Optical Add/Drop Multiplexers Based on X-Crossing Vertical Coupler Filters

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***Abstract*—A simple optical add/drop multiplexer (OADM) based on a X-crossing InGaAsP–InP vertical coupler filter is demonstrated. Laterally separated input and output waveguides and the X-crossing arrangement are achieved using wafer bonding. A sidelobe level of -26 dB and a coupling efficiency of 97% with the central wavelength at 1.56 μm were measured for an OADM with an X-crossing angle of 0.25°.**

***Index Terms*—Optical directional couplers, optical waveguide filters, wafer bonding, wavelength division multiplexing.**

I. INTRODUCTION

OPTICAL add/drop multiplexers (OADM's) [1] are the key components for wavelength-division multiplexing (WDM) systems to select and route different channels. Various OADM configurations have been investigated, including fiber or polymer gratings with circulators [2], a Mach–Zehnder interferometer with gratings [3], cascaded unbalanced Mach–Zehnder structures [4], and arrayed waveguides [5]. Compared to other OADM structures, InGaAsP–InP vertical coupler filters [6], [7] are of particular interest for OADM's because of their simple configuration, large wavelength tunability, and inherent monolithic integration with other optoelectronic devices, (such as lasers, amplifiers, and photodetectors). A limitation in vertical couplers has been coupling to conventional fibers. Direct coupling is impossible since in traditional vertical coupler filters, the spacing between the two waveguides is only about 1 μm. Etching and regrowth can be used to separate the two waveguides [8], but regrowth and lateral propagation over nonplanar surfaces is problematic. Another problem in conventional vertical coupler filters is a high sidelobe (-9 dB) due to the uniform coupling along the length of two parallel waveguides. To reduce the sidelobe, the two waveguides should be gradually coupled. This is quite difficult to realize using conventional techniques. In this letter, a simple OADM based on X-crossing InP–InGaAsP vertical coupler filter is proposed and demonstrated. With an X-crossing configuration, the two input and output waveguides can be laterally separated for direct coupling to fibers, and the sidelobe level is reduced to -26 dB.

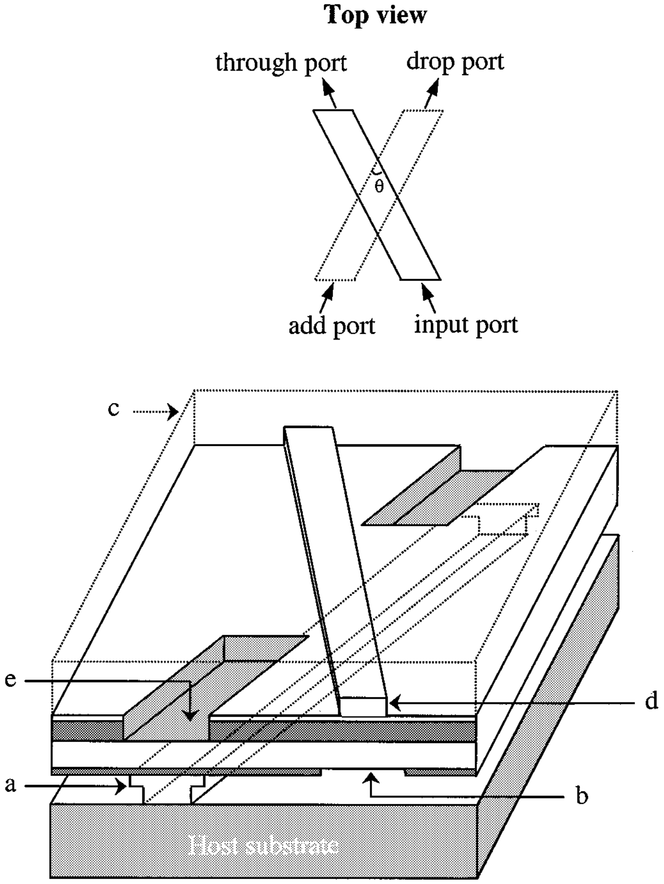

Fig. 1. Schematic drawing of an OADM based on an X-crossing vertical coupler filter. Various processing steps are also indicated (a)–(e).

