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III-V compound semiconductor strip-loaded waveguide devices for PICs: design for minimum crosstalk and high density (invited)

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ABSTRACT

Compact, low-cost photonic integrated circuits (PICs) have long been a desire of systems engineers. Unfortunately, the majority of PICs in use today use regrown buried heterostructure waveguides to achieve low crosstalk at reasonable packing density. These regrown structures are very expensive and limit PIC applications to high performance niches. The alternative low-cost approach is to use etched-rib, or strip-loaded, waveguides. Strip-loaded waveguides are simple to manufacture but may have guided slab-modes carrying unwanted light between devices within the PIC. These slab modes can result in very high crosstalk or low device density. This paper addresses techniques for control of stray light in strip-loaded PICs. Methods include mesa isolation of waveguides and ion implantation outside the waveguide rib. In addition, some devices such as Mach-Zehnder interferometers and waveguide power combiners generate radiation and slab modes as a fundamental means of operation. Improved designs for both of these structures with proper removal of both radiated and slab-mode light and high contrast-ratio operation will be covered.

2. INTRODUCTION

Photonic integrated circuits (PICs) are attractive for applications involving data transfer and signal processing using optical signals. Circuits such as local oscillator demultiplexers have recently been fabricated[1]. However, nearly all of the advanced PICs have used regrown buried heterostructures due to their simplified optical mode control and reduced crosstalk. This improved functionality comes with the requirement of epitaxial regrowth. Regrowth is an expensive, process-yield limiting-step which is the root cause for the high cost of PICs today. Simple strip-loaded ridge waveguides offer a lower-cost solution which may allow PICs to be used in consumer-oriented markets provided adequate performance can be achieved. This paper examines the technical aspects of applying strip-loaded ridge waveguides in III-V compound semiconductor PICs.

3. ETCHED RIB VERSUS BURIED HETEROSTRUCTURE WAVEGUIDES

Buried heterostructure waveguides are constructed using a layer of high refractive index on top of a thick layer of lower refractive index. The high index layer is etched through to form a rib and another layer of low-index material is regrown on top of this etched layer to completely surround the rib with low-index material. (Fig 1(a)) In contrast, a strip-loaded ridge waveguide ("ridgeguide") is formed by growing a slab structure of two low-index layers above and below one high-index layer. A ridge is then etched into the upper low-index layer to form the waveguide[2] (Fig. 1(b)). The key difference between the two structures is that waveguiding in the buried heterostructure is similar to that of an optical fiber where the waveguide core is surrounded by cladding and light can only be guided in the core region itself whereas the ridgeguide is surrounded by slab waveguides (two-dimensional "slabguides") with their own guided modes. It is these slabguides which have potential to increase crosstalk in a PIC by trapping light scattered or radiated from the ridgeguide in guided modes of the slabguide. Once in the slabguide, light is easily coupled between adjacent ridgeguides.

4. ALLOWED MODES IN THE ETCHED SLAB REGION GUIDE CROSSTALK

One solution to the slabmode dilemma is to etch the ridge sufficiently deeply that the slab outside the ridge is cutoff (i.e.. does not support any guided modes.) While this seems like an easy and effective

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solution the result is generally a multi-moded ridgeguide. The multi-mode behavior is caused by the increased effective index difference at the ridge/slab interface. (Fig. 2) Most PICs for coherent or high-speed digital applications require that the waveguides be single-moded for minimum optical dispersion such that the more deeply etched multi-moded waveguide is not useful.

