oe magazine
The Monthly Publication of SPIE—The International Society for Optical Engineering
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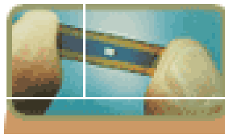

archives feature

integration in 3-D

wafer-bonding techniques yield vertically integrated optoelectronic devices.

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Photonic integrated circuits (ICs) have held the promise that the success of electronic ICs could be transferred to the realm of optics. Unfortunately, this promise has fallen short of expectations thus far. Compared with today's electronic ICs, which contain millions of transistors on a single silicon chip, the state-of-the-art for semiconductor photonic ICs has been limited to a handful of devices.

Three factors hamper the breakthrough of photonic ICs. First, the technology previously has lacked a large-scale market to push development, a situation that is beginning to change with the introduction of all-optical networks. Second, integrating a variety of photonic devices on one substrate material presents technical complications. Third, passive integrated optical devices and optical interconnects are significantly larger than their electronic counterparts.

Researchers are exploring rather complex processing techniques to overcome these problems. One technique is the universal substrate approach in which only a single compromise structure is grown.[1] The design of this structure is such that perhaps all of the individual device structures

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depart from optimum to an extent, but their integration offers an overall functional advantage. A second technique uses multiple growth steps and etch processes to yield separately optimized device structures.[2] This method complicates waveguide alignment and coupling, however. A third approach relies on selective area growth, which gives a certain degree of freedom to selectively determine the local bandgap of different devices within a single plane simultaneously.[3]

problems with photonics

Even with these techniques, large-scale photonic ICs are far from reality, primarily because the size of photonic devices (from hundreds of microns to several centimeters) limits the number of components that can be cascaded on a single chip. Waveguide interconnects present another important limitation to miniaturization.

In electronic ICs, nanoscale "wires" interconnect millions of electronic components in three dimensions. Current devices can include up to seven vertically interconnected layers, a number that will probably increase to nine by 2012. Photonic ICs, on the other hand, still rely generally on a single plane of optical waveguide interconnections that have more stringent requirements and tolerances than their electrical counterparts. Electrical currents in wires can be directed arbitrarily to different positions and layers without suffering a high loss. In photonic waveguides, the confinement of optical waves is relatively weak due to the finite refractive index contrast and the requirement for single-mode operation. Waveguides with sharp bends suffer from an unacceptable optical loss. Integration with mirrors is difficult, although recent advances in photonic bandgap waveguides have shown the potential to solve the problem of sharp bending radius.[4]

Another factor limiting the complexity of photonic ICs is that routing a large number of waveguides in two dimensions inevitably involves a large number of waveguide crossings, which increase crosstalk and loss. Conventional thin-film planar technology is not readily adaptable to vertically interconnecting multiple layers in three-dimensional (3-D) photonic ICs. Polymers may offer an option for this purpose, but without the optical properties of semiconductors, the functions of such photonic ICs are limited.[5]

To address interconnect issues, our group is using wafer bonding or wafer fusion techniques to produce 3-D waveguides. Initially developed for integrating two dissimilar materials, wafer bonding can combine two patterned wafers and enables the processing of both sides of epitaxial films.[6, 7] Thus, it offers a viable method to stack planar processed circuits vertically to form novel 3-D devices and circuits (see figure 1).

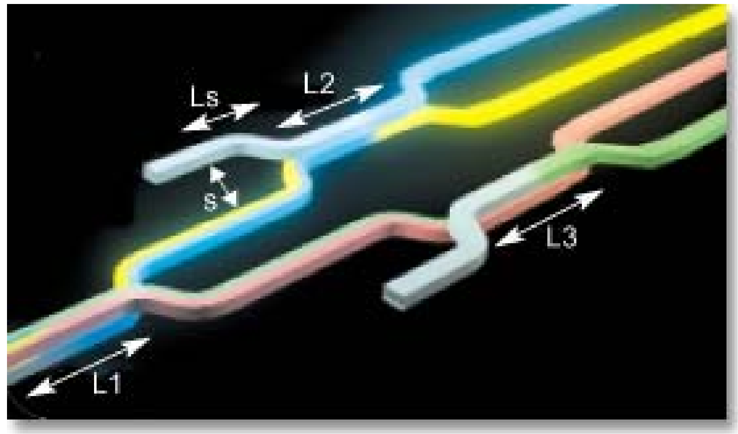

Figure 1 A four-channel multiplexer incorporates a pair of 3-D vertical couplers. Vertical coupler L_1 is 5 mm, L_2 is 2.397 mm, and L_3 is 2.37 mm. The horizontal spacing S is 10 µm, and the length of the S-bend L_s is 500 µm.

multiplexing in 3-D

One implementation of the technology is a four-channel multiplexer for optical networking applications that cascades two stages of 3-D vertical couplers of different lengths (see figure 1).[8] In this device, two waveguides of 3-D vertical couplers are cascaded by coupling vertically and separating horizontally. The operating principle of multiplexing/demultiplexing via cascaded vertical couplers is the same as that of two-mode, interference-based multiplexers. The output intensity of each stage is a periodic function of optical frequency, with the period inversely proportional to the coupler length. Vertical couplers in the first stage are twice as long as those in the second stage, so the wavelength oscillation period (channel spacing) of the first stage is half that of the second one.