II. DEVICE STRUCTURE AND FABRICATION

Fig. 1 shows the schematic drawing of an OADM. The filter consists of two vertically stacked waveguides with different quaternary compositions. The lower guiding layer is 0.21-μm-thick InGaAsP that has a bandgap at 1.4 μm, and the upper guiding layer is 1-μm-thick InGaAsP with a bandgap at 1.1 μm. Those two dissimilar waveguides have identical propagation constants at a particular wavelength (phase-matching point), and only light at this wavelength can be completely transferred from one to another waveguide after the coupling length. At other wavelengths, the coupling is very weak due to phase mismatching. This is the basic operational principle of a coupler filter. Furthermore, the two waveguides cross over each other in a simple X shape. This results in position-dependent coupling strength and suppresses the sidelobe to below -40 dB. Fig. 2 shows the calculated filter responses of an X-crossing

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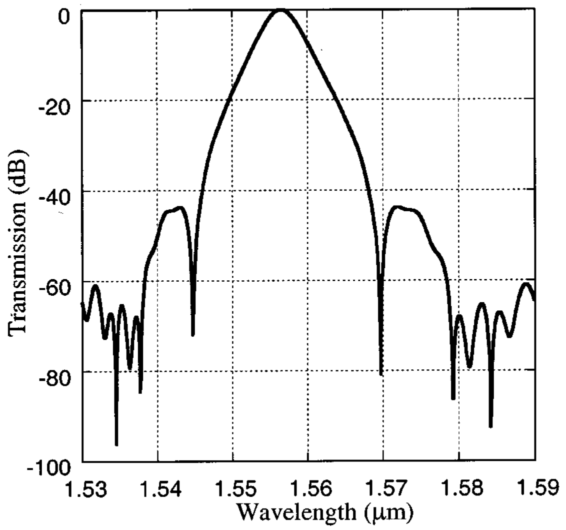
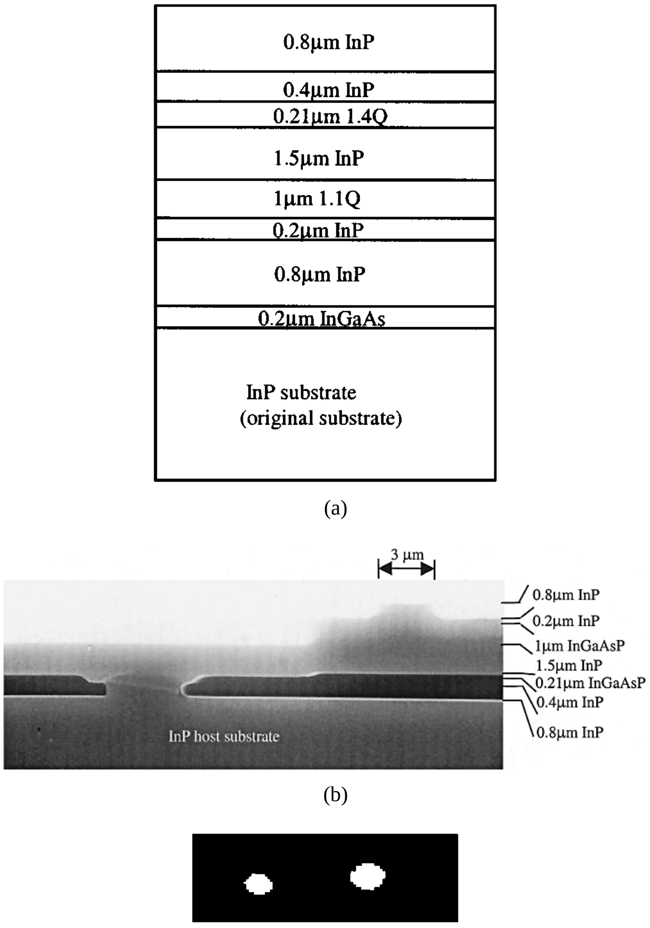


Fig. 2. Calculated filter response with 0.25° crossing angles.



