Double-Bonded InP–InGaAsP Vertical Coupler 1 : 8 Beam Splitter

Maura Raburn, Bin Liu, Patrick Abraham, and John E. Bowers

***Abstract*—A novel three-layer double-bonded InP–InGaAsP waveguide vertical coupler 1 : 8 beam splitter is demonstrated. The strongly coupled waveguides allow a 583-μm device length, more than 100 times shorter than that of the equivalent horizontal coupler. The device illustrates the use of multiple vertical-layer optical interconnects for three-dimensional routing of optical signals.**

***Index Terms*—Beam splitting, optical directional couplers, semiconductor waveguides, wafer bonding, waveguide couplers.**

I. Introduction

THE PHOTONIC integrated circuit (IC) industry has yet to witness the rapid developments made in the electronic IC industry for several reasons, one of which is the confinement of photonic circuits to two dimensions. The complexity of two-dimensional photonic ICs is limited by the substrate size and the difficulty in connecting large numbers of input and output fibers or electrical connections. By making the leap to multilayer interconnects, more compact devices can be obtained. Fewer connections between chips are required and some devices can be made smaller than their in-plane counterparts. The need to combine different materials on a single chip can be addressed as well. Three-dimensional routing of signals will thus be necessary for significantly more compact and powerful photonic ICs. However, there have been relatively few optical devices in the literature that have been developed specifically for the realization of three-dimensional photonic ICs.

Vertical directional couplers allow for very compact and fast three-dimensional optical switching devices, with coupling lengths less than 40 μm [1], [2]. Unfortunately, traditional vertical couplers have the drawbacks that the inputs and outputs are difficult to separate, and the materials are restricted by growth parameters. Wafer bonding overcomes these limitations by allowing separated input and output waveguides and the joining of materials of different lattice constants and crystallographic orientations. Using bonded vertical couplers, a large number of photonic IC planar layers of various compositions are possible, and with the right fabrication conditions, the current six to seven layers for typical electronic ICs may eventually be surpassed [3]–[5]. We describe in this letter the use of three-layer photonic interconnects to make a compact semiconductor 1 : 8 beam splitter.

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II. Device Fabrication and Structure

Cascaded 3-dB vertical couplers incorporating three layers (two InP-to-InP bondings) were fabricated. Three wafers were grown using metal–organic chemical vapor deposition (MOCVD). Due to the inversion resulting from the bonding, the order in which the wafers were processed is the opposite of the top-to-bottom order of the layers of the resulting bonded device. For the first (bottom layer) wafer, on a (001) InP substrate, a 0.5-μm InGaAsP ($\lambda_g = 1.3$ μm) guiding layer, followed by a 0.1-μm InP cladding layer were grown. All layers were undoped. The second (middle layer) wafer was grown on a (001) InP substrate as well. It consisted of a 0.2-μm InGaAs etch stop layer, followed by a 0.1-μm InP cladding layer, a 0.5-μm InGaAsP ($\lambda_g = 1.3$ μm) guiding layer, and a 0.5-μm InP support layer. For the third (top layer) wafer, on another (001) InP substrate, a 0.2-μm InGaAs etch stop layer, followed by a 0.9-μm InP cladding layer, a 0.5-μm InGaAsP ($\lambda_g = 1.3$ μm) guiding layer, and a 0.5-μm InP support layer were grown.

The device fabrication begins with the cleaving of the first wafer into a 1.3 × 1.5-cm sample, deposition of SiN, and standard photolithography with the corresponding removal of SiN to define the position of the bottom-layer waveguides. The waveguides were then etched using CH_4–H_2–Ar reactive ion etching, the SiN was removed, and the sample was bonded at 630 °C in a hydrogen atmosphere for 50 minutes to a blank sample of the second wafer cleaved to the same size. The substrate of the second wafer was removed in HCl and the InGaAs etch stop layer was removed in H_2SO_4–H_2O_2. After substrate removal, the processing for the second and third layers is identical to that of the first except that alignment marks were uncovered using infrared photolithography and wet etching with HCl and H_2SO_4–H_2O_2 after the SiN deposition. Lastly, the sample is cleaved into devices approximately 2 mm long including input and output waveguides to allow flexibility in the position of the cleave.

The waveguides were 3 and 4 μm wide. Support regions were placed 10 μm away from all waveguides to ensure that the structure did not deform. Unwanted coupling from the waveguides to the InGaAsP–InP support regions on adjacent layers will take place if the waveguides on one layer are allowed to be close to the InGaAsP of the other layer. The InP cladding region and InGaAsP guiding regions were hence removed from within 10 μm of waveguides on adjacent layers to prevent unwanted coupling.

