Generation of optical frequency combs at sub-GHz repetition rates with a hybrid-integrated mode-locked diode laser

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Optical frequency combs based on broadband-gain bulk lasers offer low intrinsic linewidths and sub-GHz line-spacing. Nevertheless, susceptibility to mechanical and acoustic perturbations and the complexity of pumping of these lasers have motivated chip-integrated extended cavity diode lasers using low-loss and long Si_3N_4 feedback circuits to extend the laser cavity for low repetition rates. Typically, saturable absorbers are used for mode-locking, however, the short upper-state carrier lifetime in semiconductor optical amplifiers requires repetition rates of a GHz or higher. We demonstrate absorber-free generation of optical frequency combs in a hybrid integrated InP-Si_3N_4 mode-locked diode laser, using a low-loss Si_3N_4 feedback circuit that extends the on-chip optical roundtrip length up to 60 cm by three highly-selective ring resonators. This enables passive as well as hybrid mode-locking with a low repetition rate of around 484 MHz.

Introduction

Optical frequency combs (OFCs) are a special class of laser sources whose optical spectrum consists of a series of equidistant frequency lines. OFCs based on optically pumped bulk lasers, e.g., Ti:Sapphire lasers or rare earth doped fiber lasers, have provided an important path to applications such precision spectroscopy [1], dual-comb spectroscopy [2], distance measurements [3] or LIDAR [4]. Having available long resonator lengths and a long (up to millisecond) lifetime of laser inversion is the key for high resolution, because low (sub-GHz) repetition rates and narrow spectral linewidths can be realized. However, the intrinsic susceptibility of bulk lasers to mechanical and acoustic perturbation, their relatively large size, and the complexity of optical pumping poses limitations for wide-spread use and out-of-the-lab systems. Recently, much effort has been put into developing OFCs in integrated photonics offering chip-based, compact, solutions with low power consumption, such as diode-pumped Kerr frequency combs [5]. An interesting alternative to avoid optical pumping are diode lasers where mode-locking, and thus frequency comb generation, is achieved with intracavity saturable absorbers. To reduce the repetition rates toward the lower GHz range, heterogeneous [6] and hybrid integrated extended cavity lasers [7] have been mode-locked using extended cavities based on low-loss Si_3N_4 feedback circuits. There, mode-locking is based on the generation of pulses with integrated saturable absorbers. However, even though much longer and low-loss waveguide cavities can be realized with Si_3N_4, a further lowering of the repetition rate into the sub-GHz range is difficult, because the relatively short upper state lifetime in semiconductor amplifiers of about 1 ns leads to instabilities that build-up between pulses from amplified spontaneous emission.

This limitation in the repetition rate motivated us to explore an alternative approach called Fourier domain mode-locking (FDML) [8], where no saturable absorber is present and mode-locking provides a quasi-continuous output. Recently, such FDML has been shown experimentally with diode lasers reaching very low repetition rates of 255 [9] and 360 [10] MHz, respectively, based on sharp spectral feedback filtering. However, these lasers were either based on bulk feedback (a Bragg fiber [9]) or the authors reported on possibly independently locked groups of modes [10]. Stable FDML with hybrid integrated lasers has been observed with sharp spectral filtering using two microring resonators [11, 12], but both repetition rates were well above the 1-GHz inverse upper state lifetime limit (around 5 and 2 GHz, respectively). A detailed physical explanation of the mode-locking dynamics, based on a resonance between relaxation oscillation and mode spacing was given recently [13]. We note that the described experimental and theoretical work is restricted to passive mode-locking, where the repetition rate is intrinsically less stable than with additional (active) external modulation, to cause hybrid mode-locking.

Here we present the generation of frequency combs with a repetition rate as low as 484 MHz using an extended cavity hybrid integrated InP-Si_3N_4 laser for FDML. The free spectral range of the laser cavity is reduced compared to that reported in refs. [11] and [12] by using a triple microring Vernier filter as a feedback mirror. This introduces sharper spectral filtering and extends the optical cavity roundtrip length to approximately 60 cm. We also demonstrate hybrid mode-locking, which stabilizes the repetition rate to the ten-kHz level through diode current modulation with an external RF oscillator.

