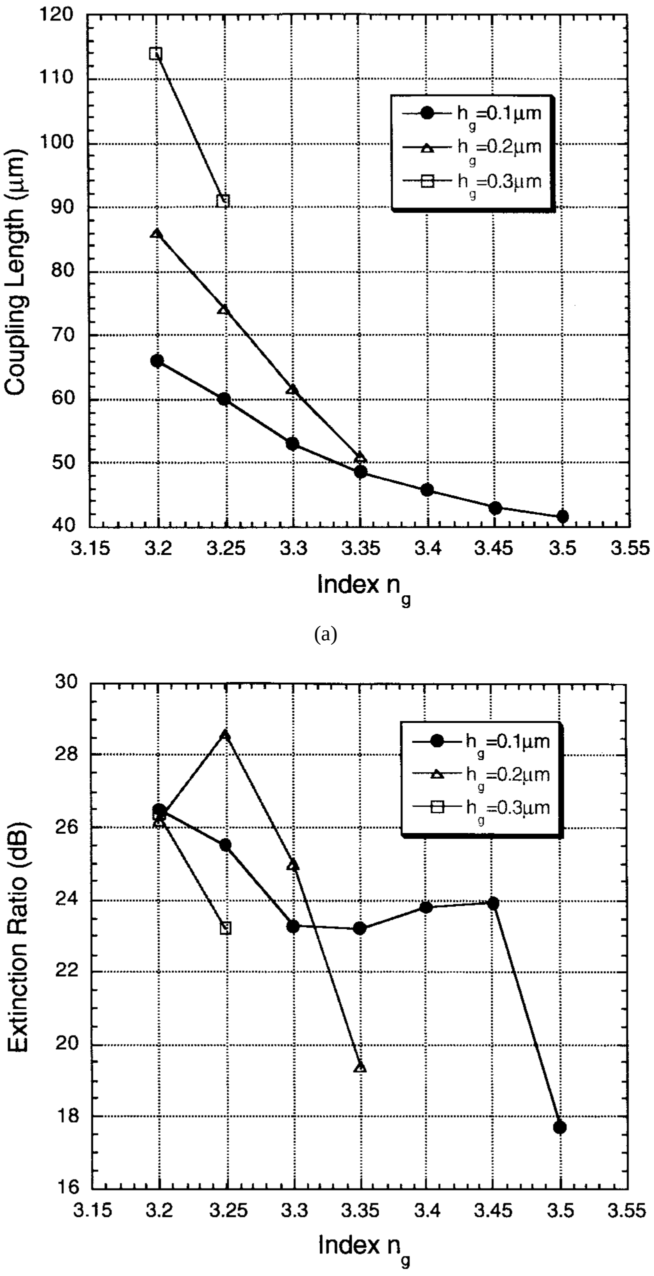


Fig. 11. Asymmetric fused vertical coupler.



(a)

(b)

Fig. 12. (a) The coupling length and (b) the extinction ratio as a function of gap layer index for different thicknesses of the gap layer, for asymmetric fused vertical coupler.

## IV. FUSED VERTICAL DIRECTIONAL COUPLER AND SWITCH

The structure of the coupler is identical to that in Fig. 2, with 0.2 $\mu$m thick InP gap layer. The material was grown by MOCVD and consisted of a 0.5 $\mu$m InGaAsP ($\lambda_{\mathrm{gap}} = 1.3$ $\mu$m) guiding layer on InP substrate, followed by 0.1 $\mu$m InP cladding layer, 20 nm InGaAsP ($\lambda_{\mathrm{gap}} = 1.15$ $\mu$m) etch stop layer and 0.4 $\mu$m InP coupling layer. To fabricate the vertical coupler, two 8 × 10 mm$^2$ samples are cleaved from the grown wafer. In the first sample the top 0.4 $\mu$m InP layer is removed. On the second sample, a ridge waveguide structure is fabricated using standard photolithography and selective wet etching. The ridges have 3–6 $\mu$m width, 0.4 $\mu$m height and they are separated by 125 $\mu$m. The two samples are then fused together at a temperature of 630°C in a hydrogen atmosphere for 30 min. Fig. 8 shows the stain-etched SEM picture of a finished fused vertical coupler (FVC). The fused interface is not visible, even after staining. There is mass transport at the edge of the ridge. This is beneficial to get a symmetric coupler and improves the side wall flatness.

