Photonic Crystal Nanocavity Devices for Nonlinear Signal Processing

This thesis deals with the investigation of InP material based photonic crystal cavity membrane structures, both experimentally and theoretically. The work emphasizes on the understanding of the physics underlying the structures’ nonlinear properties and their applications for all-optical signal processing. Based on the previous fabrication recipe developed in our III-V platform, several processing techniques are developed and optimized for the fabrication of InP photonic crystal membrane structures. Several key issues are identified to ensure a good device quality such as air hole size control, membranization of InP/InGaAs structure and wet etching. Experimental investigation of the switching dynamics of InP photonic crystal nanocavity structures are carried out using short-pulse homodyne pump-probe techniques, both in the linear and nonlinear region where the cavity is perturbed by a relatively small and large pump power. The experimental results are compared with coupled mode equations developed based on the first order perturbation theory, and carrier rate equations we established for the dynamics of the carrier density governing the cavity properties. The experimental observations show a good consistency with the numerical simulations. The results provide insight into the nonlinear optical processes that govern the dynamics of nanocavities and are important for applications in optical signal processing. As a step forward, the components are further applied for system characterizations, demonstrating their ability for fast all-optical modulation with low energy consumption. Another effort of this thesis is the theoretical design of the photonic crystal structures, such as mode adaptors for efficient in/out coupling, a four-port photonic crystal structure which allows two signals to excite different, yet spatially overlapping, resonances and are spatially separated at the output. This structure reduces the complexity of the system that usually includes band pass filters in order to distinguish the signals at the output. Finally, we may need to mention an important design: a simple and ultracompact photonic crystal structure consisting of a single cavity coupled with a waveguide, which allows very robust control of the transmission line shape. Lorentzian and Fano line shapes can be realized by varying the size of a single air-hole. Additional control of the parity of the Fano shape can be obtained by breaking the mirror symmetry of the structure. The turningpoint characteristic of Fano structures is experimentally demonstrated to allow the suppression of slow transmission dynamics, enabling us to achieve fast (20 Gbit/s) all-optical modulation with low energy consumption. Relying on spatial symmetry breaking and carrier nonlinearity, the Fano structure allows the demonstration of an enhanced nonreciprocal transmission with ultra-low power consumption and good wavelength tunability.

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