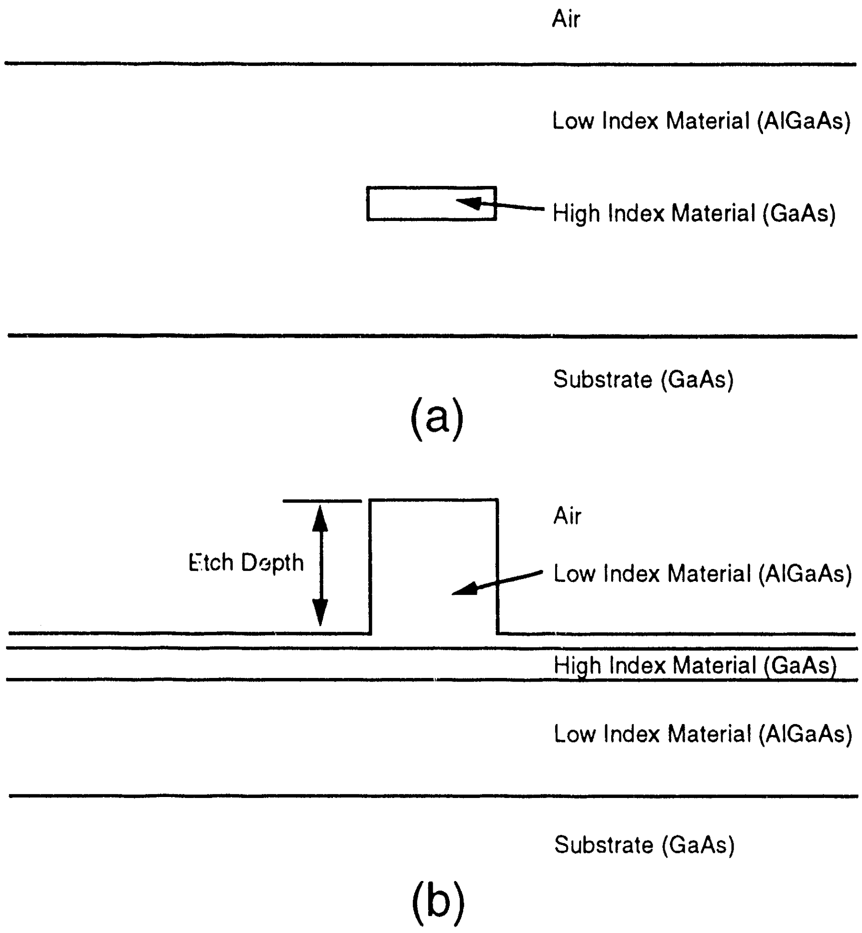
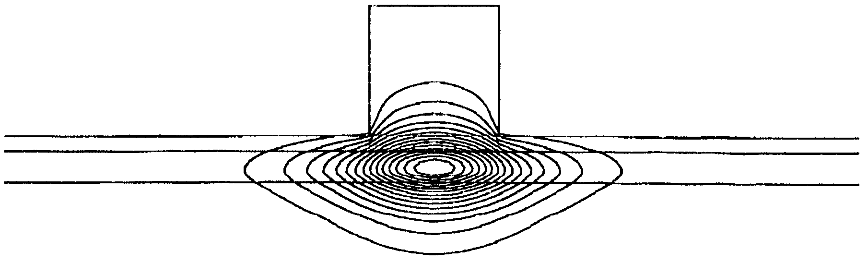


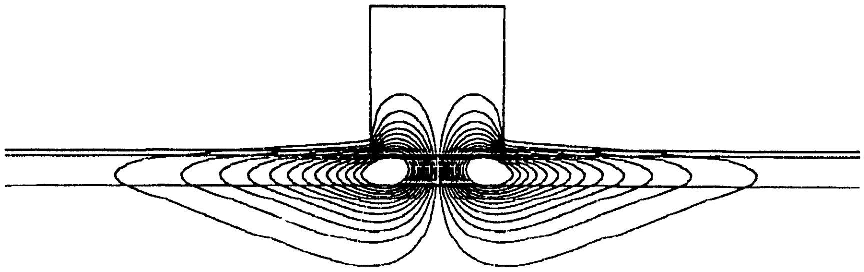
Figure 1: Comparison of buried heterostructure waveguide (a) and ridgeguide (b).