The near field pattern at the output of FVC's, 4.5 mm long, is recorded by an IR camera. The light is input from a 8 $\mu$m diameter single mode 1.55 $\mu$m fiber. It can be seen that by changing the input wavelength, light is switched from the upper to the lower waveguide. Fig. 9 shows the intensities of the upper and lower waveguides as a function of wavelength. Our measurements show that the extinction ratio can be >15 dB. This is particularly difficult to achieve in conventional high mesa vertical couplers [3]–[6]. From the oscillation

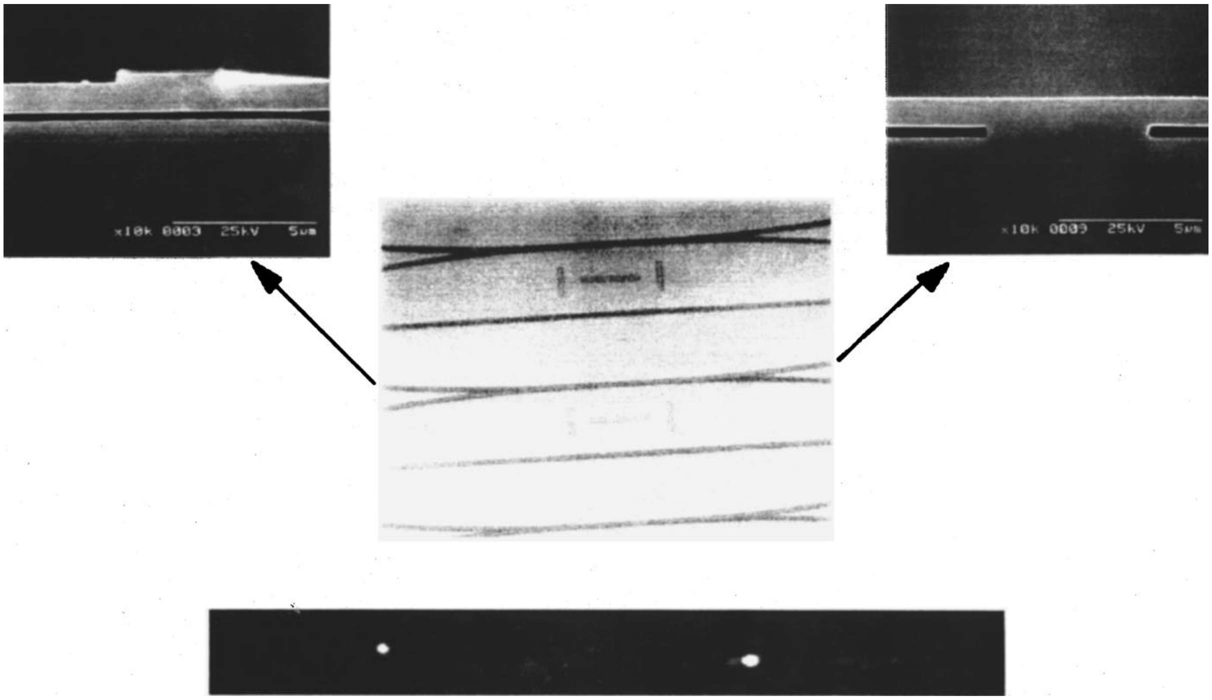


Fig. 13. SEM pictures of the separated top and bottom waveguides for an asymmetric fused vertical coupler. The bottom picture is a photograph of the near field pattern at the output of the coupler where the two waveguides are separated by 250 $\mu$m.

period (about 12 nm) and considering material and waveguide dispersions, the index difference between the even and odd modes can be calculated which is 0.0121. The corresponding coupling length is 62 $\mu$m at 1.55 $\mu$m, that agrees very well with 58 $\mu$m result from BPM simulations. Finally a PIN FVC was fabricated and characterized. The structure was identical to the one in Fig. 8, the only difference is that the top InP substrate is p-doped and the bottom wafer n-doped. It can be seen in Fig. 10 that with a bias of 2.2 V the light is switched from the top to the bottom waveguide. Electro-optic effect at such a small bias is not enough to explain the switching. We believe that thermo-optic effect plays a major role in this device because of the high leakage current and local heating of the coupler [11].

