# Frequency comb generation in III-V-on-silicon photonic integrated circuits

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**Abstract:** We present our recent work on the realization of III-V-on-silicon mode-locked lasers and integrated nonlinear waveguides for the realization of integrated frequency combs.

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## 1. Introduction

Frequency combs, sources with a spectrum consisting of many coherent lines, are very relevant for the field of optical sensing, metrology and optical communication. They enable for example the implementation of high acquisition rate spectroscopy systems through so-called dual comb spectroscopy [1], they serve – when stabilized- as a frequency ruler [2], and can be used for orthogonal frequency division multiplexing high spectral efficiency optical communication [3]. Commercial frequency comb sources are based on bulk or fiber-optic components. In order to miniaturize such systems there is a need for chip-scale frequency comb sources. In recent years much work has been performed on realizing so-called Kerr combs using high quality factor resonators. These resonators can be implemented on many platforms, depending on the wavelength range that is being considered, such as in a silicon-on-insulator [4] or SiN-on-insulator platform [5]. However, the realization of fully coherent combs using this approach is not trivial, the conversion efficiency from pump laser to the comb is quite poor, and the locking of the continuous wave pump to the high quality factor resonator is non-trivial in a setting outside of a measurement lab. Therefore we have been pursuing a different route to the realization of on-chip frequency combs: the combination of integrated semiconductor mode-locked lasers (to provide a seed frequency comb) and highly nonlinear waveguides to broaden the frequency comb spectrum further. In this paper we will elaborate on the progress we made in this field over the last year. We implement these components on a silicon waveguide platform, as it provides many interesting aspects for frequency comb generation: low loss silicon waveguide circuits (important for high performance mode-locked lasers), high confinement in the high index contrast waveguide structures (important for efficient nonlinear broadening of the frequency comb) and the possibility to co-integrate other components (photodetectors, phase tuners, modulators,...) on the same platform to build the complete system.

## 2. III-V-on-silicon mode-locked lasers

Semiconductor mode-locked lasers make use of a III-V semiconductor gain section and saturable absorber section inside the laser cavity. III-V semiconductors can be integrated on a silicon waveguide circuit by means of die-to-wafer bonding. In our work we use an adhesive die-to-wafer bonding approach using a sub-100nm thick DVS-BCB layer as the bonding agent. As the performance of mode-locked lasers critically depends on the cavity losses, we implement the majority of the laser cavity length in the silicon waveguide layer (providing waveguide losses of 0.7 dB/cm), including the mirror elements defining the laser cavity. We have explored several types of mode-locked laser geometries, including a colliding pulse Fabry-Perot type laser cavity, a colliding pulse ring-type laser cavity and a so-called anti-colliding pulse mode-locked laser. The geometry of the latter is shown in Figure 1. In this device, the saturable absorber is implemented next to the low-reflection outcoupling mirror. This configuration has been demonstrated (both theoretically and experimentally) to result in a higher optical output power and lower timing jitter [6,7]. The novel anti-colliding pulse-type III-V-on-silicon mode-locked laser demonstrated in this work shows a 1.7 kHz 3 dB RF linewidth at 4.83 GHz repetition rate under passive mode-locking, a substantial improvement over the state-of-the-art [7]. Recently we have realized 1 GHz repetition rate mode-locked lasers by implement a 3.7 cm long cavity in low loss silicon waveguides. The mode-locked laser spectrum has a 3dB optical bandwidth of 7 nm, resulting in ~ 900 frequency comb lines. Pulse widths as short as 1 ps were demonstrated. Of course, a passively mode-locked laser does not yet qualify as a frequency comb, as both the absolute position of the comb lines as well as the spacing between the comb lines can drift over time. In order to stabilize both properties we have demonstrated the injection locking of a passively mode-locked laser with a modulated CW tone, with the modulation frequency of the injected signal matching that of the repetition rate of the free running passive mode-locked laser. Using this approach the coherence of ~ 50 longitudinal modes was demonstrated [8].

