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TUNABLE MQW-DBR LASER WITH MONOLITHICALLY INTEGRATED GaInAsP/InP DIRECTIONAL COUPLER SWITCH

Indexing terms: Optoelectronics, Integrated optics, Semiconductor lasers, Optical switching

We report the successful monolithic integration of a GaInAsP/InP single-mode $\Delta\kappa$ directional coupler switch with a 4-section tunable multiple-quantum-well distributed Bragg reflector laser. We obtain several mW of output power through the switch, with ~ 10 dB crosstalk either from the internal laser source or with external light injected through the parallel input port.

Advances in photonic integrated circuits (PICs) require the development of a complete set of individual optical device designs which lend themselves to compatible and reproducible fabrication processing without sacrificing device performance. Recent efforts at integrating optical waveguide devices in series with semiconductor lasers include electroabsorption modulators,[1] Y-branching waveguide photodetectors,[2] tunable lasers with passive power combiners and amplifiers,[3] and switches.[4]

Perhaps the two most fundamental active 'integrated-optic' devices are the single-mode directional-coupler switch and the semiconductor laser. We report here what we believe is the first low-loss integration of these two devices. We have combined on a single chip a 4-section tunable multiple-quantum-well (MQW) distributed Bragg reflector (DBR) laser[5] with a novel forward-injection-based single-mode $\Delta\kappa$ directional-coupler switch. All interconnect guides employ low-loss semi-insulating upper cladding layers, with the switch and passive guides employing high-definition etch-stop-controlled buried rib waveguides. All waveguides are vertically and laterally self-aligned, and we employ a variant of a previously described GaInAsP/InP MOCVD-based growth and processing sequence, P-Pro2,[6] which permits the entire PIC fabrication with no additional growth steps beyond those required for the semi-insulating-blocked buried heterostructure laser.

The 3 mm-long PIC is shown schematically in Fig. 1. The laser is a $1{\cdot}55\,\mu m$ 4-section version of the 3-section continuously tunable MQW-DBR.[5] The 'rear' Bragg section is a long, high-reflection tunable grating, while the 'front' Bragg section is a shorter, partially transmitting internal output coupling tunable grating. The phase section provides continuous tuning of the Bragg-selected longitudinal modes, and the MQW gain region controls output power.

The parallel input port and laser feed a variant on the zero-gap or 'BOA' directional coupler switch[6] through two 5 mm-radius S-bend waveguides with $2{\cdot}5\,\mu m$ width. To promote high-definition patterning and looser mode confinement than the buried heterostructure laser region, we employ a 300 Å etch-stop-controlled buried rib geometry based on the same passive guide layer used within the laser. The switching is obtained by forward injection of carriers into the heterostructure outside the $5\,\mu m$ width of the buried rib along the $300\,\mu m$ length of the double-moded switching region. This design generates a significant differential phase shift between the even and odd supermodes, while minimising undesirable mutual overlap with the lossy index change. Beam propagation method calculations predict that for current injection limited as described with $\sim 1\,\mu m$ of diffusion, the structure should provide >25 dB extinction with $\lesssim 1$ dB of excess absorption and radiation loss.

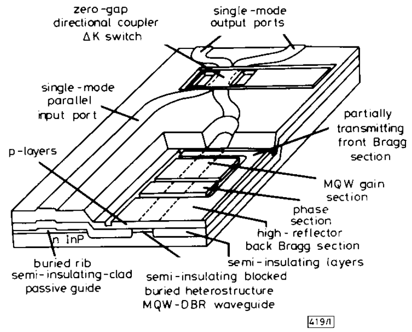

Fig. 1 *Configuration of chip*

An atmospheric-pressure MOCVD system is used in all the growth steps required for this device. The cross-section in the gain section of the laser and in the double mode region of the switch are shown in Figs. 2*a* and *b*. The laser active layer consists of four 80 Å-thick quantum wells of GaInAs separated by 100 Å-thick barriers of $\lambda_{PL} = 1{\cdot}3\,\mu m$ GaInAsP. Beneath

