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Simulations of a sub-kilohertz linewidth laser in monolithic indium phosphide

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Abstract

Narrow-linewidth lasers play a crucial role in various applications, including sensing, coherent communication, and quantum communication. Semiconductor lasers achieving narrow linewidths employ long external cavities to extend photon lifetime within the resonator. For monolithically integrated (active-passive) platforms the loss of the passive waveguides puts a limit on this approach, however. To our knowledge, the state-of-the-art linewidth for such monolithic lasers stands at 10 kHz.

We build on the extended cavity approach, designing an extended-cavity laser with several cascaded cavities. The separate cavities allow us to design the reflection spectrum as a function of wavelength and have the lasing wavelength on an upward slope of the extension reflectivity, avoiding mode-hops. This can result in a remarkable narrowing of the linewidth of the laser, beyond what is possible with a single extension. A theoretical feasibility study shows that linewidths of 0.3 kHz can be achieved in a monolithic InP platform.

Introduction

Semiconductor lasers in photonic integrated circuits are crucial for miniaturizing and enhancing the performance of optical systems, enabling compact, cost-effective, and scalable solutions for applications ranging from high-speed data communication to advanced sensors [1]. A critical parameter for semiconductor lasers is their optical linewidth, which directly impacts sensing accuracy and data rates [2, 3].

Over the past years, remarkable narrowing of the linewidth of monolithically integrated lasers has been achieved by extending the active laser cavity with a passive section, achieving linewidths down to 10 kHz [4, 5]. The optical field in these lasers is distributed between the active and passive parts of the cavity, effectively reducing the noise contribution of spontaneous emission events in the laser [6].

Our approach builds on this method but takes a more general perspective. Rather than solely focusing on field distribution between active and passive regions, we model everything outside the active material as a frequency-dependent reflectivity

$$r = r_0(\omega)e^{i\,\phi(\omega)}, \tag{1}$$

where $r(\omega)$ and $\phi(\omega)$ are the frequency-dependent amplitude and phase of the reflectivity of the field. Incorporating this frequency-dependent reflectivity in the Langevin rate equations yields a modified version of the Schawlow-Townes equation for linewidth

$$\Delta\nu = \frac{\Delta\nu_0}{F^2}, \tag{2}$$

where $\Delta\nu_0$ is the original Schawlow-Townes linewidth and F is a linewidth narrowing factor resulting from the frequency-dependent reflectivity r:

$$F = 1 + \frac{1}{\tau_0}\frac{\mathrm{d}\phi_\mathrm{r}}{\mathrm{d}\omega} + \frac{\alpha}{\tau_0}\frac{\mathrm{d}\ln{(r_0)}}{\mathrm{d}\omega} \tag{3}$$

Here τ_0 is the roundtrip time in the active part of the cavity and α is the linewidth enhancement factor. The derivatives $\mathrm{d}\phi_\mathrm{r}/\mathrm{d}\omega$ and $\mathrm{d}\ln(r_0)/\mathrm{d}\omega$ are related to the phase and amplitude of the reflectivity, as defined in (1) [6].

While previous laser designs with long passive extensions have focused on exploiting the phase derivative ($\mathrm{d}\phi_\mathrm{r}/\mathrm{d}\omega$ indicates the group delay in de passive section), our work engineers the passive extension to also utilize the amplitude derivative, as demonstrated in previous studies on heterogeneous integration platforms [7]. This work serves as a theoretical feasibility study for implementing this technique on a monolithic InP chip. The designs and parameter values are compatible with the targeted multi-project wafer (MPW) platform provided by SMART photonics [8].

Reflection spectrum calculations

To create a reflection spectrum where not only the phase but also the amplitude is dependent on the frequency, we use resonant cavities. A simple example would be a Fabry-Perot (FP) cavity as an extension to the active laser cavity, as shown in Fig. 1a. The reflection spectrum of an FP cavity has resonances depending on the roundtrip phase of the frequency of the light in the cavity. Fig. 1b shows the reflection spectrum of a 12-mm FP cavity and the transmission spectrum of a 0.3-mm active cavity. Around 12 mm, the phase derivative term in F is maximized. For longer cavities, the additional losses in the passive cavity result in an increase in linewidth again.

