Frequency stabilization of a hybrid-integrated InP-Si_3N_4 diode laser by locking to a fiber ring resonator

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Hybrid integrated diode lasers based on low-loss Si_3N_4-based feedback circuits enable advanced laser performance and embedding in photonic circuits. In particular, using high-Q Si_3N_4 ring resonators for frequency-selective feedback provides wide spectral coverage, mode-hop free tuning and ultra-narrow intrinsic linewidth. In addition, most applications also require long-term stability, which can be provided by locking the laser frequency to external references. We present the locking of a hybrid-integrated laser to a fiber ring resonance. Via controlling the diode current or a Si_3N_4 phase shifter we find a maximum full-width-half-maximum linewidth reduction from 0.32 MHz to 0.06 MHz.

Introduction

Lasers with highly stable frequencies are instrumental for many applications such as laser cooling and trapping [1] or precision metrology [2]. For short-term stability, hybrid integrated diode lasers, based on low-loss Si_3N_4-based feedback circuits, are well-suited. In particular, using high-Q micro-ring waveguide resonators for frequency-selective feedback provides wide spectral coverage even into the visible [3], mode-hop free tuning [4] and ultra-narrow intrinsic linewidth, presently as low as 40 Hz [5]. The according high level of short-time frequency stability is beneficial for applications involving fast measurements such as in coherent optical communication [6]. However, for stability on intermediate and long-term time scales, where technical noise and drifts are present, locking to reference resonators or absolute frequency references is required.
Recently, a heterogeneously-integrated diode laser was successfully locked to a mode frequency of a bulk external resonator [7], and a Bragg-waveguide-based hybrid-integrated integrated was locked to a reference absorber [8]. Here we present the first frequency stabilization of a micro-ring-based InP-Si_3N_4 hybrid-integrated laser. Using a fiber reference resonator ($Q = 4.0\cdot 10^7$), we compare the alternatives of locking via the diode current or via a Si_3N_4 phase shifter, regarding servo bandwidth and the reduction of frequency noise.

Laser design and setup

A schematic overview of the laser design is shown in Fig. 1(a), with a photograph of the laser shown in Fig. 1(b). The laser comprises an InP-based optical amplifier, which is hybrid-integrated with a Si_3N_4-based feedback circuit. The optical amplifier has a high-reflectivity coating on one facet, which forms one mirror of the laser cavity. The Si_3N_4 circuit contains two sequential microring resonators (MRR) in a Vernier loop configuration forming the other mirror. The Vernier filter also provides single-frequency operation over a wide tuning range around 1.55 µm wavelength, as well as low intrinsic linewidth via extending the effective cavity length with multiple passes through the MRRs. A tunable coupler directs part of the light to the output port. The output of the laser is available via a fiber that is butt-coupled to this output port.

The laser can be frequency controlled via the amplifier current and via heaters on the Si_3N_4 circuit. Mode-hop free tuning is possible across the laser resonator's free spectral range (≈ 2 GHz) by tuning the phase section and even further by tuning the rings synchronously as described for an earlier laser version in Ref. [4]. Assembling the laser using a printed circuit board allows for reproducible and convenient electronic control. For stable operation the assembly is placed on a Peltier element which is set to 22° C. The shown assembly also contains a duplicate amplifier and feedback circuit, but for the experiment described here we only use one circuit.

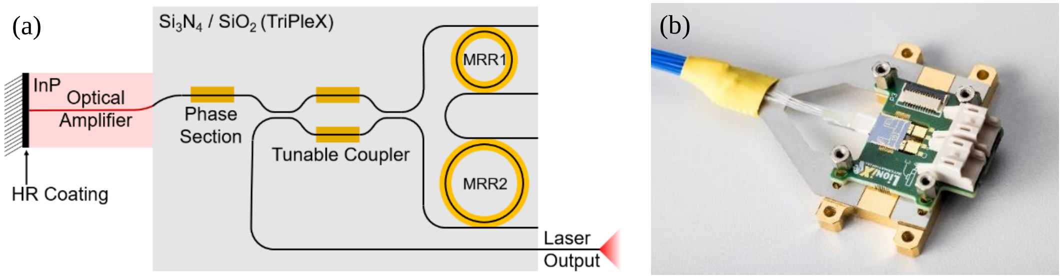

Fig. 1. (a) Schematic view of the hybrid-integrated laser. Heaters for thermal tuning of the laser are indicated in yellow. (b) Photograph of the hybrid laser assembly. Photo by Gijs van Ouwerkerk, PHIX Photonics Assembly.

For active frequency stabilization, we use a setup as schematically shown in Fig. 2. The laser output first passes through an isolator. For frequency noise analysis, part of the light is coupled out using a 50/50 fiber coupler. To detect any frequency drift, a 1.8-m long fiber ring resonator and photodiode serve as a frequency discriminator. The fiber ring resonator is based on a 90/10 fiber coupler (Thorlabs PN1550R2A2), where the 10% tap channels are connected to form a closed fiber loop. The photodiode signal is fed into a servo controller (Toptica DigiLock 110), which controls the laser to correct for frequency deviations.

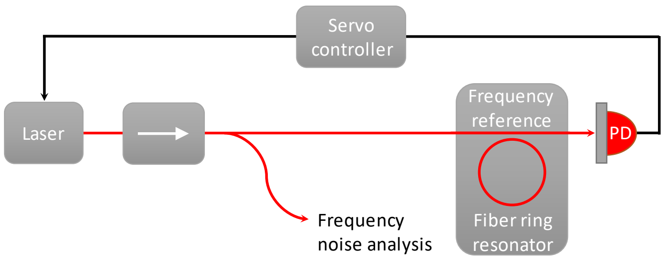

Fig. 2. Setup with feedback loop for frequency stabilization of the hybrid-integrated laser. The setup contains the laser, an isolator (⟶), a fiber loop that serves as frequency discriminator, a photodiode (PD) and a servo controller.