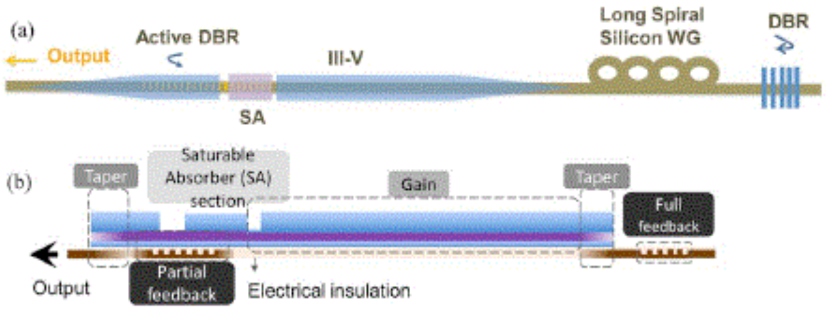

Figure 1: Layout of the III–V-on-silicon mode-locked laser cavity: (a) top view; (b) longitudinal cross-section.

## 3. Coherent supercontinuum generation in integrated waveguide circuits

As semiconductor mode-locked lasers only provide a limited optical bandwidth, there is a need to broaden these ‘seed’ frequency combs, without loosing the coherence. This can be realized using nonlinear effects in integrated waveguides. Especially high index contrast waveguide structures are well suited for this purpose, as they allow achieving high optical intensities in optical waveguides for moderate optical power. Also, the high index contrast allows for substantial dispersion engineering, which is of critical importance to the efficiency of the spectral broadening. It is well known that when a short optical pulse travels through a nonlinear waveguide, several physical effects occur that lead to supercontinuum generation. The properties of such a supercontinuum mainly depends on the input pulse duration $t_0$, peak power $P$ and the dispersion $\beta_2$ and nonlinear parameter $\gamma$ of the waveguide (or the soliton number $N = \mathrm{sqrt}\ (t_0^2/(\beta_2\gamma P)))$. For picosecond pulses (N>16) the supercontinuum generation is dominated by modulation instability [9], i.e. the parametric amplification of background noise due to the presence of the pump in typical waveguides designed for supercontinuum generation. This results in an incoherent supercontinuum and hence not a frequency comb. For ~ 100 fs pulses (N<16) soliton fission is the dominant process. This is a deterministic process and hence results in a coherent broadening of the supercontinuum. Recently we have demonstrated the use of both silicon-on-insulator and InGaP-on-insulator waveguides to realize octave-spanning frequency comb generation, starting from a ~100 fs pump pulse. Figure 2 shows an octave spanning (30 dB bandwidth) mid-IR frequency comb generated in a silicon-on-insulator waveguide using a 70 fs pump pulse at 2.25 µm wavelength (15 pJ pulse energy) [10]. Figure 3 shows an octave-spanning coherent frequency comb covering the telecommunication wavelength window, realized in an InGaP-on-insulator waveguide, using a 170 fs input pulse (1.7 pJ pulse energy) [11]. As sub-picosecond pulses are required to realize coherent frequency comb broadening and semiconductor mode-locked lasers typically produce (chirped) picosecond pulses, an additional pulse compression stage is required in between the mode-locked laser and the nonlinear waveguide to realize an integrated comb generator. This compression stage consists of a highly nonlinear, highly dispersive waveguide. The high anomalous dispersion reduces the soliton number of the pulse that is propagating through the waveguide such that coherence is maintained in the process. The main process that is occurring in the waveguide is the process of self phase modulation. This coherent process spectrally broadens the pulse, while it has only a limited influence on the pulse’s temporal profile. As a result, the pulse is heavily chirped. The leading edge is red shifted, while the trailing is edge is blue shifted. However, the anomalous dispersion in the waveguide tends to remove the chirp of the pulse by making the (trailing) blue components move faster than the (leading) red the spectral components in the pulse. As such, the combination of the high nonlinearity with the high dispersion reduces the pulse width. Due to the strong nonlinear response of silicon waveguides, a (sech) 1 ps can be compressed in a 2.5 cm highly dispersive waveguide to a 150 fs pulse, as illustrated by the simulation in Figure 4. At the same time, the spectrum of the 1 ps input pulse is broadened from 5 nm to 30 nm (at -10 dB). In the simulation, a 400 nm thick, 350 nm wide air-clad waveguide with a group velocity dispersion of -4.1 $\mathrm{ps}^2/\mathrm{m}$ was assumed to have a loss of 1 dB/cm and a nonlinear parameter of 140 + 26i 1/Wm. It has to be emphasized that this happens coherently, such that the spectrum of the pulse train remains a frequency comb.