To narrow the linewidth further, we need to tune the phase in the active cavity in such a way that we are lasing on the upward slope of the reflectivity. The steeper the slope of the reflectivity, the larger the derivative, and the larger the linewidth reduction factor F becomes. However, because the separate modes of the FP cavity lie very close together compared to the transmission of the active cavity, a mode hop will occur before we see a significant decrease in linewidth.

To achieve long cavities (for a high $\mathrm{d}\phi_r/\mathrm{d}\omega$ term) and be able to lase on an upward slope of the amplitude of the reflectivity, we propose an alternative design shown

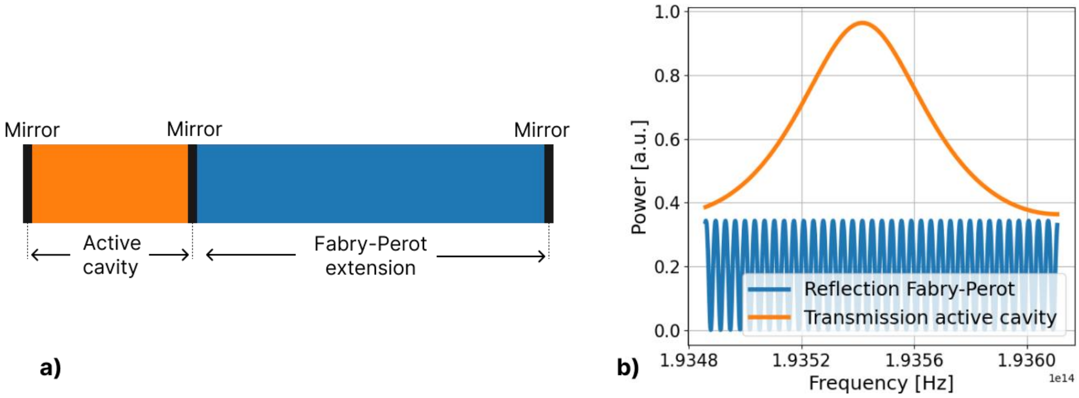

Fig. 1 a) FP extension to a laser cavity. b) Reflection spectrum of an FP cavity of 12 mm in blue and transmission spectrum of an active cavity of 0.3 mm in orange.

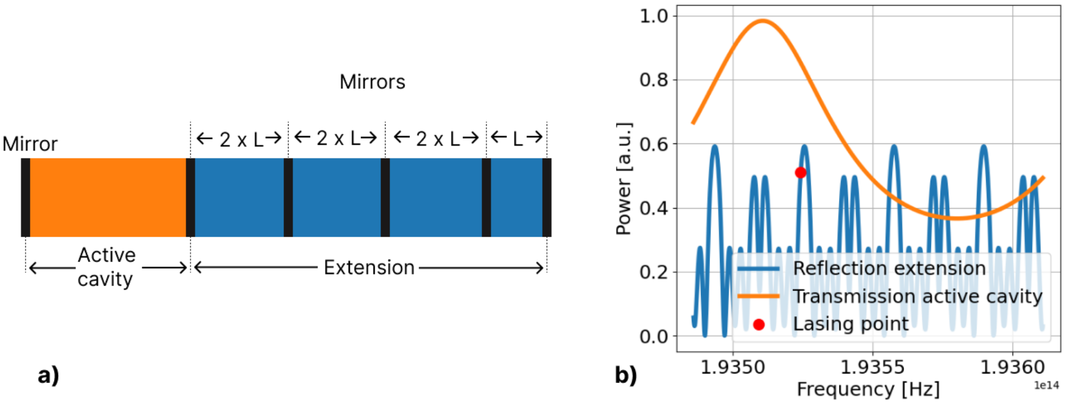

Fig. 2 a) Extended cavity laser design. Four cascaded cavities, one of length L and three of length $2L$ result in spacing of the reflectivity peaks further apart than with just a single cavity of length $7L$. b) Reflection spectrum of the cascaded cavity design in blue and transmission spectrum of an active cavity of 0.3 mm in orange. The red dot indicates the lasing frequency, situated on an upward slope of the reflection spectrum.

in Fig. 2a. It consists of an array of three shorter FP cavities of equal length and a fourth FP cavity half the length of the others. The low-reflectivity mirrors between them ensure that a significant portion of the optical field resides in the passive section. These combined cavities are similar in length to a single Fabry-Perot cavity but produce peaks in the reflection spectrum that are more widely spaced. The configuration with four shorter cavities allows us to have a long passive extension and to lase on an upward slope, avoiding mode hops. Fig. 2b shows the reflection spectrum of this cavity configuration where $L = 1.3$ mm, and the transmission spectrum of an active cavity of 0.3 mm long. The red dot indicates the lasing frequency, which is clearly on an upward slope, with a positive derivative with respect to frequency, increasing F and therefore decreasing the linewidth of the laser.

