Fused InP–GaAs Vertical Coupler Filters

Bin Liu, Ali Shakouri, P. Abraham, Y. J. Chiu, S. Zhang, and John E. Bowers, *Fellow, IEEE*

Abstract— A novel vertical coupler filter based on fused In-GaAsP–InP and AlGaAs–GaAs waveguide structures is proposed and demonstrated. The large material dispersion difference between InGaAsP and AlGaAs around 1.55 μm and similar waveguide geometries are used to realize a less sensitive polarization and narrow-band filter with two separated inputs and outputs and more than -40-dB sidelobe suppression should be possible.

Index Terms— Integrated optoelectronics, optical directional couplers, optical waveguide filters, wafer bonding.

INTEGRATED compact and narrow-band optical filters are key components for dense wavelength division multiplexing (DWDM) systems as add/drop multiplexers and demultiplexers. To date, many types of add/drop filters have been proposed and realized including diffraction gratings, arrayed-waveguide gratings, Mach–Zehnder interferometers and directional couplers. Compared to other structures, asymmetric directional coupler filters [1]–[3] using two dissimilar waveguide on III–V semiconductors are promising because of the precise control of waveguide thickness and indexes during crystal growth and monolithic integration with other devices such as optical amplifiers, photodectors, modulators, and lasers. There are, however, several obstacles to using these vertical coupler structures in system applications. The characteristics are strongly polarization dependent, launching the light into and coupling light out of two very close waveguide are very difficult and the coupling efficiency for two dissimilar waveguide geometries can be very different. In this letter, a novel vertical coupler filter (VCF) based on wafer fusion technology is proposed and demonstrated. This combines two different material systems: AlGaAs–GaAs with a low material dispersion at 1.55 μm and InGaAsP with a very high material dispersion. With a proper design, a narrow-band and polarization independence filter with two separated inputs and outputs can be easily realized, which solves all of the above problems.

It is well known that the response bandwidth of the asymmetrical directional coupler is inversely proportional to both the device length and the difference of mode dispersion in the two waveguide $\sigma = (dn_1/d\lambda) - (dn_2/d\lambda)$, where n_1 and n_2 are effective indices of the two waveguide eigenmodes. To minimize the device length and reduce the sidelobes, the filter bandwidth can only be narrowed by increasing σ. The modal dispersion depends on two factors. The first one is waveguide dispersion that depends on waveguide geometry;

the other one is the material dispersion. Vertical coupler filters realized up to now use mainly waveguide dispersion difference [1]–[3]. A narrow bandwidth requires one of the waveguide to have a very small index difference between the core and the cladding, and a large core size, while the other one should have a large index difference and a small core size. To keep the single-mode operation and a high coupling efficiency with fibers, the waveguide core size can not be too large or too small, and this limits the bandwidth of the filter. On the other hand, the difference in effective indices between TE and TM modes for a waveguide with a large index difference and small core is much more than the TE and TM difference of another waveguide with small index difference and large core size. Consequently, these devices have a strong polarization dependence. Generally the polarization dependent wavelength shift is more than 30 nm [4], [5] and that is a disadvantage in fiber optic communication systems. A birefringence compensation technique [5] has been used to solve this problem. But this needs a complicated structure design and a critical material growth. Since the polarization dependence and different coupling efficiency come from the strong asymmetry of two waveguide geometries, these problems can be solved if the two waveguide have similar structures. For these waveguide with almost identical waveguide dispersions, a large material dispersion difference between two waveguide is needed to realize a narrow-band polarization independent filter. It is known that a material has strong dispersion when the operation wavelength is near the band gap. So InGaAsP material can have much higher dispersion than AlGaAs material around 1.55 and 1.3 μm. For example, the material dispersion of InGaAsP ($\lambda g = 1.45$ μm) at 1.55 μm is $-0.48/\mu$m [6], which is almost one order of magnitude higher than that of $Al_{0.1}Ga_{0.9}As$, $-0.059/\mu$m [7]. Such a large dispersion difference is very difficult to obtain if one only uses different waveguide geometries. Unfortunately, because of the large lattice mismatch, good quality InP can not be grown on GaAs substrate or vise versa. Recently, a new technique called wafer fusion [8] or wafer bonding [9] has been developed that combines two materials with a large lattice mismatch. Wafer fusion can also be used to fabricate three-dimensional (3-D) photonic devices. For conventional vertical coupler filters, the difficulty of separating the two waveguide limits its application to WDM systems. Using wafer fusion, the two close inputs and two outputs can be easily separated in different planes [10], [11]. Fig. 1(a) is the schematic drawing of a fused InGaAsP–InP–AlGaAs–GaAs vertical coupler filter with separated inputs and outputs.