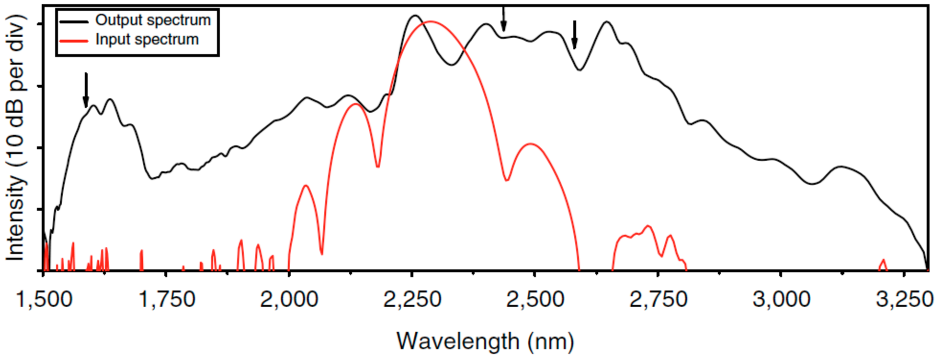

Figure 2: The input and output spectrum of the femtosecond pulses coupled to the silicon photonic waveguide. The spectrum is broadened to an octave. Its coherence was verified, by beating the spectrum with a narrow linewidth laser (at wavelengths indicated by the arrows).

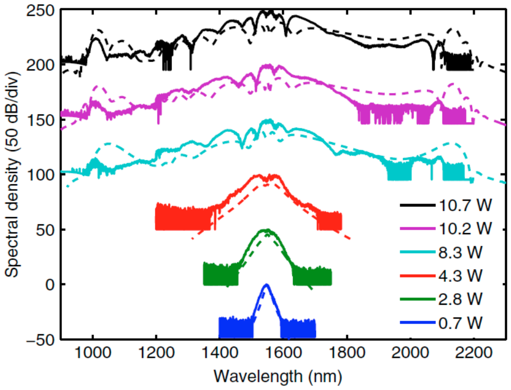

Figure 3: Telecom-wavelength-window octave-spanning frequency comb generated in an InGaP-on-insulator WG

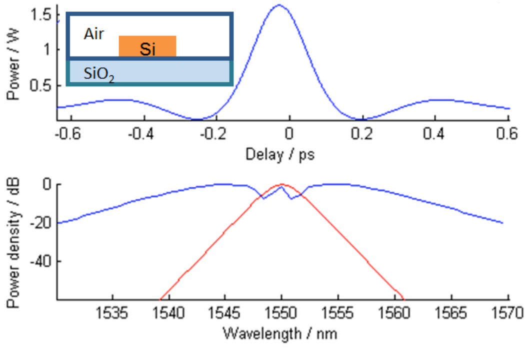

Figure 4: (top) The temporal profile of the output pulse with ~150 fs FWHM, while its input spectrum in red (bottom) is coherently broadened from 5 nm to 30 nm at -10dB at the output (in blue).

## 4. References

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