The epitaxial structure was grown using metal organic chemical vapor deposition (MOCVD).[9] It includes a 0.8-µm indium phosphide (InP) front-side ridge layer, a 15-nm indium-gallium-arsenide-phosphide (InGaAsP) etch stop layer and a 0.1-µm InP cap layer. Next to this sandwich lies a 0.5-µm InGaAsP front-side guiding layer and a 0.6-µm InP coupling layer. For the back side we use the same guiding cap, etch-stop and ridge layers, and finally a 0.2-µm indium-gallium-arsenide (InGaAs) layer that facilitates removal of the InP substrate.

We fabricated the 3-µm wide front-side ridge waveguides by reactive ion etching (RIE) and chemical wet etching. A second photolithography/wet-etch step removes the front-side guiding layer above the back-side waveguides in noncoupling areas. Next, we invert the waveguide sample and bond it to a bare InP host substrate under pressure for 50 minutes at 630° C in a hydrogen atmosphere (see figure 2). After removing the original InP substrate and InGaAs etch-stop layer, we open the alignment windows, using an infrared (IR) mask aligner in which an IR camera is used to detect alignment marks beneath the surface, and wet etching exposes the marks. Then we fabricate the waveguides on the other side, and the unneeded guiding layers are removed as before.

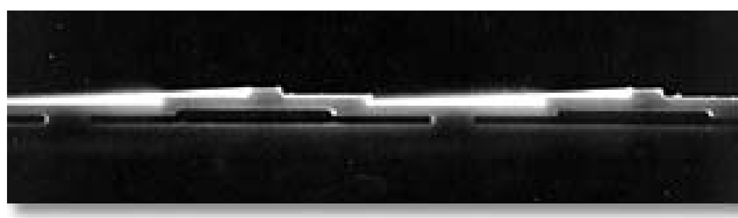

Figure 2 A scanning-electron-microscope (SEM) image shows the output facet of a four-channel MUX/DEMUX.

To characterize the device performance, light from a tunable laser was coupled to an input waveguide by a single-mode fiber, and the device output was transferred to a detector by a second fiber. An infrared camera with a 20* lens recorded the near field images. The free spectral range is about 68 nm, as can be seen in the response of channel 2 (see figure 3). The measured adjacent channel crosstalk ranges from –13 dB to –20 dB. We could further improve performance by fine-tuning the second stage of the vertical couplers to overcome fabrication imperfections. The channel spacing can be reduced by increasing the device length or by changing the wavelength dependence of the coupling coefficient.

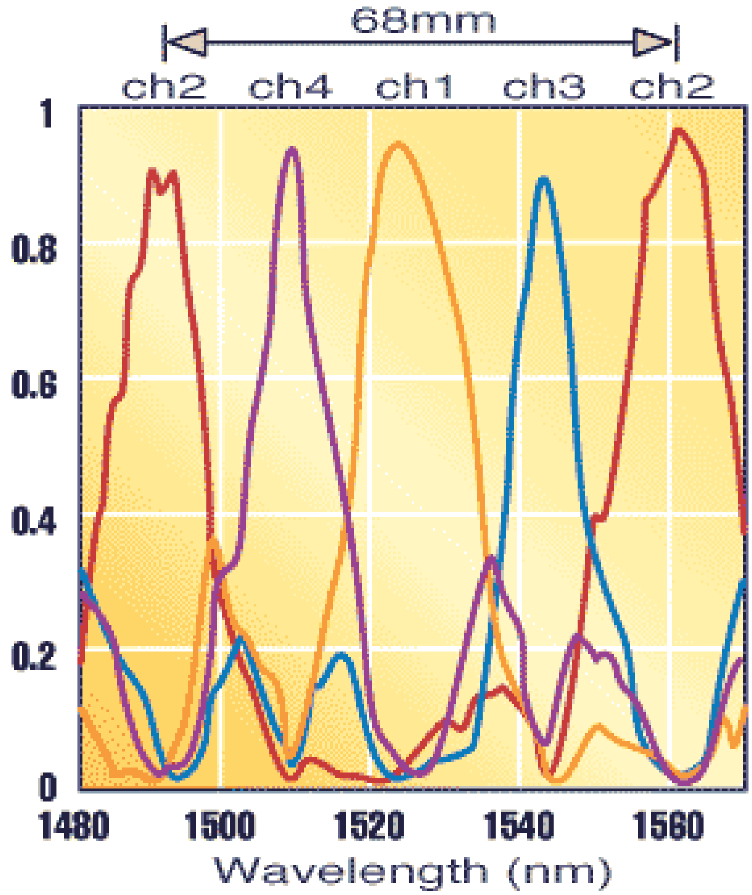

Figure 3 Output light intensity as a function of wavelength for the four channels shows a free spectral range of 68 nm.

