Generation of low repetition rate frequency combs with a hybrid integrated InP-SiN diode laser

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Abstract: We demonstrate the generation of frequency combs with a low repetition rate of 450 MHz, using a hybrid integrated InP-SiN diode laser with more than 60 cm optical roundtrip length on-chip. Comb generation is achieved without a saturable absorber, based on four-wave mixing in combination with gain-index coupling and spectrally filtered feedback; both passive and active mode-locking is observed. External modulation reduces the RF linewidth from several hundreds of kHz to the ten-kHz level.

1. Introduction

Optical frequency combs (OFCs) based on broadband-gain bulk lasers such as optically pumped Ti:Sa or Er-doped fiber lasers have gained much interest [1], for instance, in high-resolution spectroscopy [2], dual-comb spectroscopy [3] or coherent LIDAR [4]. These bulk optical approaches offer important advantages, specifically, a long optical roundtrip time for low intrinsic linewidths, a low repetition rate for a dense, sub-GHz line-spacing, and that the repetition rate can be stabilized or locked using low-noise, slow (MHz) electronics. Nevertheless, the intrinsic susceptibility vs mechanical and acoustic perturbation, the complexity of optical pumping, as well as large size and weight, have motivated the investigation of chip-integrated extended cavity diode lasers where low-loss and long SiN fiber waveguides extend the laser cavity for low repetition rates [5,6]. However, there, comb generation uses saturable absorbers to generate pulses; and in that case, the short upper state carrier lifetime in semiconductor optical amplifiers (SOAs), typically around 1 ns, imposes a limit for the lowest repetition rate in the order of a GHz. Similar limitations toward low repetition rates are found also in Kerr micro combs [7].

An option to reach repetition rates lower than the excited carrier decay rate is Fourier domain mode-locking [8] which provides frequency combs in the form of continuous-wave, frequency modulated light. Interestingly, sub-GHz repetition rates, i.e., below the named limit, have been reported [9, 10] using sharp spectral feedback filtering to confine the spectrum to a smaller number of comb lines. In [11], where spectral filtering is based on feedback from microring resonators in Vernier configuration, indeed the output is reported to be mostly frequency modulated. In good agreement with theoretical prediction [12] the first hybrid integrated diode lasers with mode-locking through sharp Vernier filtered feedback [13], showed stable comb generation as well, though with a 5 GHz repetition rate that is still above the carrier decay rate.

Here we present absorber-free passive mode-locking of a hybrid integrated InP-SiN diode laser with a line spacing (repetition rate) reduced by more than an order of magnitude compared to [13], to 450 MHz, following an earlier improvement by a factor of two [11]. We achieve this with a highly spectrally selective, triple Vernier-filtered feedback that extends the on-chip optical roundtrip length to more than 0.6 meters. Making use of the low roundtrip frequency, we stabilize the repetition rate to the ten-kHz level, by adding a weak, 450 MHz modulation (AC) to the DC drive current of the diode amplifier.

2. Experiment

The hybrid integrated InP-SiN diode laser used for the experiments is shown in Fig. 1, with a waveguide design similar to what is described in [14]. For the generation of optical frequency combs, the laser is operated in two ways, firstly, through passive mode-locking using only a DC current for pumping. Secondly, we use a signal generator to slightly modulate the gain (additional AC), to actively support and stabilize the mode-locking (hybrid mode-locking). In the following section, we present both mode-locking techniques and the according frequency combs.

Figure 1: Schematic view of the hybrid integrated laser using three micro ring resonators (R1, R2, R3) for sharp spectrally filtered Vernier feedback. A phase section is used to tune the frequency of longitudinal laser cavity modes relative to the Vernier filter frequency.
2.1 Passive mode-locking

First, we set the three micro ring resonators to a common resonance and use the phase section to tune a laser cavity mode to the peak of that resonance. Hence, the laser is brought to single-frequency operation. Next, as described in [13] the phase section is tuned again, to cause the oscillation of multiple modes. Further fine-tuning then induces mode-locking and comb generation. Figure 2a shows the output displayed by an optical spectrum analyzer (OSA, resolution limited to 200 MHz), suggesting the presence of a set of equidistant comb lines.

![Figure 2](image)

Figure 2: a) Optical spectrum at 50 mA DC pump current, b) the corresponding RF spectrum shows an FSR of 451 MHz, c) RF spectrum without and with the external modulation

To confirm mode-locking, we also recorded the RF spectrum of the output with an electrical spectrum analyzer (see Fig. 2b). The RF spectrum reveals an equidistant line spacing and thus mode-locking. The observed repetition rate is close to 450 MHz. This value is much lower than what was reported in [13]. The observed mode-locking without using a saturable absorber had been coarsely described as based on four-wave mixing between two longitudinal modes tuned to approximately equal net gain [13], while a detailed description revealed the roles of Henry’s linewidth enhancement factor and the beating of the modes becoming resonant with the relaxation oscillation frequency for achieving mode-locking [12].

2.2 Active mode-locking

Passive mode-locking may be advantageous as it does not require any external oscillator and is thus obtained with less technological effort. However, with passive mode-locking, the pulse repetition rate remains intrinsically unstable in the form of timing jitter. In Fig. 2c, shown in blue, it can be observed that the linewidth of the fundamental RF peak, which quantifies the instability of the repetition rate, is indeed rather broad. A Voigt fit yields a Gaussian linewidth component of 290 kHz (FWHM) and a Lorentzian component of 680 kHz. To stabilize the repetition rate, we perform active mode-locking by modulating the gain of the laser with a weak AC signal (power -5 dBm) at 451 MHz from an external generator, superimposed to the 50 mA DC current (power 17 dBm) with a Bias-T. The red trace in Fig. 2c shows that with external modulation the RF linewidth of the laser becomes much narrower. A Voigt fit delivers a Gaussian component of about 20 kHz with a negligible Lorentzian part. This linewidth narrowing indicates a rather stable repetition rate in this hybrid mode-locking regime. Our numerical simulations with a transmission line model [16] qualitatively confirm the stabilization of the repetition rate.

3. Conclusion

We have presented on-chip generation of optical frequency combs with a low repetition rate of around 450 MHz using passive and hybrid mode-locking, making use of sharp Vernier intracavity filtering. Our numerical simulations are in good qualitative agreement and predict that even lower repetition rates and line spacings might be achievable with further cavity length extension.

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5. References