Using (2), we can calculate the theoretically achievable linewidth. Taking into account typical losses and lengths of building blocks on the SMART platform, it is projected that linewidth as low as 0.3 kHz can be attained for this laser design, at a laser output power of 5 mW.

Simulations

We simulated the proposed laser design in time domain traveling wave (TDTW) software PICWave from PhotonDesign [9]. The constructed circuit is shown in Fig. 4a. The front distributed Bragg reflector (DBR) has a length of 200 µm, the middle gratings all have a

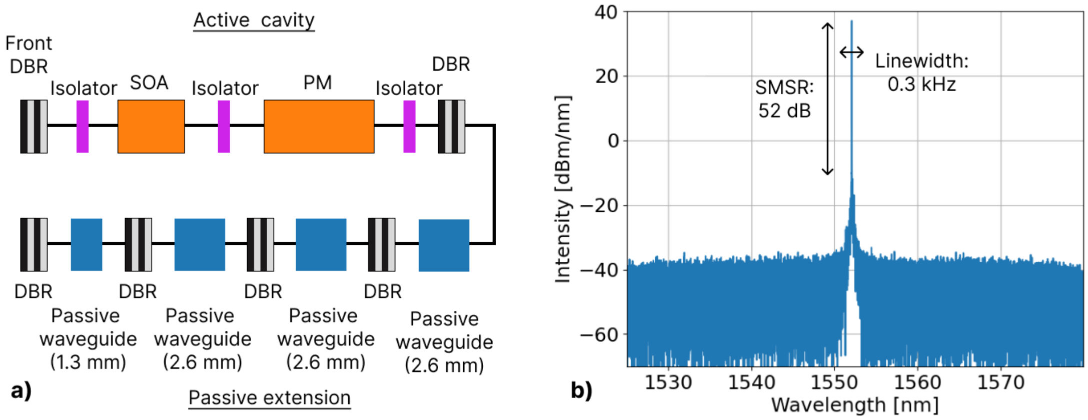

Fig. 3 a) Overview of the simulated circuit in PICWave. b) Simulated laser spectrum using PICWave.

length of 10 µm, and the rear DBR has a length of 1000 µm. The grating pitch of all DBRs is 0.237 µm. The semiconductor optical amplifier (SOA) has a length of 300 µm and the phase modulator (PM) has a length of 500 µm. The long passive waveguide sections are 2.6 mm long and the short passive waveguide section has a length of 1.3 mm. In the simulations, we apply a bias current of 80 mA to the SOA and adjust the phase with our PM in such a way that we achieve minimum linewidth. The simulation result is shown in Fig. 4b. The laser achieves single-mode lasing at a wavelength of 1552 nm with an output power of 5.4 mW and a sidemode suppression ratio (SMSR) of 52 dB. The linewidth of the simulated laser is 0.3 kHz.

Discussion

The results of the simulations in PICWave are in line with what is expected from our calculations. When the active cavity is biased correctly, the reflection of the passive extension reduces the linewidth drastically, showing that, theoretically, linewidths of around 0.3 kHz are achievable in monolithic InP. This would be more than an order of magnitude lower than the current state of the art.

Conclusion

Integrated narrow linewidth lasers are essential for fields such as optical sensing and coherent communication. To achieve narrow linewidth, lasers with a long passive extension are used. By constructing this extension out of several cascaded cavities, we can engineer the reflection spectrum in such a way that we achieve linewidth narrowing beyond what is possible with just a simple, long, passive extension. Simulations confirm our calculations and show a possibility of going down to linewidths as narrow as 0.3 kHz at lasing powers around 5 mW in a monolithic InP platform.

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