The detailed structure of the proposed fused vertical coupler filter is illustrated in Fig. 1(b). The upper InGaAsP–InP waveguide consists of a 0.4-μm InGaAsP ($\lambda g = 1.45$ μm) guiding
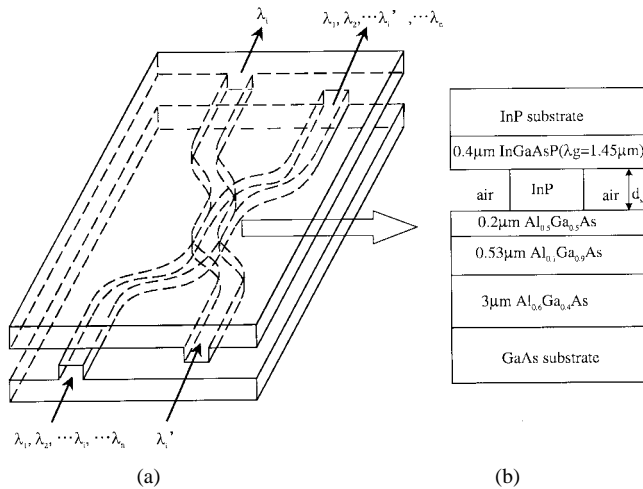
Fig. 1.   (a) The proposed fused vertical coupler with separated inputs and outputs for add/drop applications. (b) The detailed structure of fused In-GaAsP–InP and AlGaAs–GaAs filter.
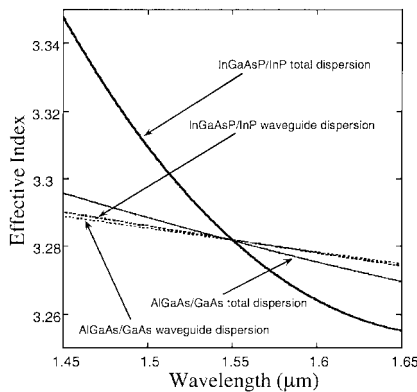

Fig. 2.   The calculated waveguide dispersions and total dispersions of In-GaAsP–InP and AlGaAs–GaAs waveguide.

Fig. 3.   The calculated effective index for TE and TM modes. The In-GaAsP–InP waveguide has 0.4-μm quaternary ($\lambda_g = 1.37$ μm) core and 0.1-μm InP cladding layer. The AlGaAs–GaAs waveguide is similar as before except the core thickness is 0.46 μm.

Fig. 4.   The response of an X-crossing fused vertical coupler filter with $\theta = 0°$ and $0.16°$. $d_s = 1.2$ μm. The insert is the schematic drawing of X-crossing fused vertical coupler filter.

layer and an InP cladding layer. The lower AlGaAs–GaAs waveguide includes a 0.53 μm $Al_{0.1}Ga_{0.9}As$ core and a 0.2 μm $Al_{0.5}Ga_{0.5}As$ cladding layer. Those two waveguide are phase matched at 1.55 μm. Fig. 2 shows waveguide and total dispersions of 3 μm wide upper InGaAsP–InP and lower AlGaAs–GaAs waveguide calculated by a transfer matrix method with effective index approximation. The index data are taken from [6] and [7]. The waveguide dispersions of the two waveguide are very small and almost identical, so the material dispersion dominates in our vertical coupler filter. In the current structure, because of similar waveguide structures, there is only 8-nm polarization dependent wavelength shift which is much less than the value of more than 30 nm in the conventional vertical coupler filter. It is easy to realize polarization independent vertical coupler filters by replacing 1.45-μm quaternary with 1.37-μm quaternary. This is shown in Fig. 3. Since the material dispersion of 1.37-mm quaternary is a little lower than that of 1.45-μm quaternary, a small bandwidth will be sacrificed in this structure.