An alternative solution to the crosstalk problem might be to etch deep trenches on both sides of the waveguide but far enough away so as not to disturb the fundamental waveguide mode. This would also have the effect of providing electrical isolation if needed. However, such a trench creates, in effect, a very wide mesa waveguide capable of supporting many optical modes. (Fig. 3) This highly overmoded mesa traps light scattered or radiated from the ridgeguide allowing it to propagate along the mesa and scatter back into the central ridgeguide. This behavior of capturing radiated light and allowing it to scatter back into the fundamental mode is disastrous for waveguide devices, such as y-junction power combiners[3], that rely on radiation of excess or off-state light as a fundamental means of operation.

Since deeply-etched waveguides are overmoded and mesa isolation traps light, allowing it to scatter back into the ridgeguide, neither of these approaches is an effective solution. Another approach is to increase the absorption of light in the slabguide region so that crosstalk is minimized. This can be achieved by ion implantation of atomic species, such as oxygen, into the slabguide outside the rib. (Fig. 4) In this configuration, the slabguide outside the rib has a sufficiently high optical absorption coefficient that most of the scattered and radiated light leaving the ridgeguide is absorbed before it can propagate any significant



(a)



(b)

Figure 2: Contours of constant electric field at 1.32 μm wavelength for fundamental mode of single moded ridgeguide (a) from Fig. 1(b) and guided second-order mode (b) established by increasing the etch depth compared to (a).

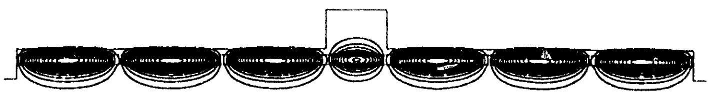


Figure 3: Contours of constant electric field at 1.32 μm wavelength for just one of the high-order slabguide modes created by etching mesa isolation trenches in an attempt to eliminate crosstalk between waveguides.

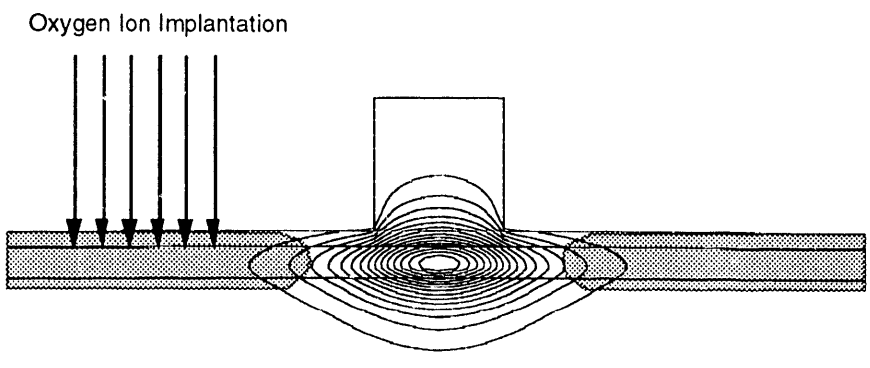


Figure 4: Illustration of oxygen ion implantation into the slabguide region of the waveguide of Fig. 2(a). An added absorption of 100 cm^{-1} due to implant damage is assumed for simulation purposes.

distance. This absorption effectively prevents crosstalk between ridgeguides without the necessity of etch isolation.

5. THE MACH-ZEHNDER INTERFEROMETER AS AN EXERCISE IN PIC FABRICATRION

The Mach-Zehnder interferometer[4] (Fig. 5) is a good test bed for PIC technology, especially PICs employing coherent signal processing techniques. To make a Mach-Zehnder interferometer requires monolithic integration of single-mode waveguides, waveguide power splitters with very nearly equal power in each of the output arms, electrooptic phase modulators[5], and a phase-sensitive power combiner which couples in-phase light from each arm of the Mach-Zehnder into the output waveguide while ensuring that out-of-phase light does not couple into the output waveguide.

