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Abstract

Silicon photonics has become a fundamental technology for the development of photonic integrated circuits, driven by the compatibility with CMOS, scalability, and reduced fabrication costs. Among the most relevant building blocks, microring resonators (MRRs) and hybrid integrated tunable lasers play a central role in applications such as optical communications, signal processing, and microwave photonics. However, as integration density and optical power increase, nonlinear optical, free carrier, and thermal effects strongly affect device performance, stability, and dynamical behavior. It is imperative that these effects are modelled with precision in order to guarantee reliable design and optimisation.

The present doctoral thesis addresses the modelling and physical interpretation of nonlinear phenomena in silicon-based integrated photonic devices, with particular emphasis on microring resonators with complex waveguide cross sections and hybrid integrated tunable lasers employing silicon and silicon nitride passive feedback cavities. The primary objective is to develop computationally efficient models that are also physically accurate, with the capability to capture the interplay between optical fields, carrier dynamics, and thermal effects. These models will be validated through comparison with experimental measurements.

A two-dimensional distributed modelling framework based on the finite element method has been developed within the SISCAP platform to describe nonlinear effects in MRR. The proposed model represents a refinement over conventional lumped approaches in that it resolves the spatial distribution of free carriers and temperature. This facilitates accurate analysis of devices with non-standard geometries, including rib or hybrid Si/PolySi waveguides. Numerical results demonstrate that waveguide geometry has a significant effect on carrier diffusion and heat dissipation, thereby governing nonlinear losses and resonance stability. In the course of the present study, a range of configurations was analysed. Of these, the Si/PolySi three-wing rib geometry was found to provide improved mitigation of nonlinear and thermal effects. This is due to enhanced lateral carrier spreading and reduced carrier lifetime. The model's accuracy has been validated through quantitative congruence with experimental transmission measurements, thereby substantiating its status as a reliable and adaptable design instrument for high Q MRRs.

The thesis then investigates the nonlinear dynamics of hybrid integrated tunable lasers incorporating narrowband passive feedback based on silicon nitride resonators. The experimental and numerical results obtained have demonstrated the emergence of a self-pulsing regime, characterised by the presence of optical spectra resembling combs. A thorough examination has shown that this regime originates from the undamping of relaxation oscillations. These oscillations are driven by asymmetric detuning between the lasing frequency and the reflectivity peak of the passive cavity. Time-delayed simulations demonstrate a high degree of congruence with optical and radio frequency measurements, thereby substantiating the proposed physical interpretation. The pulsing operation is stable and self-contained, and is achieved purely through passive cavity design, without requiring saturable absorbers or external modulation.

Finally, hybrid tunable integrated laser architectures employing microring based feedback cavities are analysed, with a comparison made between silicon nitride and silicon platforms. It has been determined that Kerr nonlinearities in silicon nitride are negligible, thereby ensuring the stability of laser operation. Conversely, silicon-based cavities permit the development of more compact designs; however, this is achieved at the expense of an increased sensitivity to free carrier-induced instabilities. In conclusion, the present thesis provides validated modelling tools and clear physical understanding of nonlinear dynamics in silicon photonic devices, thus supporting the design of compact, stable, and CMOS-compatible integrated photonic sources.