Using a 3-D beam propagation method (BPM), the performance of fused filters is simulated. When the separations of two waveguide $d_s = 1.2$, 1.6, and 2 μm, the corresponding coupling lengths (100% power transfer) are 1, 4.5 mm, and

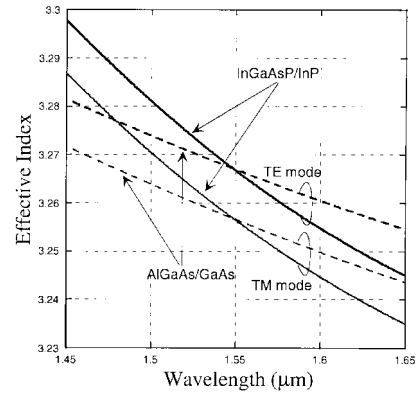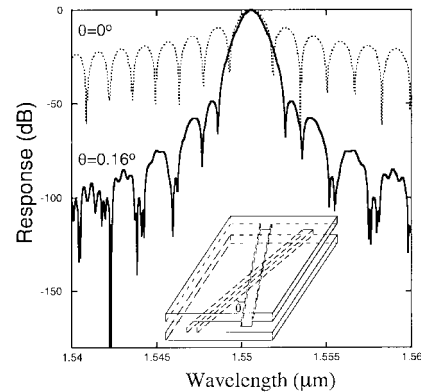2 cm and the bandwidths are 4, 0.8, and 0.2 nm at the coupling length. As we expected, the central wavelength is independent of the separation distance of two waveguides and the bandwidth is inversely proportional to the coupler length. Because of uniform coupling, there is a -9-dB sidelobe, which is too high for practical application. By using an X-crossing structure [12], the sidelobe can be suppressed to more than -40 dB, which satisfies the requirement of most WDM systems. Fig. 4 shows the calculated response of an X-crossing fused vertical coupler with a crossing angle $\theta = 0.16°$ using coupled mode theory. One should note that the fabrication of an X-crossing vertical coupler filter structure with separated inputs and outputs is very easy with the use of wafer fusion technology.

We have fabricated a fused straight ($\theta = 0°$) vertical coupler filter based on MBE grown GaAs and MOCVD grown InP waveguide. The structure is shown in Fig. 1(b) and the separation of the two waveguides is 1.2 μm, which corresponds to 1-mm coupling length. A 3 mm long device has been measured. Fig. 5 shows the measured response. The 3-dB bandwidth is 1.2 nm, which agrees very well with theoretical value of 1.3 nm. The measured coupling efficiency (the optical power from the output waveguide divided by the sum of the optical power from both the
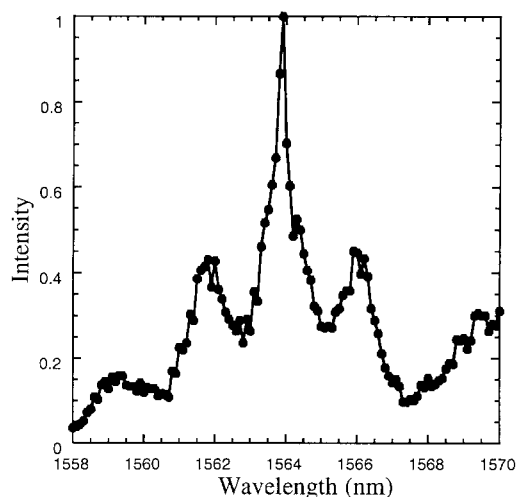
difference between InGaAsP–InP and AlGaAs–GaAs waveguide, this kind of fused filters will be very promising in WDM systems. Furthermore, these fused waveguide structures can be used to realize tunable wavelength lasers and wavelength selective detectors.

Fig. 5.   The measured response of a 5-μm-wide fused vertical coupler.

output and input waveguide) of the current device is about 50%. The polarization dependent wavelength shift is only 5 nm. Theoretical calculations predict a 7-nm shift, and as shown in Fig. 3, this polarization dependence can be eliminated with proper design. To optimize the design of fused InP–GaAs coupler, one should take into account material losses. The bandgap of InGaAsP guiding layer is closer than GaAs–AlGaAs material to the operation wavelength at 1.55 μm. One thus expects larger band-to-band absorption in InGaAsP waveguides. However in doped materials, free carrier absorption increases and dominates when the wavelength is farther from the bandgap. We have measured 4–6-dB/cm optical propagation loss for both InP–InGaAsP and GaAs–AlGaAs waveguides at 1.55 μm. We did not notice substantial increase in loss for the lower bandgap material InGaAsP. The fusion process adds 1–3-dB/cm loss [10].

In conclusion, a novel fused vertical coupler filter has been demonstrated. Due to its inherent polarization-independence and narrowband that comes from a large material dispersion

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