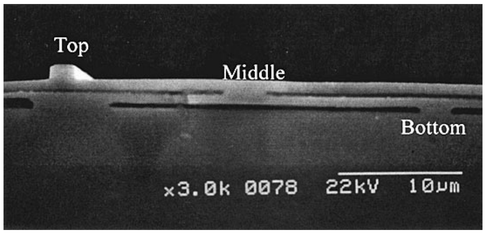

Fig. 1. SEM of output waveguides. From left to right, top, middle, and bottom waveguides are shown. Bonded region below top waveguide is for support.

Fig. 1 shows a SEM of the cleaved side of the device. To prevent a coupling asymmetry due to the lack of a 0.5-μm InP support layer above it, the top layer waveguide (1.4 μm high) was made taller than the bottom and middle layer waveguides (0.6 μm high).

III. Device Design

The principle of operation of the 1 : 8 beam splitter is one of two-mode interference. That is, the coupling of light is due to the overlap of the evanescent fields of the two waveguides such that after a given length, light entering one waveguide will couple half of its power to the other waveguide if the propagation constants of both individual waveguides are similar. Using the three-dimensional finite-difference beam propagation method (BPM [6]), the performance was simulated for various materials, coupling lengths, s-bend lengths, and waveguide heights. 1.3-μm InGaAsP ($n = 3.37$) was chosen as the waveguide layer rather than InGaAsP of a larger index of refraction because lower index waveguide layers result in shorter coupling lengths; this can be explained in a coupled-mode picture as an increase in the overlap integral of the two modes of adjacent waveguides [7]. The choices of waveguide height and separation were also influenced by the high index of the waveguide layer. For the structure described earlier, thinner waveguide layers, by providing less modal confinement, will also increase the overlap integral between modes of adjacent waveguides and will thus reduce the coupling length [7]; less separation between waveguides will also provide shorter couplers. With the material and waveguide heights used above, the 3-dB coupling lengths for the three stages of the 1 : 8 splitter are 37 μm, 39 μm, and 47 μm, respectively. The total device length, not including the straight input and output waveguides appended for ease of cleaving, is 583 μm.

By contrast, a beam splitter made from horizontal couplers using the same material and waveguide heights and widths as in layer 1, and with 1 μm separation between waveguides would have a 3-dB coupling length of 4.73 cm for a single stage consisting of straight waveguides only. Using s-bends long enough to allow the same output waveguide spacing as the bonded splitter, the total device length would be approximately 14 cm. Although a smaller waveguide separation would allow a shorter coupling length, the difficulty in making reproducible and uniform narrow-gap (<1 μm) horizontal couplers have hindered their development for ultra-short splitting and switching devices [7]. Thus, vertical couplers offer a great advantage in terms of device compactness.

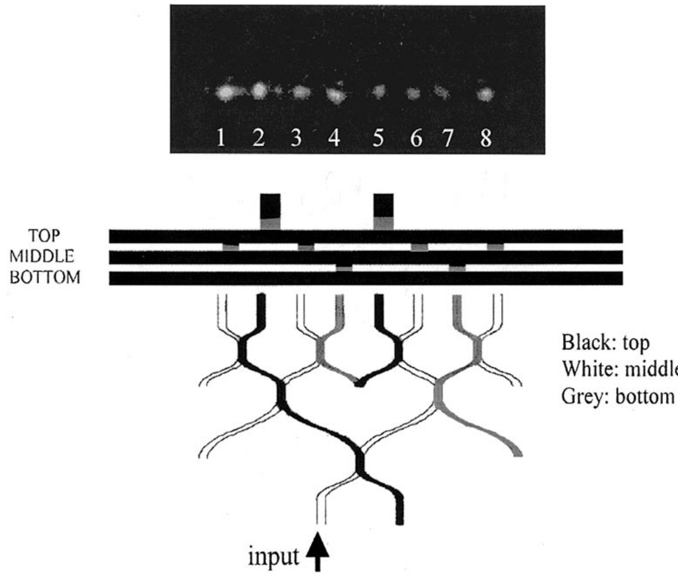

Fig. 2. Device output at $\lambda = 1483$ nm as captured by IR camera, and corresponding waveguide layout.

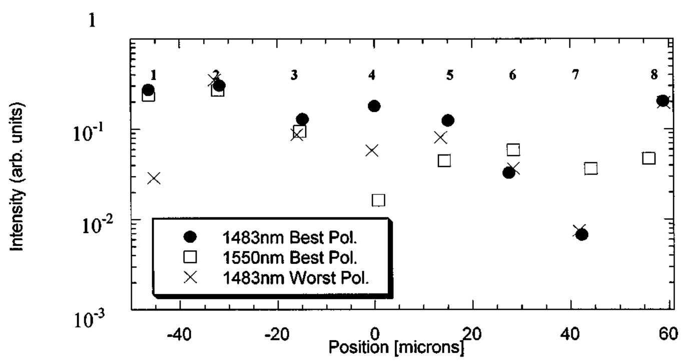

Fig. 3. Peaks of line scan of device output at 1483 and 1550 nm for best polarization and at 1483 nm for worst polarization.