## V. ASYMMETRIC FUSED VERTICAL DIRECTIONAL COUPLER

In order to fabricate multilevel 3-D photonic integrated circuits, an asymmetric fused structure is needed (see Fig. 11). By repeating the fusion process, one can obtain multiple layers of waveguide interconnects. For fabrication, first, a set of ridge waveguides on a InP wafer are defined using the usual wet- and dry-etching techniques. Subsequently, a wafer is bonded on top of the waveguides. After removing the substrate of this top wafer using selective etching, a second set of waveguides is fabricated. These top waveguides are coupled vertically to the waveguides beneath them in areas where the two structures are connected by wafer fusion. The issue of alignment in the coupling regions is facilitated using infrared photolithography. Even though the top and bottom waveguides are very dissimilar, by matching the modes effective indexes, one can theoretically achieve coupling lengths of the order of 60 $\mu$m with 25 dB extinction ratio [see Fig. 12(a) and (b)]. Fig. 13 displays the SEM cross section of the bottom and top waveguides along with the near field infrared image at the output of an InGaAsP asymmetric coupler where the two waveguides are separated by 250 $\mu$m.

## VI. PROSPECTS FOR GaAs FUSION

Wafer fusion technique can also be used to fabricate vertical couplers in other materials. To investigate the optical loss due to fusion process in AlGaAs, a single mode waveguide structure similar to the one in Fig. 7 was fabricated. The reference structure was based on GaAs substrate, with 2.5 $\mu$m $Al_{0.4}Ga_{0.6}As$ bottom cladding layer, 0.2 $\mu$m $Al_{0.15}Ga_{0.85}As$ core region, 0.3 $\mu$m $Al_{0.4}Ga_{0.6}As$ slab layer and 0.6 $\mu$m $Al_{0.4}Ga_{0.6}As$ ridge. The waveguides were 3 $\mu$m wide and they exhibited a loss of about 5 dB/cm. This high loss was due to the poor quality of the sidewalls. SEM pictures revealed a roughness on the order of one micron. Single mode waveguides with a fused interface in the middle of the slab layer (i.e., 0.15 $\mu$m away from the core region), had an excess loss of about 3 dB/cm at 1.55 $\mu$m wavelength.

It will be difficult to achieve ultra short coupling lengths with fused vertical couplers at shorter wavelengths (e.g., 850 nm). If the single mode AlGaAs waveguide structure described above has only 0.1 $\mu$m ridge height and is coupled vertically to an identical waveguide, the coupling length at 850 nm is over 500 $\mu$m. The same structure at 1.55 $\mu$m wavelength will have a coupling length of about 5 $\mu$m.

## VII. SUMMARY AND CONCLUSION

In conclusion, wafer fusion technique for fabrication of vertical couplers and switches is described. Very short directional couplers with a coupling length from 40 to 220 $\mu$m and high extinction ratios from 20 to 32 dB can be realized. These extinction ratios can be further increased using a slight asymmetry in waveguide structure. It is shown that 1.1 dB/cm excess optical loss is introduced due to fusion process in InP based waveguides at 1.55 $\mu$m wavelength. Fused straight vertical directional couplers separated by 0.6 $\mu$m gap layer exhibit a coupling length of 62 $\mu$m and a low switching voltage of about 2.2 V. These fused waveguides give us the added advantage of vertical dimension by separating the input and output waveguides to realize compact and scalable 3-D photonic integrated circuits.

