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ULTRA-COMPACT, LOW-LOSS DIRECTIONAL COUPLER STRUCTURES on InP for MONOLITHIC INTEGRATION

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Directional couplers are key components in integrated optoelectronics, being used in power-dividers, modulators and switches, wavelength (de)multiplexers, and polarization splitters. Their major drawback for monolithic integration is their large size, typically several millimeters or more, due to the branching guides used to separate optical inputs/outputs of the coupler.[1] While compact waveguide bends suitable for sub-millimeter branching circuitry have been available for some time,[2,3] interconnection of these bends to couplers is problematic due to difficulties in launching optical fields which will provide high extinction. In particular, the abrupt branching guide-to-coupler transitions resulting from the large index differences required for compact bends can degrade coupler crosstalk.[4] Here we demonstrate that high extinction and compact size can be achieved by combining deeply-etched monomode guides for compact bends with zero-gap, multimode interference couplers. Such couplers have previously been proposed for easing the fabrication of zero-gap couplers by eliminating the need for well-defined Y-junctions;[5] here we show that they are suitable for high extinction (24-28dB), polarization-insensitive, compact (submillimeter) devices with low on-chip insertion loss.

Our waveguides are conventional, single-mode InGaAsP ($\lambda_g = 1.0\mu m$)/InP single-heterostructures (fig. 1) with ribs etched through the InGaAsP cores for compact bend performance. Rib fabrication was formed by dry etching through a resist mask using either Cl_2/Xe^+ CAIBE or CH_4/H_2 RIE. Straight guide losses were 0.8 to 1.1dB/cm and 2.2dB/cm for CAIBE and RIE fabrication respectively, as determined from Fabry-Perot measurements on different guide lengths using $\lambda = 1523$nm, TE-polarized light. These losses are comparable to the best achievable using wet chemical etching.[2]

We conservatively employ circular bends of $R = 300\mu m$ radius (simulations suggest $R = 200\mu m$ suffices for low loss). Our S-bend guides using this radius are only 244μm long in total (input plus output branching) for 30μm guide separation. To minimize bend mismatch losses, we employ offsets at all bend junctions. Bend losses were evaluated with Fabry-Perot techniques by comparison of bends to straight waveguides on the same chip.

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Excess bend losses for the series connection of two S-bends (input plus output for coupler application) were only 0.3dB above the straight reference guides for both polarizations.

Our coupler design (fig. 2) employs a multi-moded, zero-gap interference region, with input guides positioned so as to excite all four coupler modes. The operating principle involves self-imaging,[6] in which coupler input fields are replicated at the coupler output for coupler lengths which are multiples of $3L_{\Pi}$, where L_{Π} is the beat length for the two lowest-order modes. At these lengths, a super-resonance occurs in which all the excited modes interfere constructively. Because of the self-imaging, issues of gradual branching into the coupler become irrelevant. That is, coupler performance becomes insensitive to details of the input field distributions. Lossless couplers are only achievable for cross-, bar-, and 3dB-power splitting. These splitting ratios are sufficient for many applications, however, such as switches, star couplers, and balanced coherent receivers.

While it is possible to design couplers operating at L_{Π} by positioning input guides to avoid excitation of certain coupler modes,[5] we employ here structures which ONLY function at $3L_{\Pi}$, NOT at L_{Π}, to further reduce sensitivity to input placement. Simulations show that this results in looser fabrication tolerances and permits larger spacing between input guides. We use a gap $>2\mu m$ between input guides, which need not be accurately defined, eliminating problems associated with Y-junction fabrication. This gap also eliminates crosstalk between branching guides at the input and output (measured better than 30dB). The $3L_{\Pi}$ design does result in larger devices (cross-state $500\mu m$, 3dB state $250\mu m$ coupler lengths), however, for total device (coupler plus branching) length of 744 (cross) and $494\mu m$ (3dB).

We fabricated a series of passive couplers of differing length, all on a single chip, with S-bend input/output branching identical to those above. SEM micrographs (fig. 3) of the resulting devices show smooth sidewalls for low scattering loss and well-defined gaps between input guides. Devices were characterized by transmission measurements after AR coating endfacets to avoid Fabry-Perot effects; on-chip insertion loss was measured relative to reference straight guides and S-bends without couplers on the same chip. The measured dependence of power splitting and loss on coupler interference length agrees well with simulations, as shown in fig. 4 for $\lambda = 1523$nm, TE light. Both simulated and experimental values in this figure include S-bend losses. We obtain 27.6dB extinction for the cross-state, and a splitting ratio of 49.8:50.2 for the 3dB-state device. The insertion losses of these devices were 0.4-0.7dB with respect to straight reference guides. These values include S-bend/branching losses, indicating that the couplers themselves exhibit low losses (≤ 0.4dB). Thus, our results demonstrate that multimode interference couplers can be used with deeply-etched rib guides to achieve submillimeter devices (including S-bends) with high extinction and low insertion loss. Our data (fig. 4) also present a clear demonstration of the super-resonance phenomenon in self-imaging: while low-loss 3dB- and cross-states are achieved at $3L_\Pi/2$ and $3L_\Pi$, poor crosstalk and insertion loss occur at lengths $L_\Pi/2$ and L_Π associated with conventional couplers. Finally, experiments using TM polarization show essentially no change in coupler behavior: 28.4dB extinction and 0.6dB loss in the cross-state, and 49.9:50.1 splitting ratio and 0.5dB loss for 3dB splitters.

In conclusion, we have shown that ultra-compact directional couplers with short (244μm) branching inputs/outputs and high performance (high extinction, low insertion loss, low polarization sensitivity) can be realized by using multimode interference structures to eliminate difficulties with abrupt input/output junctions and branching constraints. Thus, this work can lead to an entire class of ultra-compact integrated optic devices based on such couplers. For example, combining our coupler structures with previously demonstrated compact phase-shifters[7] should create switching devices in which the input/output branching, as well as the interaction region, are extremely compact. Replacing our S-bend structures with integrated mirrors (of the type described in ref. 8) will achieve even shorter devices, at the expense of increased branching insertion loss.

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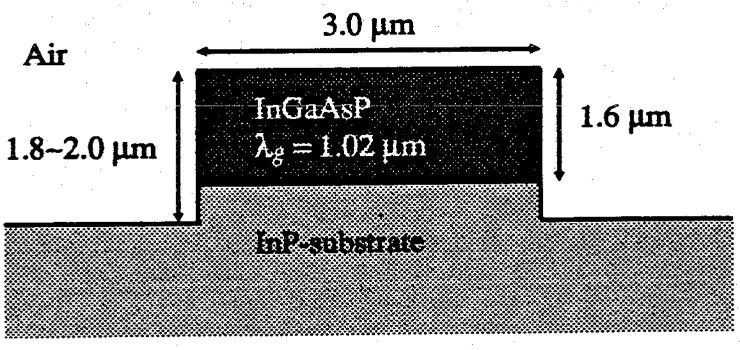

Fig. 1: Waveguide cross-section.