Experimental results

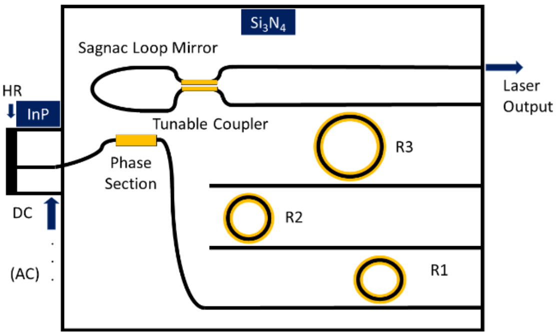


Figure 1: Schematic view of the hybrid integrated laser

The hybrid laser that is used for the experiments is presented in Fig. 1. The laser cavity comprises two components, an InP gain chip and a Si_3N_4 feedback chip. The gain chip is equipped with a semiconductor optical amplifier (SOA), which at the left end is coated with a highly reflective (HR) mirror, and at the other end with an anti-reflective (AR) mirror. The Si_3N_4 waveguide circuit comprises three microring resonators (MRR) of different radii, which form part of the feedback mirror and restricts the number of oscillating longitudinal modes of the laser. The feedback chip is equipped with thermoelectrical heaters (yellow in Fig. 1) to fine-tune the cavity length with the phase section, for adjusting the resonances of the microresonators and to adjust the output coupling. A spiral (not shown in Fig. 1) increases the cavity length of the laser and helps reduce the laser's free spectral range (FSR). Back reflections at the InP and Si_3N_4 interface are reduced by both tilting the waveguides with regard to the facet normal and an anti-reflection coating on the InP facet.

To generate the frequency-modulated optical frequency combs, the laser is operated in two ways. First, passive mode-locking is realized using a low DC current (50 mA) for pumping. Secondly, hybrid mode-locking is performed by applying an additional AC current component with a signal generator, which modulates the gain of the laser and stabilizes the mode-locking operation. In the following, we present both mode-locking techniques and their effect on the RF and optical linewidths of the laser.

Passive mode-locking

Firstly, we tune the laser as a single-frequency laser by adjusting the three micro-ring resonators to a common resonance, until single-frequency oscillation is achieved. Next, we detune the phase section which causes multimode oscillation. Further fine-tuning induces mode-locking which shows up as an optical comb spectrum as in Fig. 2a. To provide higher resolution, we recorded the RF spectrum with a photodiode and an electrical spectrum analyzer (ESA, Keysight N9000B CXA). The RF spectrum shows a single fundamental frequency and its harmonics, proving that the optical lines are equidistant, thereby confirming mode-locking. The RF spectrum shows a repetition rate of around 484 MHz. This is more than an order of magnitude lower than in the first demonstration with two microring resonators [11], about a factor of five lower than in [12], and it is a factor of two below the lifetime-limit of 1 GHz for standard mode-locking.

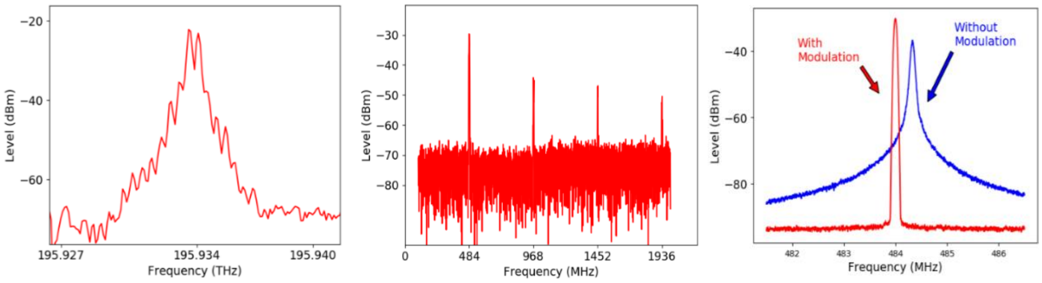


Figure 2: a) Resolution limited optical spectrum at 50 mA DC pump current, recorded with an optical spectrum analyzer (OSA, WaveAnalyzer). The spectrum displayes 15 equidistant comb lines, b) the corresponding RF spectrum shows an FSR of 484 MHz and c) RF linewidth without and with modulation