add/drop devices

Again using MOCVD on an InP substrate, we also have grown an x-crossing vertical add/drop filter.[10] The structure consists of two vertically coupled ridge-loaded waveguides. As with the MUX/DEMUX example, wafer bonding and double-sided processing are the keys to realizing x-crossing structures. To fabricate this device, we first formed the lower InGaAsP ridge waveguides using reactive ion etching or chemical wet etching to generate a 0.8-µm-high, 3-µm-wide ridge (see figure 4). Next, using chemical etching we removed the 1.4 µm quaternary layer below the top 1.1-µm InGaAsP waveguides at two ends of the sample to eliminate unneeded coupling. We inverted the structure and fused it to a second InP substrate under pressure and in a hydrogen atmosphere; then we removed the original substrate and the etching-stop layer in another wet-etch step. After fabrication of the upper 1.1-µm quaternary waveguides, we removed the 1.1-µm InGaAsP layer above the lower 1.4-µm InGaAsP waveguide region.

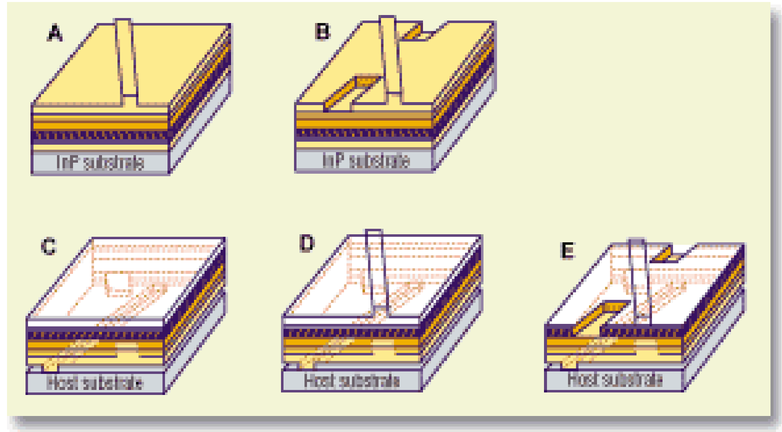

Figure 4 Fabrication steps for an x-crossing coupler include (a) forming the upper waveguide, (b) removing the InGaAsP layer, (c) inverting the sample to bond to a host layer and to remove original substrate and etch stop layer, (d) fabricating another waveguide, and (e) removing the InGaAsP layer.

The transmission spectra of the TE mode from input port to the drop and through ports with the crossing angle of 0.25° show a 3-dB bandwidth of 6 nm (see figure 5). The device suppresses the sidelobe level to below –25 dB. The coupling efficiency from the add port to the through port, which strongly depends on the crossing angle, exceeds 97%.

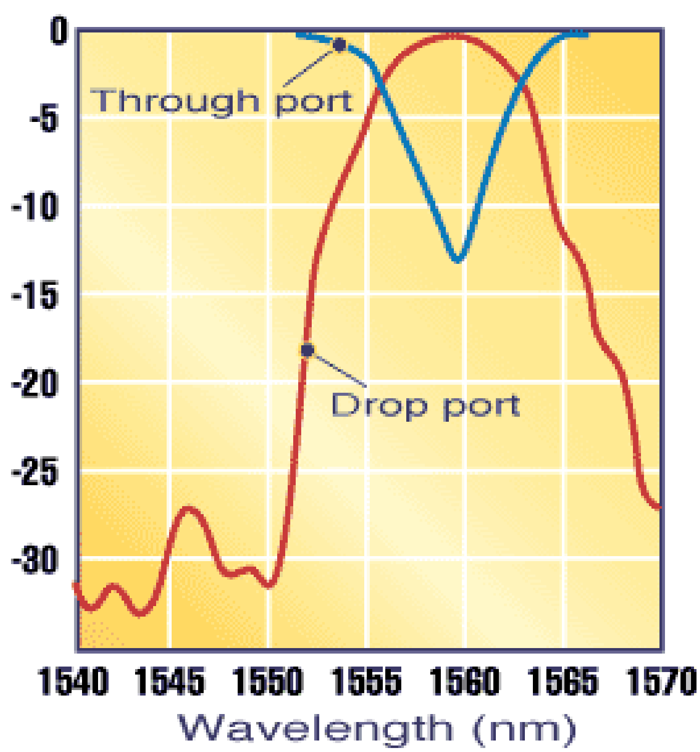

Figure 5 Transmission spectra of the TE mode shows a 3-dB bandwidth of 6 nm. Data have been normalized to the total

output power from through and drop ports.