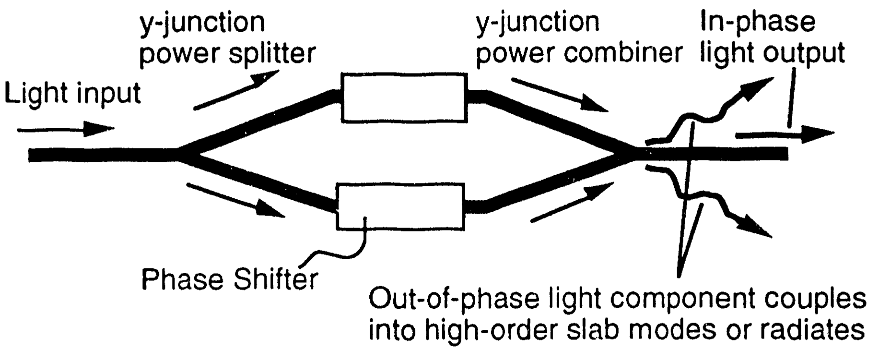
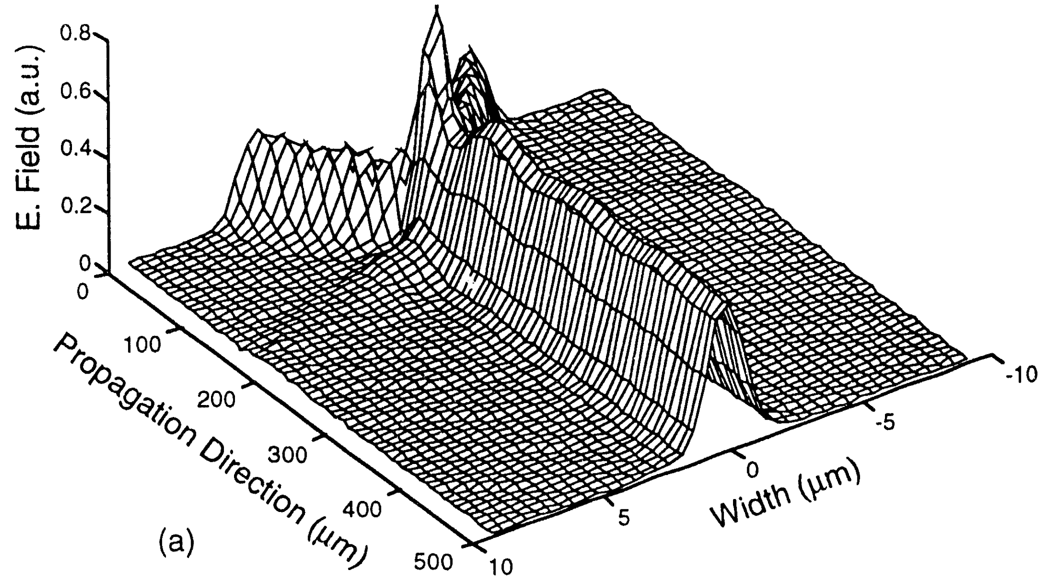


Figure 5: Schematic representation of a Mach-Zehnder interferometer.

The key component of a good Mach-Zehnder is not the phase modulator but the optical power splitter and power combiner. Provided that a given phase modulator design can establish a minimum π phase delay, the detailed performance of the modulator only affects second-order properties of the Mach-Zehnder such as overall length and modulation bandwidth. The contrast ratio of the Mach-Zehnder is a direct result of the optical power splitter and combiner. On the input side, any deviation from a 50% power split into the two phase modulator arms degrades the on/off ratio at the output due to an imbalance in the amplitude of the signals in each arm, preventing complete destructive interference in the optical power combiner section. Similarly, if the power combiner does not couple equal portions (preferably 100%) of the power from each arm into the single output waveguide the contrast ratio will be reduced. An equally important, and often overlooked, aspect of optical power combiners is removal of excess optical power in the off-state of the device. As indicated in Fig. 5, in the off-state the y-junction power combiner couples the excess power into output modes other than that of the output waveguide. These other optical modes are the often overlooked "fourth port" of the y-junction power combiner and consist largely of radiation modes but in the case of the ridgeguide-type combiner the slabguide modes accept the bulk of the off-state excess power. Thus, correct management of the slabguide modes is of critical importance for ridgeguide-type PICs.