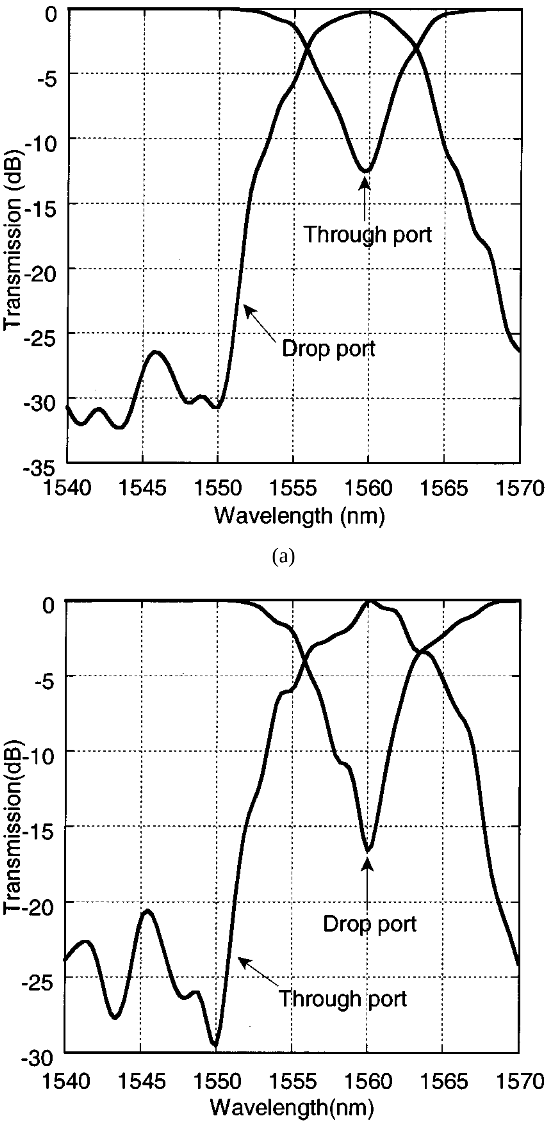
(a)

(b)

(c)

Fig. 3. (a) The detailed MOCVD grown structure, (b) the SEM picture of the output facet, and (c) the near-field pattern at the output facet.

filter with an X-crossing angle of 0.25°. To calculate this response, we first used the effective index method to calculate the effective indexes of individual waveguides. The X-crossing structure was then divided into many short sections, each assumed to have a position-independent coupling coefficient. Last, a transfer matrix method based on coupled-mode theory [9], [10] was used to simulate the filter response. This approximate method is an efficient way for the purpose of design.



(a)

(b)

Fig. 4. The TE mode transmission spectra of an OADM with X-crossing angle of 0.25°: (a) input port to drop and through ports and (b) add port to through and drop ports.

In this work, the X-crossing structure is fabricated by wafer bonding. A conventionally processed epitaxial layer structure is inverted and bonded to a new host substrate [11]. After removing the original substrate, the exposed backside of the epitaxial structure can be processed as well. Since the wafer bonded interface has good electrical and optical properties, one can repeat this process and fabricate novel multilevel three-dimensional photonic integrated circuits.

The device structure was grown by metal–organic chemical vapor deposit (MOCVD) on an InP substrate. The detailed structure is shown in Fig. 3(a). First, InGaAsP ($\lambda_g = 1.4\ \mu$m) ridge waveguides are formed by MHA ($CH_4/H_2/Ar$) reactive ion etching (RIE) and wet etching ($HCl : H_2O$) [Fig. 1(a)]. The ridge height is 0.8 μm, and its width is 3 μm. The 1.4-μm quaternary