Wafer fusion techniques also have been used to combine InP and gallium-arsenide (GaAs) waveguides. This method ultimately can be used to combine active and passive photonic devices based on different substrate materials (see figure 6), helping realize the early promise of photonic ICs. oe

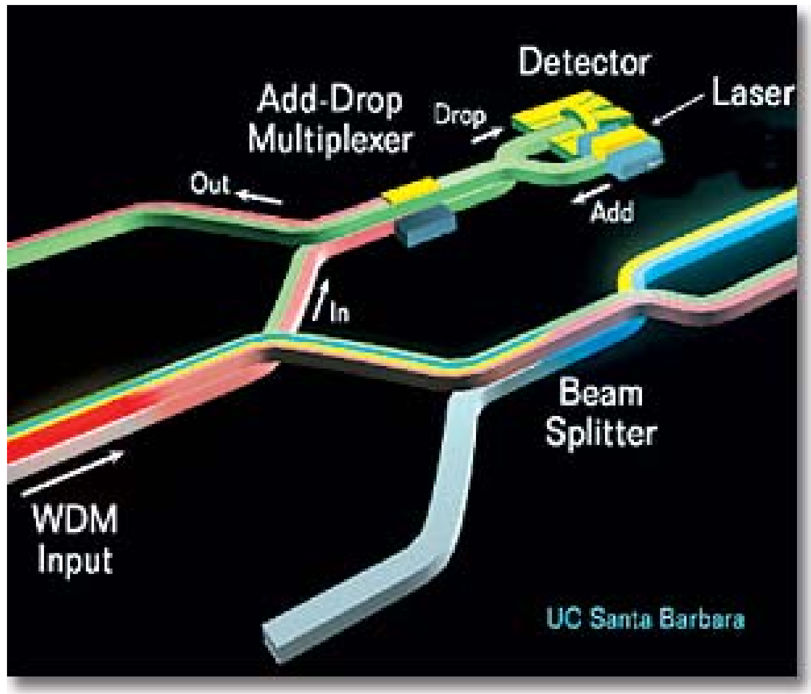

Figure 6 Wafer fusion techniques can integrate active and passive devices.

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Enhancing network performance

Planar lightguide circuits (PLCs) promise to reduce costs through high-volume wafer-scale processing while allowing integration of multiple functions on a single substrate to increase functionality while reducing the footprint. In many ways, the transition from discrete optical components to PLCs mirrors the transition in the electronics industry from the use of discrete transistors to the use of integrated circuits.

In a typical planar lightguide circuit, a silica (glass) waveguide is lithographically patterned on a silicon substrate. The fabrication technique allows wafer-scale processing, automation, integration of multiple functions, and customization to individual requirements. Silica-on-silicon is the most commonly used PLC platform due to its close index match to silica fiber and the maturity of the processing equipment, but waveguides can be fabricated using polymers, silicon-oxynitride, and pure silicon.

While high-channel-count dense-wavelength-division-multiplexing (DWDM) technology allows network designers to greatly increase capacity on a fiber, it requires efficient and cost-effective filtering components. Thin-film filters are currently the most popular filter type, but they do not scale well to high channel counts or dense channel spacings. Arrayed waveguide gratings (AWGs), PLC components in which multibeam interference allows the simultaneous filtering of 40 channels or more, can provide the desired cost, size, and functionality needed for high-bandwidth systems (see figure

1).

In DWDM systems, it is critical to ensure equal power across the wavelength channels as the signals are transmitted through multiple optical amplifiers. Variable optical attenuators (VOAs) allow individual channels to be balanced to compensate for amplifier nonlinearities and to avoid receiver saturation. While single-channel VOAs exist, the same inefficiencies occur as with thin-film filters when the channel count increases. A VOA can be created on a PLC by creating an interferometric waveguide structure and controlling the relative phase of one arm. Heating one arm of the interferometric structure triggers controlled interference at the output, introducing attenuation. With solid-state design, the devices offer higher reliability and robustness than mechanical VOAs.

Switching is another function that is required in an optical network, either for protection routing or for cross connects. Low-port-count switches can be made with PLC structures very similar to the VOA described above, but with the output controlled to be either completely on or off. For high-port-count applications, other technologies may be more suitable.

Finally, hybrid products can be created by bonding active elements to the PLC platform. An example of such a product is an optical channel monitor, created by bonding a detector array to the output of an AWG to monitor individual channels. This type of product is needed as more functionality is created in the optical layer, for example to monitor the signal quality and detect if wavelengths are switched in a mesh network.

—Bob Shine, WaveSplitter Technologies, Inc.

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