Fig. (6) shows computer simulation of ridgeguide-type y-junction power combiner operation using wide-angle beam propagation analysis with transparent boundary conditions. Beam intensity profiles at various stations along the coupler are shown for both the in-phase (Fig. 6(a)) and out-of-phase (Fig. 6(b)) conditions. This particular design uses the singlemode waveguide of Fig. (2) with a 4° total angle between the input arms of the y-junction, the optical wavelength is 1.32 μm. When the light in both input arms is in phase, almost all the intensity is captured in the central waveguide. When the input light is out of phase power couples into the slabguide modes surrounding the output ridgeguide, leaving the central guide with a near-zero intensity. This behavior of coupling large amounts of light directly into the slabguide modes greatly enhances crosstalk in ridgeguide-type PICs.



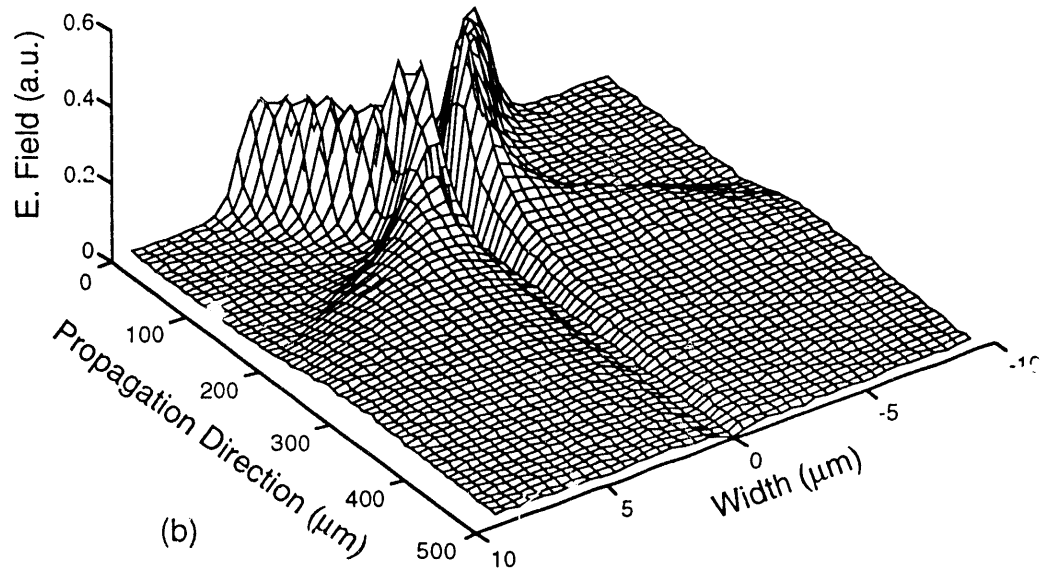


Figure 6: Computer simulations of y-junction power combiner operation at 1.32 μm wavelength. Waveguides used are from Fig. 2(a). Upper plot (a) is for light from both input arms in phase. Lower plot (b) is for light from both input arms out of phase.

