Design and Optimization Studies of Electroabsorptive and Carrier Injective Microring Resonators for Optical Switching and Logic Gate Applications

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by

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Abstract

Optical interconnects are the promising solution to the drawbacks of electrical interconnects in integrated circuits (ICs). The demand for higher packaging density in ICs along with large bandwidth and high speed signal processing requirements can be satisfied by microring resonators (MRRs), which can act as modulator/switch and signal processing unit in optical interconnects. This thesis mainly focus on the design and optimization studies of MRRs based optical switches/modulators and optical logic gates with electroabsorption (EA) and carrier injection (CI) as the modulation mechanisms. EA and CI modulation mechanisms varies the absorption and refractive index of the light guiding region in the MRR configurations with respect to the applied bias and results in optical switching by shifting the resonant wavelength. The proposed group III-V semiconductor MRR switches/modulators are highly compatible for integration with other optoelectronic devices.

Optical switches in optoelectronic ICs demands for small footprinted devices which can provide with high contrast ratio (CR) and low insertion loss (IL) at low drive fields in optical window regime. We propose an approach to optimize the performance of resonant wavelength switching in quantum confined stark effect (QCSE) based double ring resonator. The waveguides of MRR are configured as p-i-n diode structure. Multiple InGaAsP/InP quantum wells (QWs) incorporated in the intrinsic region of MRR structure varies absorption in accordance with applied field and introduces switching. Our analysis on the proposed EA MRR portrays the dependency of switching performance characteristics over ring resonator coupling coefficients, applied field and operating wavelength quite apart from QW parameters. Performance analysis on conventional QW based EA modulator points out that the wider QWs attains higher absorption change with applied field and leads to better ON-OFF ratio at the output. However, the results in this thesis reveals that the QCSE based MRR optical switches can achieve higher CR for narrow wells by optimizing ring resonator parameters and operating wavelength.

The implementation of directed logic gates using EA and CI based p-i-n diodes embedded in the waveguiding regions of optical MRR is proposed and analysed. The optical logic gates are realized by representing the operands as the applied bias on the rings while the operation results of logic gates appears as in the form of light intensities at the output

ports of MRR. The light guiding core region of EA based MRR logic gate configuration is composed of InGaAsP/InP QWs and the cladding is made of InP. However, the intrinsic region in CI based MRR gate configurations are made of bulk GaAs with AlGaAs as the p and n type barriers to obtain refractive index variation due to bandfilling, bandgap shrinkage and free carrier absorption effects. The proposed configurations are optimized (in terms of coupling coefficient, operating wavelength and applied field) to achieve better performance in logic operations such as AND, OR, NAND, XOR, XNOR, Fredkin and inhibitor gates. EA modulation mechanism fails to implement OR and NOR gates on a parallel MRR configuration due to significant Q-factor reduction as the absorption increases with applied field is also investigated and the same configuration successfully realizes OR and NOR gate based on CI mechanism. A novel triple ring resonator configuration is proposed which can simultaneously realize optical OR and AND or NAND and NOR gates at the output ports. We propose CI based off axis MRR configuration to realize inhibitor logic gates and the dependency of output port intensities on the coupling coefficients and wavelength is optimized for performance enhancement.

We also analyze the dynamic behaviour of GaAs based p-i-n diode configured single MRR modulator with bias assisted CI as modulation mechanism. The output of the proposed MRR depends on the time dependent nature of injected carriers and resulting refractive index variations relative to the external applied voltages on the ring. Modulation characteristics depends on the electrical performance of p-i-n structure used in MRR to implement the bias. Transient response of p-i-n during turn ON and turn OFF is considered to analyze the overall performance of MRR modulator for high bit rate operations. We demonstrate numerically that the bit rate is limited by the time dependent behaviour of injecting carriers into intrinsic region through which light propagates. A deviation from expected output spectrum is observed when certain non-resonant wavelengths passes through this proposed modulator configuration and exhibits resonant characteristics during the switching transient period. Our analysis can provide a guide for suitable selection of operating wavelength by considering limitations imposed by carrier dynamics on modulator with wavelength division multiplexed signal as the input to the bus waveguide. We also depicts the dependency of applied field and coupling factors over rise time, fall time transients and memory effect of ring resonator over transmitted bits.