Summary of the scientific achievements for Marie Curie ITN cQOM

Fellow: Michael Geiselmann
Principal Investigator: Tobias Kippenberg
Academic/Industrial Institution: Ecole Polytechnique Fédérale de Lausanne
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The main focus of the research during this fellowship was based on photonic chip based Silicon Nitride (SiN) micro resonators. This material allows an integrated platform for nonlinear optics that can be fabricated on wafer scale, scalable in cost and volume and thus is interesting for applications. In 2007 it was shown that optical frequency combs could be generated in micro resonators producing a repetition rate in the GHz domain[1], which conventional frequency combs cannot provide. This would allow radio frequency generation in the tens of GHz regime synthetized directly from an optical carrier. However it was soon realized that these microresonator-based frequency combs had a high noise in the radio frequency domain[2], one criteria that inhibited these combs to be used in applications where a coherent spectra was necessary. One key element of frequency combs however is a self-referencing method that then enables their use in metrology applications[3]. For this purpose the optical spectrum has to span at least 2/3 of an octave and at the same time fulfil the coherence requirement. In 2013 it was shown that solitons in microresonators could be one way to generate coherent frequency combs[4]. However these combs were only generated in crystalline resonators that are difficult to integrate with further photonic platforms. Furthermore only a narrow band spectrum was achieved. During this fellowship I supervised two PhD students working in fabrication of these SiN devices as well as on the generation of optical frequency combs in SiN. We were able to show for the first time that soliton generation was possible in SiN microresonators. This is the first time solitons were observed in an integrated platform that can be combined with other integrated elements such as lasers or detectors. Moreover these solitons in SiN emit a dispersive wave due to proper dispersion engineering, allowing the spectrum to span 2/3 of an octave, having comb lines also in the normal dispersion region (Fig.1 e). This dispersion engineering is mainly done by tailoring the geometry of the SiN resonator and is sketched in Fig 1. For the first time we showed that such a broadband comb is fully coherent and can be directly used for several applications. In a collaboration with KIT the comb source was used to transmit a telecommunication signal at 20 Tbit/s. An additional important point is that thanks to the well studied Lugatio Lefever equation (nonlinear Schrödinger

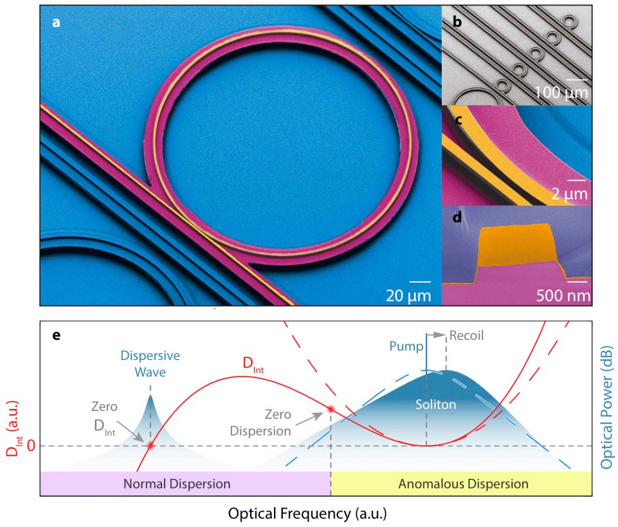

Figure 1: a) Colored SEM picture of the microresonator and coupling waveguide. b) Several resonators with coupling waveguides. c) Close up on the coupling region with 300nm gap. d) Cross-section of the resonator where SiN is marked colored in orange and SiO_2 in purple. e) Sketch for the integrated dispersion (red line) that has to be engineered to obtain soliton generation and dispersive wave emission outside the anomalous dispersion window.

