A wavelength multiplexer using cascaded three-dimensional vertical couplers

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A four-channel wavelength multiplexer/demultiplexer for sparse wavelength division multiplexing was demonstrated using cascaded three-dimensional (3D) vertical couplers. 17 nm channel spacing with crosstalk less than 15 dB was achieved. Strong coupled vertical couplers were fabricated using wafer bonding to invert a conventionally processed epitaxial layer and bond to a new host substrate. This technology makes the fabrication of 3D photonic integrated circuits and the realization of multilevel optical interconnects possible. © *2000 American Institute of Physics.*
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Increasing integration density is a key factor to reduce cost and improve performance in optoelectronic circuits. In conventional wafer processing, only one side of epitaxial films are used to fabricate photonic integrated circuits. If both sides of the epitaxial layers can be processed, three-dimensional (3D) structures can be fabricated and the integration density can be considerably increased. Since epitaxial layers, by themselves, are too thin to handle and process directly they must be transferred and bonded to other host substrates. For optoelectronic device applications, the bonded interface must be both electronically and optically transparent to make multilevel electrical and optical interconnects possible. The requirement for optical transparency means that the conventional bonding techniques such as flip-chip solder bonding are not suitable for photonic integration. Wafer bonding,[1,2] on the other hand, provides an interface with low electrical and optical loss.[3–5] In this letter, we demonstrate a wavelength multiplexer by cascading strong coupled 3D vertical couplers using wafer bonding technique and double-sided processing.

Wavelength multiplexers and demultiplexers (MUX/DEMUX) are the essential components in wavelength division multiplexing (WDM) networks. Although multiplexers based on directional couplers have been studied for a long time, they are applicable only to the case where the channel spacing is quite large (e.g., 980 and 1550 nm or 1300 and 1550 nm).[6] This is because of the weak wavelength dependence of the coupling coefficient in horizontally arranged directional couplers. Otherwise a very long device length is required. Compared to horizontal couplers, vertical couplers offer much stronger coupling since the thickness of the guiding layer and the space between two waveguides can be very small and precisely determined by the epitaxial growth.[4,7] The multichannel multiplexers with narrow channel spacing can be achieved by cascading several strongly coupled vertical couplers. However, separating the two input and output waveguides in conventional vertically coupled twin waveguide structures is difficult. This limits practical applications, and makes the cascading of several vertical couplers impossible. This problem is solved using double-sided epitaxial layer processing by wafer bonding in this letter.

The schematic drawing in Fig. 1(a) shows a four-channel multiplexer, which cascades two stages of 3D vertical couplers with different lengths. As can be seen in Fig. 1(b), the two waveguides of the 3D vertical couplers are coupled vertically and separated horizontally in different planes. This separation makes the cascading of vertical couplers possible. The operation principle of a multiplexer by cascading verti-

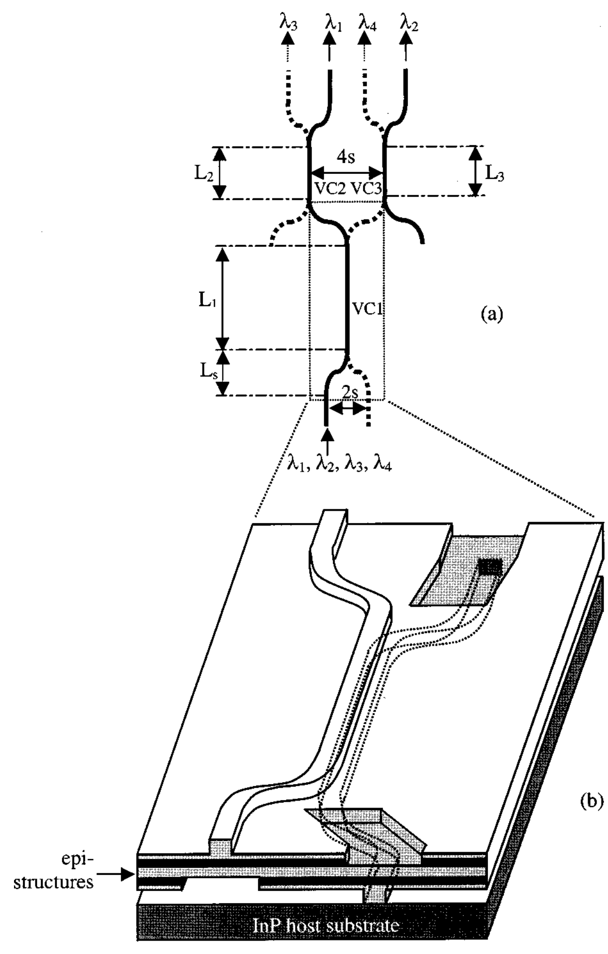

FIG. 1. (a) Schematic drawing of a four-channel MUX/DEMUX. Solid lines are the top waveguides and the dashed lines are the bottom ones, and (b) 3D vertical coupler with horizontally separated input and output waveguides.

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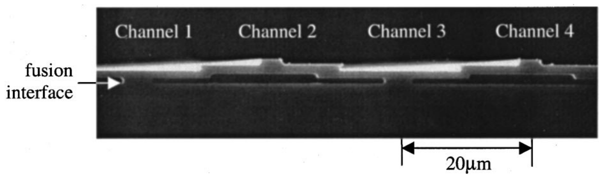

FIG. 2. The SEM picture of the output facet of a four-channel MUX/DEMUX.

cal couplers is the same as that of two-mode-interference (TMI) based multiplexers.[8,9] The output intensity of each stage is a periodic function of the optical frequency. The period is inversely proportional to the coupler length. Vertical coupler 1 (VC1) is twice as long as that of VC2 in the second stage, so the wavelength oscillation period (channel spacing) of VC1 is half that of VC2. VC3 has nearly the same wavelength period as VC2, but the peaks in the output should be shifted by a quarter period to match the channels. This can be achieved by a small adjustment to the length of VC3. In our design, after considering the coupling in the *s*-bend regions using a 3D beam propagation analysis, the parameters are chosen: $L_1=5$ mm, $L_2=2.397$ mm, $L_3=2.37$ mm for the vertical couplers and $s=10\,\mu$m, $L_s=500\,\mu$m for *s*-bends.