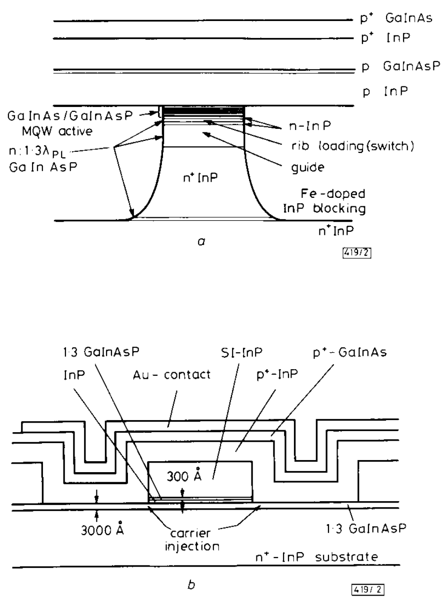

Fig. 2

a Cross-section of buried heterostructure laser waveguide in gain section

b Cross-section of buried rib waveguide in switching region

For clarity, some structure in upper and lower cladding is not shown the MQW active layer are a thin upper and a thicker lower $\lambda_{PL} = 1{\cdot}3\,\mu m$ GaInAsP waveguide layer, with thicknesses of 300 and 2700 Å, respectively. They are separated from the active layer and each other by 600 and 300 Å stop-etch layers of InP, respectively. The MQW active and thin upper waveguide layers are etched off in the phase and Bragg regions. A first-order grating is formed, in both Bragg regions, with conventional holographic means on the second thicker waveguide layer. Using an SiO_2 mask, a deep etch is made through all the layers in the laser region to laterally define the waveguides. Outside the laser only a shallow etch is made through the thin upper waveguide layer to define the rib waveguides. A regrowth of Fe-doped semi-insulating InP is used to confine the current to a $2\,\mu m$ width in the Bragg, phase and active regions. This layer also serves as a low-loss upper cladding layer in the passive waveguides. Two openings are etched in the semi-insulating layers on each side of the double mode region to allow carrier injection. A second regrowth of *p*-InP and *p*-GaInAs is then performed. This forms the upper cladding and contact layer in the laser and active portions of the switch, and overgrows the semi-insulating inP in the passive portions of the device.

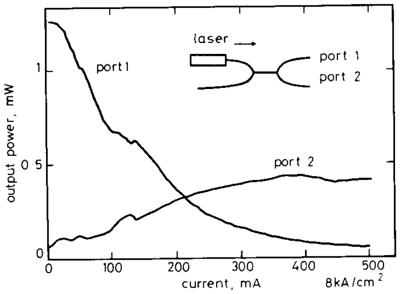

Fig. 3 *Output power in directional-coupler switch output ports as function of injected current using internal laser*

Experimentally, lasers have thresholds in the 40–50 mA range. Measured through the switch, the sum of the output ports with no AR coatings to increase throughput provides ~5% differential quantum efficiency for ~2 mW of CW switched, tunable output power at ~100 mA laser drive. The linewidth of the laser is measured with the delayed self-heterodyne method, and has a linewidth floor over much of the operating range at a value of 3 MHz. The quasicontinuous wavelength tuning range, varying the Bragg and phase section bias currents, is larger than 50 Å. CW switching curves are shown using the internal laser in Fig. 3 and for an external $1{\cdot}5\,\mu m$ TE-mode laser injected into the parallel input port in Fig. 4. Extinction of the internal laser is 14 dB, while extinction of the external laser is 13 dB. For the internal laser, switching crosstalk is −13 and −9 dB at the low and high current states of the switch, while for the parallel input port the corresponding crosstalk is −14 and −6 dB. The features visible on the internal laser curve result from phase shifts in the reflection from the output ports which have not yet been AR-coated. The characteristics of the switch for TM mode propagation, measured by changing the polarisation of the external laser, are very similar but display a reduction in the current sensitivity of ~10%. This result, due to the different confinement factor for TE and TM modes, agrees well with theoretical calculations. Since the index change used for switching is based on forward injection of free carriers into the $\lambda_{PL} = 1{\cdot}3\,\mu m$ GaInAsP guide layer, the modulation bandwidth will be limited by the free carrier lifetime in this layer. The small-signal modulation bandwidth was measured, and displayed a smooth roll-off with a −3 dB frequency of 50 MHz. This corresponds to a free carrier lifetime of 3 ns, which is quite reasonable.

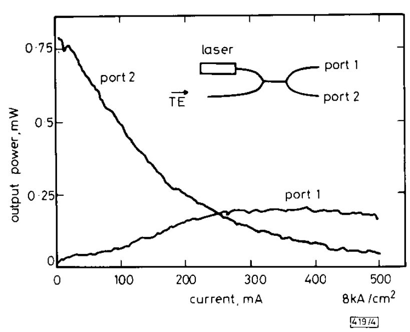

Fig. 4 *Output power in directional-coupler switch output ports as function of injected current using external laser*

Total insertion loss using long-working-distance microscope objectives was 12·5 dB for coupling into the parallel input port. With no AR coatings, previous experience suggests that ~8 dB of this is input-output coupling loss, leaving only ~4·5 dB excess radiation, absorption and scattering loss in the parallel input guide, bending switch feeds and the switch itself. While switching current densities are reasonable, absolute currents are high because in this first design iteration current was injected into $10\,\mu m$-wide channels on each side of the coupling region. Since only $\sim 1\,\mu m$ is required to effect the same behaviour, currents should be easily reduced below 100 mA. More importantly, both the required current densities and the induced absorption losses during switching will also be reduced substantially with improved current rejection from the switching region core.

In conclusion, we have demonstrated a fabrication-compatible directional-coupler switch and tunable MQW-DBR laser using conservative and reproducible processing steps. We expect to improve performance further, and feel that implementation in more complex PICs, such as integrated balanced heterodyne receivers, looks very promising.

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