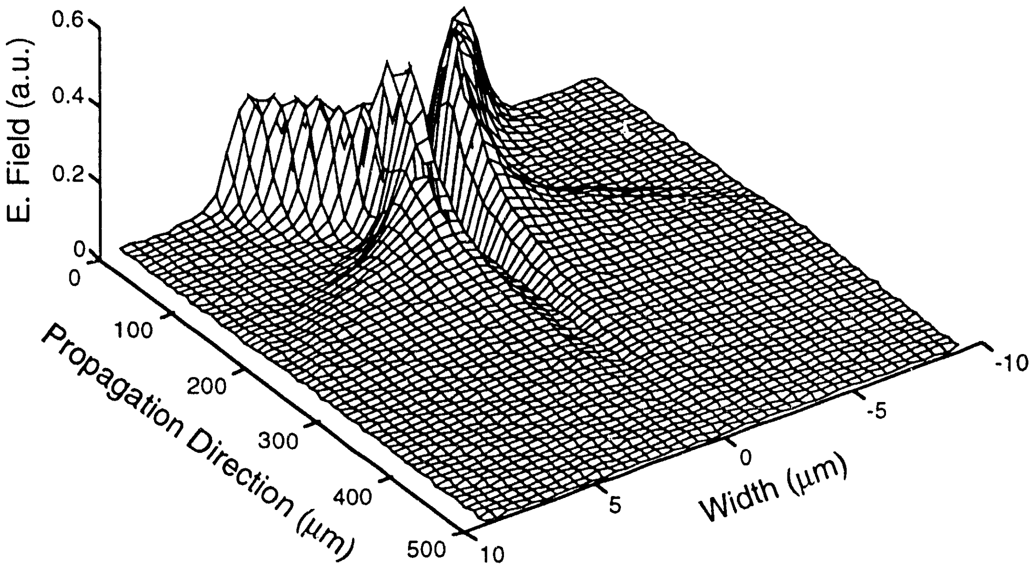


Figure 7: Computer simulations of y-junction power combiner operation at 1.32 μm wavelength with 100 cm^{-1} added loss in the slabguide region. Waveguides used are from Fig. 4. Plot is for light from both input arms out of phase.

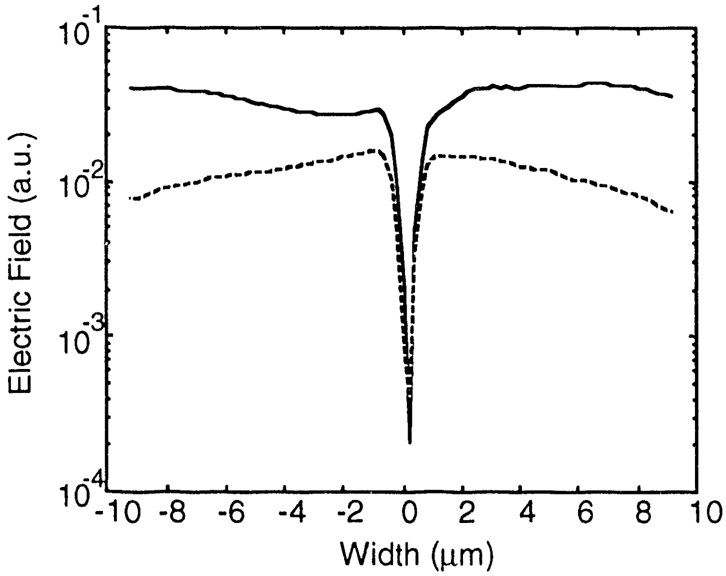


Figure 8: Electric field profiles at output of y-junction power combiners of Figs. 6(b) and (7). Lossy slabguide, dashed line, shows effects of absorption compared to lossless slabguide, solid line.

One effective solution for management of light coupled into the slabguide modes is to use the ion implantation scheme of Fig. 4 to increase the absorption of light in the slab region, preventing it from reaching other parts of the circuit or scattering back into the output waveguide. Fig. (7) illustrates the effects of 100 cm^{-1} added loss in the slabguide region of the y-junction power combiner in Fig. (6). With the added loss, although light still couples strongly into the slabguide modes it is quickly absorbed within 300 μm of the y-junction. Fig. (8) compares field profiles of lossy and lossless slabguides. Profiles aretaken from the data of Figs. (6b) and (7) at a propagation length of 500 μm. The key feature of this plot is that power in the slabguide is suppressed 12 dB due to the added loss after only 500 μm propagation length.

6. CONCLUSIONS

In conclusion, ridgeguide PICs are attractive for low-cost, high-volume applications involving data transfer and signal processing using optical signals. However, slabguides inherent in the ridgeguide design result in enhanced crosstalk and reduced circuit performance unless steps are taken to eliminate propagation of optical power in the slabguides. One useful technique to prevent propagation of slabguide modes is to enhance the absorption of light in the slab region.

7. ACKNOWLEDGMENTS

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