equation) this behavior can be modeled and

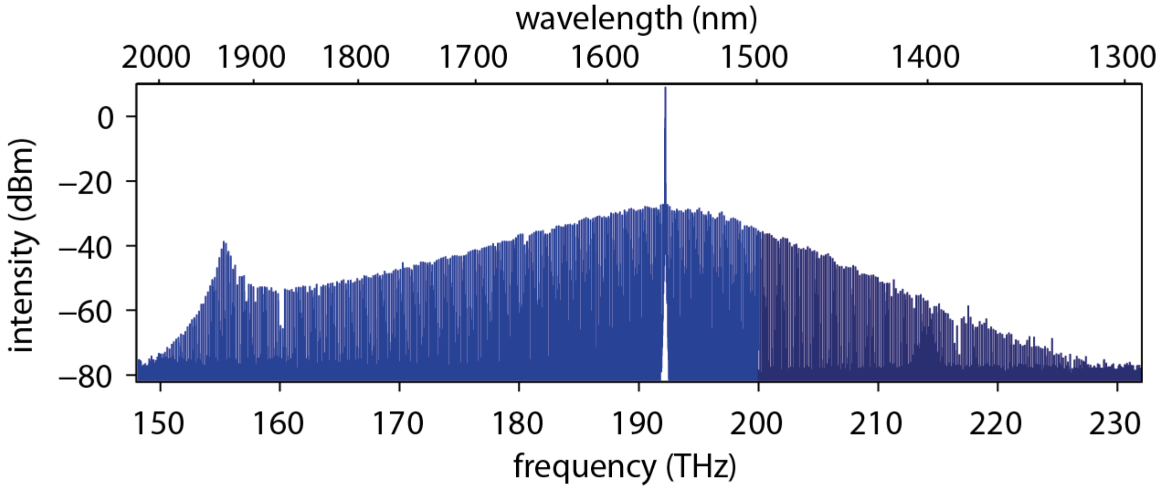

Figure 2: Spectrum of a coherent frequency comb formed by a single soliton and dispersive wave emission.

predicted.

Another very important issue addressed in this fellowship was the characterization of the SiN in order to optimize the fabrication process as well as the physical fiber chip and waveguide resonator coupling. For this purpose an automated characterization setup was designed with a Master student I supervised. This setup now fully automates the measurement of the quality factor and transmission in a SiN photonic chip and is used to optimize the fabrication process.

Scientific output:

I contributed during my fellowship to these scientific publications. A list of all submitted work is given below:

- Photonic chip based optical frequency comb using soliton induced Cherenkov radiation, V. Brasch, M. Geiselmann, T. Herr, G. Lihachev, M. H. P. Pfeiffer, M. L. Gorodetsky, T. J. Kippenberg, submitted to Nature Photonics
- Raman induced soliton self-frequency shift in microresonator Kerr frequency combs, M. Karpov, H. Guo, A. Kordts, V. Brasch, M. Pfeiffer, M. Zervas, M. Geiselmann, T.J. Kippenberg, submitted to PRL
- Photonic Damascence Process for Integrated High-Q Microresonator Based Nonlinear Photonics, M. H. P. Pfeiffer, A. Kordts, V. Brasch, M. Zervas, M. Geiselmann, J. D. Jost, T. J. Kippenberg, submitted to Nature Photonics

I had also the possibility to present my research in several conferences:

- IEEE Benelux Annual Symposium, Twente, Netherlands, 11/2014
- Physics of Quantum Electronics PQE 2015, Snowbird, USA, 01/2015
- Integrated Photonics Research, Boston, USA, 06/2015

Bibliography

1. Del'Haye, P. *et al.* Optical frequency comb generation from a monolithic microresonator. *Nature* **450,** 1214–7 (2007).
2. Herr, T. *et al.* Universal formation dynamics and noise of Kerr-frequency combs in microresonators. *Nat. Photonics* **6,** 480–487 (2012).
3. Diddams, S. A. *et al.* Direct Link between Microwave and Optical Frequencies with a 300 THz Femtosecond Laser Comb. (2000).
4. Herr, T. *et al.* Temporal solitons in optical microresonators. *Nat. Photonics* **8,** 145–152 (2013).