Hybrid mode-locking and linewidth comparison

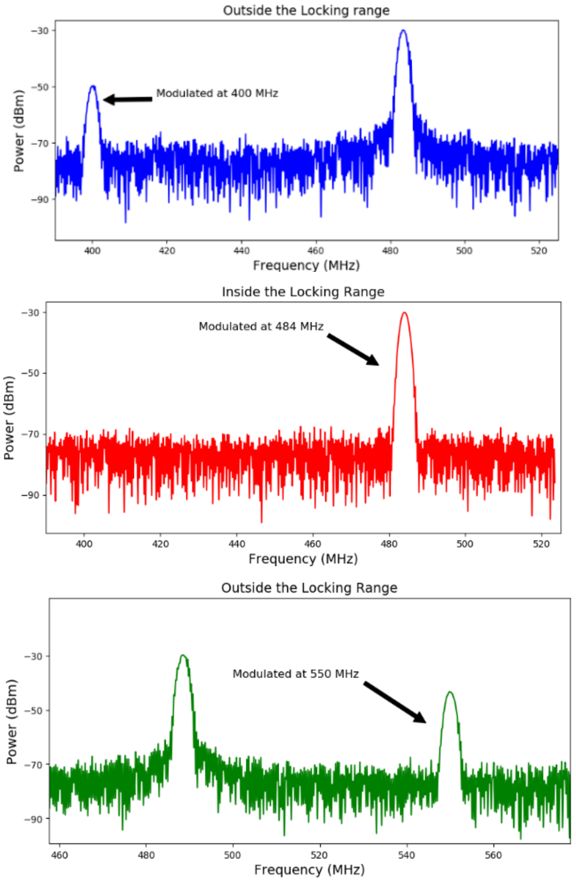
Implementing passive mode-locking is simpler in terms of technological effort, as it does not require an external RF oscillator. However, it suffers from an intrinsic instability of the pulse repetition rate due to pulse jitter. In contrast, hybrid mode-locking using additional modulation with an external RF oscillator, synchronous with the passive mode-locking frequency, promises a stabilized repetition rate. We stabilize the pulse repetition rate with an external oscillator that modulates the laser gain with a weak AC signal (-5 dBm) at 484 MHz, superimposed to the 50 mA DC current (17 dBm power).

Figure 2c shows a comparison of the repetition rate linewidth obtained with passive and with hybrid mode-locking. With passive mode-locking (blue trace) the RF fundamental linewidth is rather broad. A Voigt fit yields a Gaussian linewidth component of 67 kHz (FWHM) and a relatively big Lorentzian component of 5.8 kHz seen as wide wings farther from the line center. With hybrid mode-locking, this changes clearly, as the free-running repetition rate becomes locked to the external modulation frequency. In Fig. 2c, the Gaussian component is reduced to 44 kHz, and the Lorentzian component is too small to be retrieved.

For characterization of the optical linewidth, we used delayed-self heterodyne detection [14] with an acousto-optic modulator at 80 MHz and a fiber delay line of approximately 2.5 km. The Voigt fit analysis yields a Gaussian linewidth component of 80 kHz (FWHM) and a Lorentzian component of 30 kHz with passive mode-locking. With active modulation, i.e., hybrid mode-locking, we obtain linewidth values of 103 kHz and 24 kHz for the Gaussian and Lorentzian components respectively.

Locking range

Measuring the size of the locking range is important for judging the robustness of the repetition rate locking vs drifts of the resonator length. We have measured the locking range by stepwise tuning the external oscillator frequency around the passive repetition rate, while recording RF spectra as shown in Fig. 3. As soon as the oscillator frequency is brought into the locking range, the free-running (passive) repetition rate is extinguished and replaced by a single peak at the external frequency. Using these observations, we determined a relatively wide RF locking range of approximately 40 MHz.


Outside the Locking range

Inside the Locking Range

Outside the Locking Range

Figure 3: RF spectra from the passively modelocked laser when tuning the additionally applied external modulation frequency. In (a) and (c) the laser is modulated outside the locking range. In (b) the laser is modulated at the frequency corresponding to the FSR ,i.e. at 484 MHz.

Conclusion

We have demonstrated the generation of on-chip optical frequency combs at a low repetition rate of 484 MHz via passive and hybrid mode-locking, using a long-cavity hybrid integrated InP-Si_3N_4 diode laser. To explore the potential for a further lowering of the repetition rate, we have performed numerical simulations with a transmission line model based on [15]. The calculations show qualitative agreement with promise that lower repetition rates would become possible with further extended cavity lengths and steeper feedback filtering.

References

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