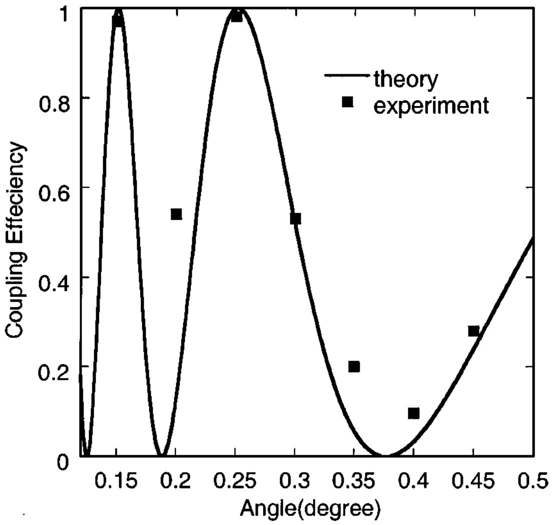


Fig. 5. Calculated and measured coupling efficiency as a function of crossing angle.

layer below the top InGaAsP InGaAsP ($\lambda_g = 1.1$ μm) waveguides at two ends of the sample is removed by chemical etching ($1:1:10$–$H_2SO_4:H_2O_2:H_2O$) [Fig. 1(b)]. Then the sample is inverted and bonded to a second bare InP substrate under pressure and H_2 atmosphere [11]. After removing the original substrate and 0.2-μm InGaAs etch stop layer [Fig. 1(c)], the upper 1.1-μm quaternary waveguides are fabricated [Fig. 1(e)] and the 1.1-μm InGaAsP layer above the lower 1.4-μm InGaAsP waveguide region is removed as before [Fig. 1(e)]. Fig. 3(b) shows the scanning electron microscope (SEM) picture of the output facet of an OADM with a crossing angle of $\theta = 0.1°$.

III. RESULTS

A tunable semiconductor laser with a polarization controller was used as a light source to measure the performance of the OADM. Single-mode fibers were butt-coupled to the input and output waveguides. Fig. 3(c) shows the near-field pattern at the output facet. The transmission spectra of the TE mode from input port to drop and through ports of an OADM with the crossing angle of 0.25° are shown in Fig. 4(a), where the data have been normalized to the total output power from through and drop ports. The 3-dB bandwidth is 6 nm. The sidelobe level has been suppressed to below -25 dB in this device. The fiber-to-fiber loss is about -21 dB. The transmission spectra from add port to through and drop ports are also shown in Fig. 4(b). The corresponding fiber-to-fiber loss is about -25 dB, which is higher than the loss when light launches from the top waveguide. This is because the 1.4-μm InGaAsP waveguide has a higher absorption than the 1.1-μm InGaAsP waveguide at 1.55 μm. The coupling efficiency from add port to through port is above 97%, which strongly depends on the crossing angle. Fig. 5 shows the calculated and measured coupling efficiency as a function of crossing angle, calculated using the effective index method and coupled-mode theory as described before. We note that the sidelobe in Fig. 4(b) is about -21 dB, and there is a difference between Fig. 4(a) and (b). One reason is because the 1.4-μm InGaAsP waveguide is a multimode waveguide, and multimode interference occurs when light is launched from this waveguide. The current device is polarization dependent. There is about 60-nm wavelength peak shift between TE and TM modes. Future work will focus on reducing the polarization sensitivity of this device by cascading two X-crossing structures, where one is for TE mode and another is for TM mode. Fiber-to-fiber loss can be reduced using tapered input and output waveguides.

IV. CONCLUSION

A very simple OADM based on X-crossing InGaAsP–InP vertical coupler filters with laterally separated input and output waveguides has been successfully demonstrated. The sidelobe level has been reduced to -26 dB, and the coupling efficiency is above 97%. To our knowledge, these are the best reported results so far for vertical coupler filters. Compared to other OADM structures, X-crossing vertical coupler filters can avoid complicated material regrowth and grating fabrication. These filters are attractive and low-cost candidates for OADM in WDM networks. Double side wafer processing by wafer bonding is an enabling technique to fabricate novel and high-performance waveguide devices and photonic integrated circuits.

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