Single mode continuous wave laser design based on cold-cavity simulations

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We present designs of single mode continuous wave lasers deploying ring resonators as intra-cavity filters and multimode interference reflectors and distributed Bragg gratings as feedback elements. The designs were modelled using cold-cavity calculations. The lasers are designed in an InP-based generic technology platform using the commercially available building blocks.

Introduction

Semiconductor single mode continuous wave (CW) lasers are ubiquitous components utilized in numerous applications from telecom, datacom, metrology to sensing. A wide variety of laser cavity geometries has been proposed and demonstrated through the years. E.g. distributed feedback (DFB) lasers [1], distributed Bragg reflectors (DBR) lasers, lasers using ring resonators and Vernier effect [2], deploying asymmetric Mach-Zehnder interferometers (AMZI) [3], V cavity configuration [4]. The different designs each have properties, such linewidth, side mode suppression ratio (SMSR), spontaneous emission coupling to the lasing mode, cavity losses and tuneability that make them suitable for a particular application. While most of these properties are tightly linked to the material platform used, the laser geometry is always crucial for obtaining the desired single mode operation.

In order to achieve the latter, a longitudinal mode must meet threshold condition (round trip gain of unity) before the other competing longitudinal modes. Designing a single mode laser with a complex cavity and a wide parameter space such as the cavity length and cavity modes spacing, wavelength selectivity of intra-cavity filters, wavelength dependent modal gain and losses etc. is not trivial. Many simulation tools are available for studying either just the response of the intra-cavity filter or the complete laser structure in the time domain or in steady state. The output of such tools are usually used as guidelines for designing a laser. In this paper, we present a cold-cavity [5] method for steady state simulations which can be used to design a laser cavity, calculate the round trip gain difference that each cavity mode experiences and the resulting SMSR at threshold. We use these simulations to design single mode lasers on an InP-based generic technology platform [6] with the commercially available building blocks.

Cold-cavity simulator

In a cold-cavity simulation the steady state electric field strength is calculated in a resonator (laser cavity) for a fixed value of gain and phase matching. It is a method for designing a laser cavity, determining the difference in round trip gain of longitudinal modes and used to optimize the laser design in order to maximize the latter. This is a critical parameter which ultimately has an impact on the laser SMSR in the above-threshold operation.

For these steady-state simulations, we use a T-matrix formulation [7], a convention for describing the input and output waves of multiport circuits (Fig. 2(b) dashed rectangle). T-matrices are mathematically equivalent but not as intuitive as scattering matrices. The

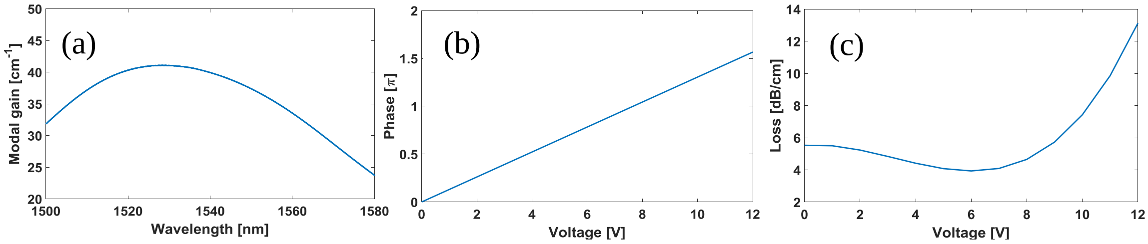

Figure 1. (a) SOA modal gain for current density 2.5 kA/cm^2, (b) Phase shift for 1 mm long ERM as a function of voltage, (c) Loss per unit length as a function of voltage for ERMs from experimental results.