Measurement results

To characterize the spectral response of the frequency discriminator, we scanned the laser frequency over a range of 0.2 GHz via tuning the diode current around 100 mA, and recorded the signal on the photodiode. Fig. 3(a) shows the recorded signal, normalized to the maximum transmission. Based on the measured full-width-half-maximum (FWHM) of 4.9 MHz and the free-spectral range of 111 MHz, we calculate a Finesse of 23 and a Q-factor of $4.0 \cdot 10^7$ for these fiber ring resonances.
Since the laser has multiple frequency controls, the feedback signal to stabilize the laser frequency can be applied in different ways. We used both the modulation input to the amplifier current controller, and the phase section heater voltage as frequency control

signals. Fig. 3(b) shows the recorded modulation magnitude for both controls as functions of modulation frequency, when the laser frequency is set to the steep slope of a resonance as shown in Fig. 3(a). Both approaches provide a strong modulation response at low frequencies, while only current modulation reaches into the MHz range. At high frequencies, the modulation bandwidth for the amplifier current is only limited by the modulation input of the current source, while the phase section bandwidth is determined by the relatively slow thermal response of the phase section to an applied control signal.

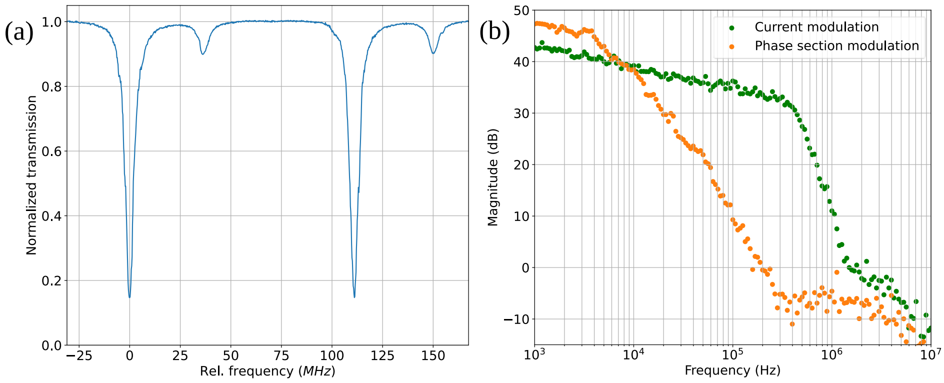

Fig. 3. (a) Normalized transmission through the fiber ring resonator, recorded by scanning the laser current. (b) Magnitude response for modulating the amplifier current and phase section of the laser.

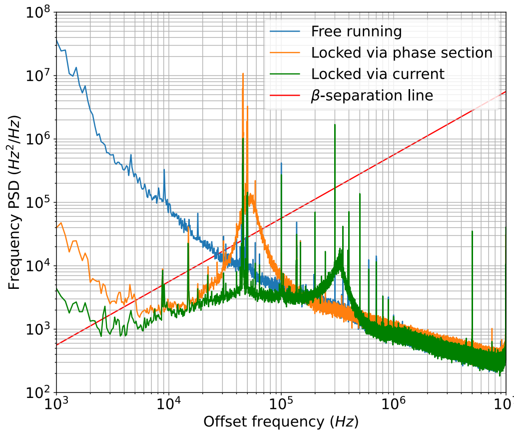

Fig. 4. Recorded frequency-noise power-spectral-density (PSD) for the free-running laser in comparison with the frequency-stabilized laser. Feedback is applied both to the amplifier current and the phase section.

To measure how much the frequency locking improves the frequency stability of the laser, we recorded the frequency-noise power-spectral-density (PSD) of the free-running and the locked laser, as displayed in Fig. 4. For the free-running laser (blue line) the frequency noise decreases with a 1/f dependency for low frequencies, which is typical for technical noise. At high noise frequencies, beyond 7 MHz, the noise levels off to a white noise level of 0.33 kHz^2/Hz. Multiplying this level with π provides an intrinsic linewidth of 1.0 kHz. Integrating the surface that exceeds the β-separation line [9] provides a free-running FWHM linewidth of 0.32 MHz, based on an integration time of 1 ms.

For locking the laser, the servo gain was maximized up to where the servo loop remains stable. Using both the current (green line) and the phase section (orange line) we successfully locked the laser frequency to the fiber ring resonator. The respective FWHM linewidths are 0.06 MHz and 0.18 MHz, for locking via the current and phase section. This is a linewidth reduction of up to a factor of 5 compared with the free-running laser.

More specifically, it can be seen that the locking reduces the noise level at low frequencies, between 1 kHz and 100 kHz, and strongest at around 2 kHz, by up to three orders of magnitude. The present limitations in feedback bandwidth lie at 54 kHz for locking via the Si_3N_4 phase section and at 0.33 MHz for the amplifier current.

Summary and conclusion

We have stabilized the emission frequency of a hybrid-integrated diode laser by locking it to a resonance of a fiber-based ring resonator. This laser provides a low intrinsic linewidth of 1.0 kHz on short timescales and a FWHM linewidth of 0.32 MHz. Frequency stabilization further reduces the FWHM linewidth to 0.06 MHz for an integration time of 1 ms. Acting on the diode amplifier current provides a higher servo bandwidth than the 54 kHz speed of thermal phase section. Using a faster stress-optic modulator [10] instead of a heater, could further increase the servo bandwidth into the MHz range. As a future step, the laser could be locked to an integrated high-Q waveguide resonator [11] or a molecular absorption line, such as acetylene [12] to provide long-term stability. This would enable a compact and frequency-stable light source integrated on a chip.

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