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Fused vertical couplers

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A vertical directional coupler fabricated using wafer fusion is demonstrated with a very short coupling length of 62 μm. The optical propagation loss introduced by the fused layer is investigated. An excess loss of 1.1 dB/cm at 1.55 μm was measured for waveguides which incorporate a fused junction near the core region. Fused vertical couplers make it possible to realize three-dimensional waveguide structures and compact switching arrays and they solve some of the topology problems of large switch arrays. © *1998 American Institute of Physics.* [S0003-6951(98)02221-9]

Compact semiconductor optical waveguide switches are critical components in photonic integrated circuits for high-speed optical communication networks and optical information processing. A large-scale switching array requires low space consumption, so it is essential to minimize the length of each switch. Conventional directional couplers with laterally arranged waveguides[1] cannot achieve very short coupling lengths because of low modal overlap and because of technological limits to obtaining uniform and small gap layers. Vertical directional couplers, on the other hand, can offer a short coupling length which is even smaller than 100 μm.[2,3] The difficulty of separating the two vertical coupled waveguides into two distinct inputs and outputs limits the application of these couplers to large-scale switching arrays. In this letter, we demonstrate a fused vertical coupler (FVC) with a very short coupling length, which can solve this problem.

Wafer fusion is a powerful technique to fabricate structures that cannot be realized by conventional epitaxial growth and processing. In addition to the inherent advantage of combining material with different lattice constants,[4] wafer fusion can give an extra degree of freedom in the design and fabrication of three-dimensional (3D) photonic devices.[5] By displacing the input and output waveguides vertically in different planes, scaling of switch arrays to large sizes is easy to realize (Fig. 1). In order to switch a large number of input waveguides, it is essential to have compact, high extinction ratio fused vertical couplers. In the following, we will analyze theoretically and experimentally straight fused vertical couplers.

The structure of the FVC is shown in Fig. 2. The material was grown by metal–organic chemical-vapor deposition and consisted of a 0.5 μm InGaAsP ($\lambda = 1.3$ μm) guiding layer on an InP substrate, followed by a 0.1 μm InP cladding layer, a 20 nm InGaAsP ($\lambda = 1.15$ μm) etch-stop layer, and a 0.4 μm 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 μm InP layer is removed. On the second sample, a ridge waveguide (WG) structure is fabricated using standard photolithography and selective wet etching. The ridges have 3–6 μm width, 0.4 μm height, and they are separated by 125 μm. The two samples are then fused together at a temperature of 630 °C in a hydrogen atmosphere for 30 min. Figure 1 shows the stain etched scanning electron microscope (SEM) picture of a finished FVC. The fused interface is not visible, even after staining. This is an indication of the high quality of the fusion process. There is mass transport at the edge of the ridge. This is beneficial in obtaining a symmetric coupler and improves the sidewall flatness.

The near-field pattern at the output of the FVCs is recorded by an IR camera and is shown in Fig. 3. The light is the input from a 8 μm diam single-mode fiber. The total length of the FVC is 5.5 mm. It can be seen that by changing the input wavelength, the light is switched from the upper to the lower waveguide. Since the shapes of the two waveguide modes are very similar, one can obtain a high extinction ratio. Our measurement shows the extinction ratio is about 15 dB. This is particularly difficult to achieve in conventional high mesa vertical couplers.[2] BPM[6] simulations show that extinction ratios up to 20–35 dB are possible. Figure 4 shows the intensities of the upper and lower waveguides as a function of wavelength. From the oscillation period (about 11.5 nm), and considering material and waveguide disper-

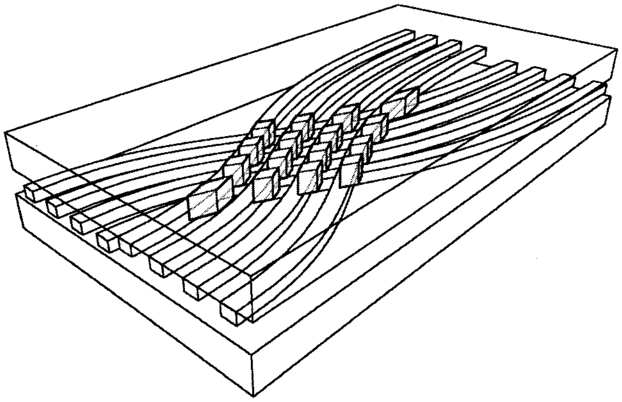

FIG. 1. 4×4 crossbar switch array based on vertical coupling between two substrates.