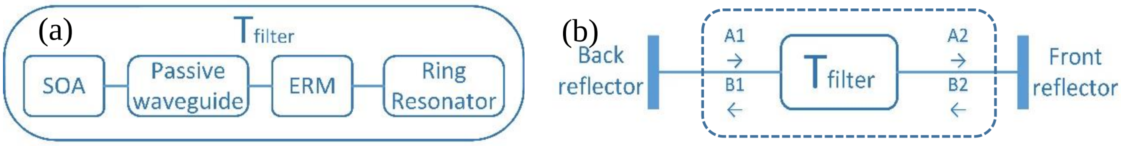

Figure 2. (a) Example of an intra-cavity filter and definition of the total T-matrix, (b) forming the cavity using two reflectors.

matrix elements in a way lack a direct physical interpretation but they are very useful because they reduce the calculation of the intra-cavity filter response formed by a combination of different elements to a matrix multiplication. We set T-matrices for gain elements – semiconductor optical amplifiers (SOA), electro-refractive phase modulators (ERM), passive waveguides, DBR gratings and other necessary used components. The SOA spectral dependence of modal gain at 2.5 kA/cm^2 (Fig.1 (a)) is obtained by a commercial time-domain simulator (PICwave) which uses parametrized experimental data. The phase shift of the ERMs (Fig.1 (b)) is based on experimental as their losses (Fig.1 (c)) as a function of voltage. The losses of passive waveguides and other components such as multimode interference (MMI) couplers are also based on experimental data.

After having set the T-matrices for each of the elements, we can calculate by matrix multiplication the total response of the intra-cavity filter. This is shown for an example laser cavity which includes only an SOA, passive waveguides, ERM and a ring resonator in Fig.2 (a). In order to calculate the cold-cavity response of the laser cavity we need to close the cavity by either forming a linear cavity using mirrors or a ring cavity. These mirrors can be either DBR gratings for which we can also calculate their reflectivity and phase response using the T-matrix method or MIR's in which we assume flat spectral response. The latter assumption is acceptable because we will be looking at simulations at a narrow band but for simulations regarding wideband tuning a more detailed model for the MIR's should be used. Here we use a linear cavity configuration as shown in Fig.2 (b). Using the equations from the definition of a T-matrix

$$A_1 = A_2T_{11} + B_2T_{12} \quad (1a)$$

$$A_2 = A_2T_{21} + B_2T_{22} \quad (1b)$$

and the equations derived from the laser geometry as shown in Fig.2 (b)

$$B_2 = A_2R_{FR} + ASE \quad (2a)$$

$$A_1 = B_1R_{BR} \quad (2b)$$

where R_{FR} and R_{BR} are the front and back mirror electric field reflectivity respectively and ASE is the amplified spontaneous emission which is used as input to the system and using the assumption $T_{21} = T_{21} = 0$, which means that there are no spurious reflections in the cavity filter (Fig. 2(a)), we find that the electric field after a round-trip can be written as

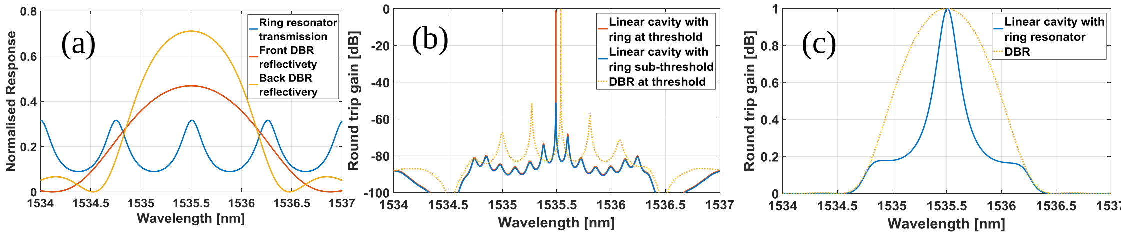

Figure 3. (a) Response of ring resonator and DBR gratings, (b) Spectra of linear laser with ring resonator below threshold (blue) and at threshold (orange) and DBR laser at threshold (yellow dashed line), (c) total filter response of linear cavity with ring resonator and DBR laser (blue and dashed yellow respectively)

$$G_{RT} = ASE\frac{T_{22}R_{BR}}{T_{11} - R_{FR}T_{22}R_{RF}}$$

The variables T_{11} and T_{22} are wavelength dependent and their values change as we change the modal gain of the SOA element. As we will see in the next part, starting from low values of gain we can obtain sub-threshold spectra and by slowly increasing the modal gain we can reach the threshold condition where the lasing mode reaches a round trip gain equal to one.