The epitaxial structure is grown using metal organic chemical vapor deposition (MOCVD). It includes a 0.8 μm InP frontside ridge layer, a 15 nm InGaAsP (band gap 1.1 μm) etch stop layer, a 0.1 μm InP cap layer, a 0.5 μm InGaAsP (band gap 1.3 μm) frontside guiding layer, a 0.6 μm InP coupling layer, the same backside guiding, cap, etch stop, and ridge layers, and finally a 0.2 μm InGaAs layer used to remove the InP substrate. First, the 3 μm width frontside ridge waveguides are formed by reactive ion etching (RIE) and chemical wet etching. The frontside guiding layer above the backside waveguides in noncoupling areas is removed by another step of photolithography and wet etching. The waveguide sample is then inverted and bonded to a bare InP host substrate under pressure for 50 min at 630 °C in H_2 atmosphere. After removing the original InP substrate and InGaAs etch stop layer, the alignment windows are opened by photolithography and wet etching to expose alignment marks, then the other side waveguides are fabricated and the unneeded guiding layers are removed as before. Figure 2 shows a scanning electron microscope (SEM) picture of the output facet of a four-channel device. The device length is about 1.4 cm after cleaving both facets. The transferred and bonded thin epitaxial film is robust and it is processed using the same techniques as other planar photonic integrated circuits.

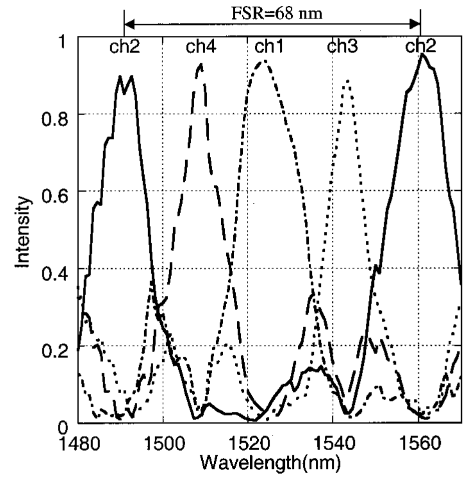

FIG. 4. Four-channel multiplexer transmission spectra.

To characterize the device performance, light from a tunable laser was coupled to an input waveguide by a single mode fiber. The light at the output was collected by another single mode fiber that was connected to a detector. The near field images were recorded by an infrared (IR) camera with a 20× lens. Figure 3 shows the near field images at different wavelengths: 1508, 1524, 1543, and 1561 nm, which are the peak response of the four channels. The corresponding output light intensity as a function of wavelength for the four channels is shown in Fig. 4. The free spectral range is about 68 nm, as can be seen in the response of channel 2. The channel spacing is 17 nm for a four-channel multiplexer. The measured adjacent channel crosstalk ranges from −13 dB to −20 dB. This can be further improved by fine tuning the second stage of vertical couplers to overcome fabrication imperfections. The channel spacing can be reduced by increasing the device length or the wavelength dependence of the coupling coefficient. Figure 5 shows the transmission spectrum of a 2-channel MUX/DEMUX with an 8 mm interaction length. The channel spacing is about 11 nm.

In conclusion, a four-channel wavelength multiplexer

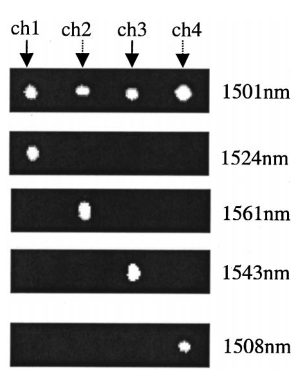

FIG. 3. Near field images of a four-channel multiplexer at different wavelengths.

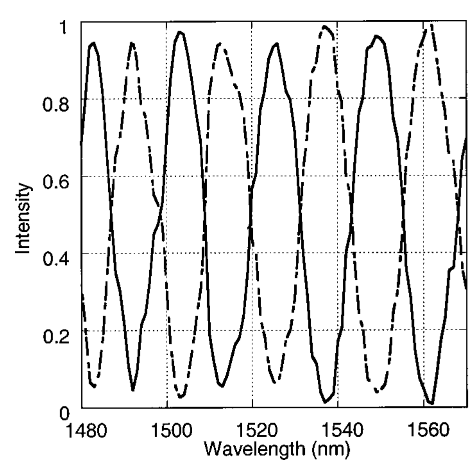

FIG. 5. The transmission spectrum for a two-channel MUX/DEMUX with an 8 mm interaction length.

using cascaded 3D vertical couplers has been successfully demonstrated. 17 nm channel spacing with crosstalk less than 13 dB–20 dB is achieved. By cascading additional stages of vertical couplers, a multichannel MUX/DEMUX can be realized. Using wafer bonding, a conventionally processed epitaxial layer can be inverted and bonded to a new host substrate. The backside of the epitaxial films can then be processed as well. This kind of double-sided processing makes the fabrication of 3D photonic integrated circuits possible and increases the integration density.

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