IV. Results

The device output at $\lambda = 1483$ nm as captured by an infrared (IR) camera and the corresponding waveguide positions are shown in Fig. 2. Light from a tunable semiconductor laser is coupled to the waveguides via a single-mode lensed fiber. The output beams have slight height differences corresponding to the waveguide heights. They are separated by 15 μm for ease of coupling to the output fiber.

To measure the polarization and wavelength sensitivity of the device, the output of the device was coupled to a single-mode lensed fiber connected to a detector. The output fiber was mounted on a computer-controlled adjustable xyz stage, and was scanned across the output waveguides at different polarizations and wavelengths. As shown in Fig. 3, although the splitter can operate at different wavelengths and polarizations, the ratios of light intensity coupled to the various output waveguides changes somewhat. The unevenness in splitting is thought to arise from the less-than-ideal alignment obtained with a standard mask aligner, as the alignment tolerance was simulated to be approximately 0.25 μm. It is believed that more uniform splitting could be obtained through the use of a stepper mask aligner. The wavelength dependence could be lessened by

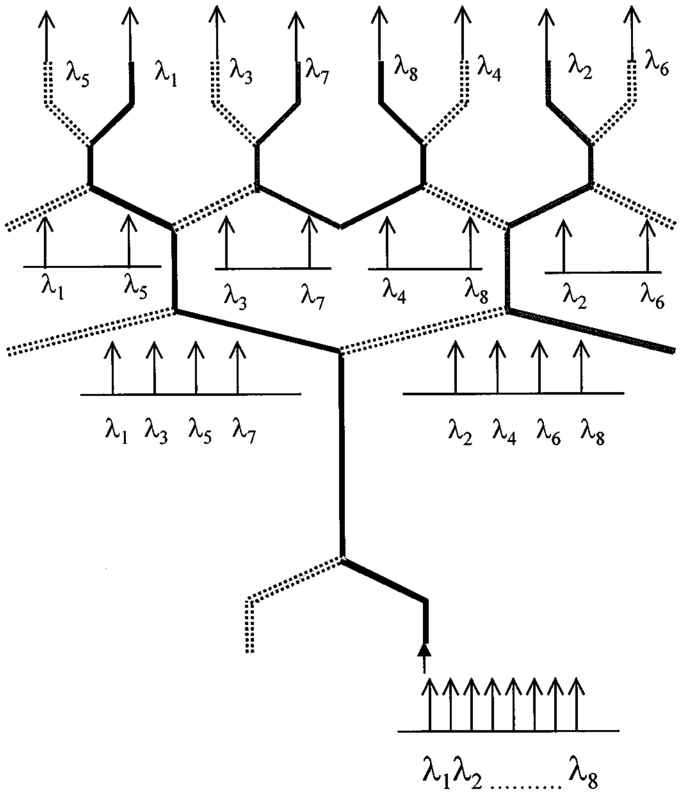

Fig. 4. Proposed demultiplexer with structure similar to that of beam splitter except for the coupler lengths.

designing even shorter couplers, for which the s-bends provide all of the coupling. The polarization dependence is a function of the structure and material parameters as well; the device could be made polarization-independent through a modification of waveguide design [8].

A Fabry–Perot resonance technique was used to measure the waveguide optical loss [9]. Straight waveguide regions were cleaved off of the sample and tested to give 1 dB of loss per 583-μm 1 : 8 splitter length. Total s-bend losses were calculated using BPM [6] to be 0.9 dB.

Future considerations include an optimization of the waveguide s-bends through use of the conformal transformation method [10]. The default s-bend shape provided by the BPM simulation program [6] was composed of two circular arcs. This design does not provide a minimum s-bend loss; a further reduction could be obtained through a conformal transformation analysis.

Another direction to be investigated is the transformation of the three-layer beam splitter into a demultiplexer through a change to the lengths of the coupling regions. This would be achieved by utilizing the wavelength dependence of the coupling. Couplers on each successive stage can be chosen to have lengths such that every other channel is split to a different output waveguide, as shown in Fig. 4.

V. Conclusion

A novel three-layer bonded vertical coupler 1 : 8 beam splitter is demonstrated. To our knowledge, this is the first three-layer three-dimensional waveguide beam splitter. A device length of 583 μm, two orders of magnitude smaller than the length of an equivalent horizontal coupler splitter, is obtained. This illustrates the powerful potential of the use of wafer bonding to fabricate three-dimensional photonic integrated circuits.

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