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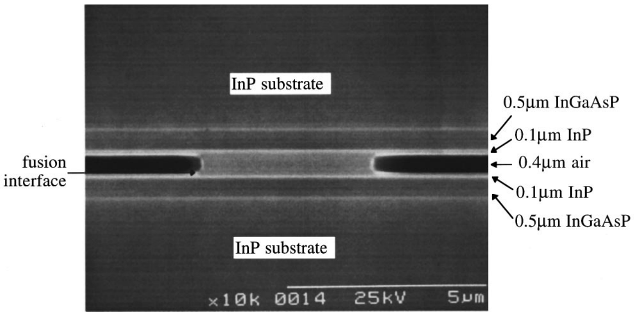

FIG. 2. The stain etched SEM picture of a fused vertical coupler.

sions, the index difference between the even and odd modes can be calculated, which is 0.0124. The corresponding coupling length is 62 μm at 1.55 μm, which agrees well with the theoretical value of 58 μm, derived from 3D BPM calculations. One important advantage of this strong vertical coupling is the capability of attaining highly selective WDM add/drop multiplexers by making longer couplers with significant overcoupling. Figure 4 illustrates the possibility of a lossless combination or splitting of two signals separated by just 6 nm. The wavelength selectivity of a FVC can be enhanced by using strong asymmetry in the waveguide structure.

To investigate the optical propagation loss at 1.55 μm due to the fused interface, two single-mode ridge waveguides are fabricated. The first one has a 0.5 μm InGaAsP (1.3 μm quartenary) core region, a 0.2 μm InP slab layer, and a 0.6 μm InP ridge height. The second sample is identical to the first except for a fused interface in the middle of the InP slab layer, where the mode field is as high as 50% of the maximum. A Fabry–Perot resonance technique is used to measure the optical loss.[7] The second sample shows only 1.1 dB/cm excess loss due to the presence of the fused interface compared with the unfused single-mode waveguides. We believe it can be reduced further with the improvement of the fusion process.

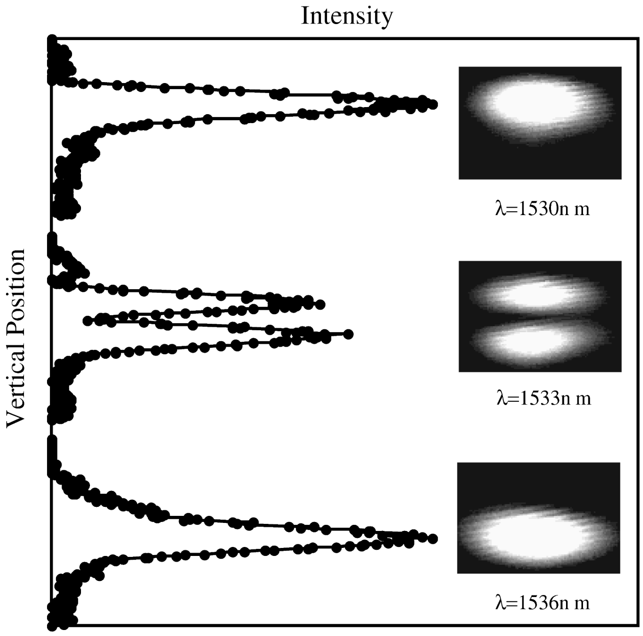

FIG. 3. Photograph of the near-field pattern at 1530, 1533, and 1536 nm. The width of the ridge is 3 μm, and the distance between the upper and the lower WGs is 1.1 μm. The left curve is the profile of the near field.

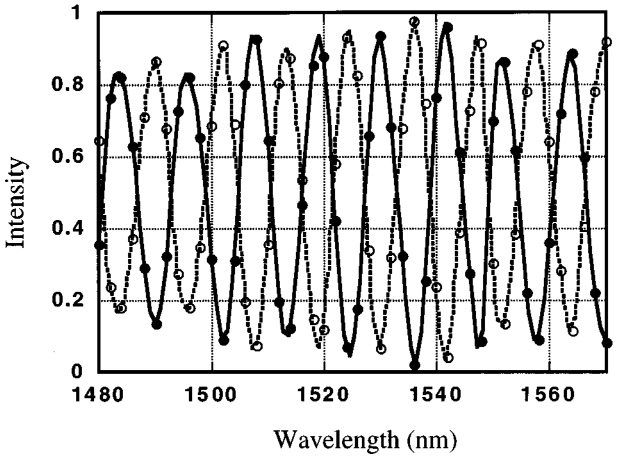

FIG. 4. Measured intensity of the upper (closed circle) and lower (open circle) waveguides as a function of wavelength.

The issue of uniformity for fused waveguides is very important for large-scale monolithic integration. For the present size of our fused wafer (8×10 mm^2), we found very good uniformity in terms of excess loss or coupling length. More than 90% of the waveguides can work well, even for the ones near the edge of the fused wafers. We have also checked the multimode behavior of the 150 μm width slab fused waveguides. They do not show any dark spots or dead regions.

In conclusion, a fused vertical coupler was demonstrated with a 62 μm coupling length. It is shown that 1.1 dB/cm excess optical loss is introduced due to the fusion process, which is even lower than the loss caused by doping. The fused vertical couplers and waveguides give us an added advantage of vertical dimension by separating the input and output waveguides to realize compact and scalable 3D directional coupler structures.

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