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**Ali Shakouri** received the undergraduate degrees from University of Paris, France, and Ecole Nationale Superieure des Telecommunications de Paris, France. He received the Ph.D. degree from the California Institute of Technology, Pasadena, in 1989, 1990, and 1995, respectively. His dissertation was on electron transport in quantum well infrared photodetectors.

He is currently an Assistant Professor at the University of California at Santa Cruz. His research interests are in wafer-fused optoelectronics, fiber-optic telecommunication systems, and integrated cooling of electronic components.

**Bin Liu** received the B.S. degree from Zhejiang University, China, in 1990 and the M.S. degree from Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, China, in 1995. He is currently pursuing the Ph.D. degree at the University of California at Santa Barbara.

His research includes the simulation and fabrication of wafer-fused semiconductor waveguide, coupler, filter, and switch.

**Boo-Gyoun Kim** was born in Taejon, Korea. He received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1979 and the M.S. degree in electronic engineering from KAIST, Seoul, in 1981. He received the Ph.D. degree in electrical engineering from the University of Southern California at Los Angeles, in 1989.

He joined the Department of Electronic Engineering at Soongsil University in 1981 and is an Associate Professor in the School of Electronic Engineering at Soongsil University. During the summer of 1993, he was a Visiting Researcher of IBM Almaden Research Center, San Jose, CA. During the 1997 academic year, he was a Visiting Associate Professor in the Department of Electrical and Computer Engineering at the University of California at Santa Barbara. His main research interests are in the areas of optical communication devices and systems.

**Patrick Abraham** received the M.S. and Ph.D. degrees in material science from the University C. Bernard Lyon 1, France, in 1984 and 1987, respectively.

He was a researcher at Centre National de la Recherche Scientifique (CNRS), France, and worked until 1988 at the Laboratoire de Physico-Chimie Minerale, France. He is currently a research engineer at the University of California at Santa Barbara, where his research interests include MOCVD growth, compliant substrates, and wafer bonding.

**Andrew W. Jackson**, photograph and biography not available at the time of publication.

**Arthur C. Gossard** (SM’88) received the B.A. degree in physics (summa cum laude) in 1956 from Harvard University, Cambridge, MA, and the Ph.D. degree in physics from University of California at Berkeley, in 1960.

From 1960 to 1987, he was a Member of Technical Staff at AT&T Bell Laboratories and since 1987 he has been Professor of Materials and Electrical and Computer Engineering at University of California at Santa Barbara. His research involves the growth of artificially structured materials by molecular beam epitaxy. His special interests are the growth of quantum wells and superlattices and their application to high- performance electrical and optical devices.

Dr. Gossard is a Fellow of the American Physical Society. He received the Distinguished Technical Staff Member Award from AT&T Bell Laboratories in 1983, the Oliver E. Buckley Condensed Matter Physics Prize from the American Physical Society in 1984, and the Leigh Page Prize Lecturer from Yale University Physics Department in 1986. He was elected to Membership of the National Academy of Engineering in 1987.

**John E. Bowers** (S’78–M’81–SM’85–F’93) received the M.S. and Ph.D. degrees from Stanford University, Palo Alto, CA.

He is Director of the Multidisciplinary Optical Switching Technology Center (MOST), and a Professor in the Department of Electrical and Computer Engineering at the University of California at Santa Barbara (UCSB). He is a member of the Heterogeneous Optoelectronics Technology Center and the NSF Center on Quantized Electronic Structures. His research interests are in the development of novel optoelectronic devices for the next generation of optical networks. His research interests include novel ways of growing quantum wires and dots using MBE and MOCVD, techniques to fuse dissimilar materials together for new devices and improved performance, the design of quantum-well structures for high-speed light generation and detection, and the design of high-speed time-division multiplexed systems and devices. He has worked for AT&T Bell Laboratories and Honeywell before joining UCSB in 1987.

Dr. Bowers is a fellow of American Physical Society and a recipient of the IEEE LEOS William Steifer Award. He is a recipient of Sigma Xi’s Thomas F. Andrew prize and the NSF Presidential young Investigator Award and NSF graduate fellowship.