Simulation results and laser designs

A) Linear cavity with a ring resonator and DBR gratings

We first simulate a linear cavity laser with a 1 mm long SOA, DBR gratings as mirrors of 300 and 40 μm length and a ring resonator with 80 μm ring radius in the cavity. The coupling with the ring resonator is implemented with 3 dB 1x2 MMI's which have typical insertion loss below 1dB. The total length of the cavity is approximately 2.5 mm corresponding to cavity mode spacing of ~16 GHz. The normalized response of the frequency selective elements, ring resonator and DBR's is shown in Fig.3 (a). The DBR reflection window is about 1.2 μm and the ring resonator free spectral range (FSR) is about 0.7 μm.

A below threshold spectrum is depicted in Fig.3 (b) (blue curve) where the filter structure and the cavity modes are visible. Increasing the gain until the lasing mode at 1535.5 nm reaches a value close to unity (0.99 in this case) produces a spectrum as the orange curve in Fig. 3(b). By inspecting the total filter response at the wavelengths of the lasing mode and the second most powerful mode we can find out how much difference in gain was necessary in order to obtain the exhibited SMSR at threshold. In this case we find that the two modes have a round trip gain difference of 27% (1.4dB).

For comparison a DBR laser is also simulated and plotted along with the previous structure, linear cavity with a ring filter. The DBR laser has approximately half cavity length which almost doubles the cavity modes FSR. In this case the neighboring competing modes are further away from DBR reflectivity maximum thus experiencing less round trip gain and making the lasing conditions more favorable. However, the resulting difference in round trip gain is only 10% (0.45 dB) (Fig.3 (c), yellow dashed line) thus significantly reduced compared the previous laser geometry. This is also reflected in the SMSR at the threshold as observed from the spectrum in Fig. 3(b) (yellow dashed line).

B) Linear cavity based on Vernier effect

Wavelength selectivity based on the Vernier effect is a widely known technique which simultaneously offers wavelength tuneability if resonators can be tuned. Vernier effect is

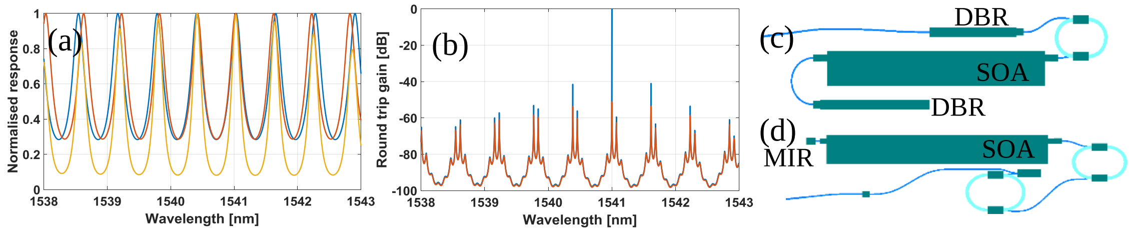

Figure 4. (a) Ring resonators transmission spectra (blue and orange) and total filter response (yellow), (b) Spectra of Vernier laser below threshold (orange) and at threshold (blue), (c) Linear cavity laser design with DBRs and ring resonator, (d) Linear cavity laser based on Vernier effect

based on the use of two or more resonators which are slightly detuned in order to obtain constructive interference at the desired wavelength and significantly increase the total FSR. Here we deploy the Vernier effect based on two ring resonators with radii of 106 and 108 μm which give a total FSR of 90 nm. We use a 1 mm long SOA and close the cavity using a 100% reflective 1-port MIR on one side and a 50% reflective 2-port MIR on the other. For the MIRs we also assume 1 dB insertion loss. Fig. 4(a) shows the transmission spectra of the two rings (blue and orange curves) and the total filter response (yellow). In Fig. 4(b) the sub- and at threshold spectra (orange and blue respectively) are shown. The resulting SMSR is a result of just 1.6% (0.08dB) in round trip gain difference which however should be enough to give single mode operation.

Finally, in Fig.4 (c) and (d) the two linear laser geometries (linear laser with an intra-cavity ring resonator and Vernier effect respectively) which were discussed above are shown as designed for a multi-project wafer run in an InP-based generic integration platform.

Summary

We simulate two different laser geometries using a cold-cavity simulator, a linear laser with an intra-cavity ring resonator and a linear laser deploying Vernier effect. The former is also compared to a similar DBR laser structure and shows improved SMSR. The two laser designs are also designed and submitted for a multi-project wafer run and will be fabricated in an InP-based generic integration platform.

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