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Observation of nonlinear dynamics and transition to chaos in Photonic Integrated Circuits

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Photonic Integrated Circuit (PIC) technology has revolutionized the application and fabrication of opto-electronic devices. Most affected by this development is the field of telecommunications, where both active and passive photonic devices are key components in the optical networks. PIC based optical components are cheaper to fabricate than their stand-alone counter parts, multifunctional, low energy consumers and much smaller in size. These qualities make PICs very attractive from a mass-integration point of view and they are generally viewed as the successors of electronic ICs.

Light-matter interaction in semiconductor materials involves several timescales and the interplay between these timescales is one of the main causes of the unpredictable nonlinear dynamics that opto-electronic devices are known to exhibit [1]. Due to the small distances on PICs, it was generally assumed that the various timescales will equalize and that they will exhibit less nonlinear dynamics than their stand-alone counter parts. Indeed, the decrease in size made fewer modes of operation available, but the decrease in losses and the closeness of the components on a PIC allowed for much stronger coupling between components and the nonlinear dynamics remained in a large parameter range.

In this work we demonstrate that the nonlinear dynamics exhibited by the PICs are stable, well-classifiable from a bifurcational theoretical point of view and reproducible from batch-to-batch. Furthermore, using a novel method of analysis developed by us, one can locate regions of both ‘stable’ (i.e. cw-operation) and dynamical output and therefore modify the application schemes of PICs, so as to avoid the dynamics, if desired. Theoretically, each configuration on a PIC will require its own modeling, while experimentally a general method, can be devised for the visualization and analysis of the nonlinear dynamics. We use an integrated Colliding Pulse Mode Locked semiconductor Laser (CPMLL) [2] as a ‘black box optical system’ for the demonstration of the existence of nonlinear dynamics in PICs, including chaos, in the 1 GHz range. We use a 4 GS/s oscilloscope with a 1 GHz analogue bandwidth for the detection of the output power and acquire approximately 5 to 10 data points per period of the oscillations. Our method is unique in that we use statistical methods to refine our analysis and therefore are able to apply such analysis to optical systems, whereas normally one would require ~1000 data point per period to be able to analyze the dynamics.

Using a set of systematically measured power time series and RF-spectra as a function of the pump current and voltage over the absorber of the CPMLL, we can show the occurrence of a so-called Hopf-bifurcation, where self-oscillations start and a limit-cycle type of dynamics are initiated. These self-oscillations become more complex and evolve into chaotic dynamics. The chaotic dynamics are ended in another self-oscillation type of dynamical attractor. In bifurcation theory, this is a well-known scenario, a so-called period-doubling route in and out of chaos and it can for the first time be consistently demonstrated in PICs. It should be noted that the analysis is purely experimental and due to our ‘black-box’ approach we do not have to rely on exact theoretical modeling of the device and can use generalized theory, like for instance the assumption that the noise is additive in the electrical field. We have also measured regions of cw-operation and mode-locking in these devices, and although we analyze the most asymmetric of our CPMLLs, where there is supposed to be no mode-locking, we were able find a parameter range where mode-locking did occur.

References:

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