Design of feedback insensitive InP ring laser

T.T.M. van Schaijk, E.A.J.M. Bente and D. Lenstra

The optical isolators used to protect semiconductor lasers against optical feedback cannot be integrated. Therefore we propose to fabricate a laser that has a strongly reduced sensitivity to feedback. Simulations show that such a device can be realized by employing a ring laser in which the clockwise and counter-clockwise modes are not coupled. To achieve unidirectional lasing, this work proposes to use an intra cavity weak optical isolator based on two phase modulators that are driven 90 degrees out of phase. Simulations show up to 3% of intensity feedback can be tolerated without any distinguishable effect on the laser light.

Introduction

For decades laser performance has suffered from the effects of external optical feedback (EOF). This is light that is reflected back into the laser by one or more reflectors outside of the cavity[1]. In traditional fiber coupled lasers, the effects of EOF can be greatly reduced by placing it in series with an optical isolator. An isolator that can be integrated on a chip is demonstrated in [2], but its performance does not meet the requirement of more than 30 dB of isolation.

This paper proposes to utilize the isolator presented in [2] in a different way. Instead of using it to directly suppress EOF, it is used to provide a gain difference between the clockwise (CW) and counterclockwise (CCW) modes of a ring laser. This allows unidirectionally lasing without introducing any optical coupling between the CW and CCW modes (except for the coupling introduced by the EOF). Thus the EOF cannot coherently interact with the lasing mode in this laser, although effects through variations in the carrier density may still be present. Analysis shows that this can be accomplished with much weaker, intra-cavity, optical isolation than would be required to directly suppress feedback. In this paper we will present an analytical analysis of this type of laser that is subsequently compared to an advanced numerical simulation. On the basis of these analyses, we predict that an isolation of 7 dB is sufficient to withstand EOF of up to 3 %.

Design of the laser

The key to achieving feedback insensitivity that is described in this paper is to separate the EOF from the lasing mode. As mentioned above, this can be most easily done by employing a ring laser architecture. If such a laser is lasing in the CW mode, then the EOF will return to the CCW mode. The CCW mode can then influence the lasing mode in two ways: Firstly it can affect the carrier density in the active material of the laser, and thereby indirectly affect the lasing mode. This effect can be reduced by minimizing the amount of light in the CCW mode. Secondly, the CCW mode can directly influence the lasing mode

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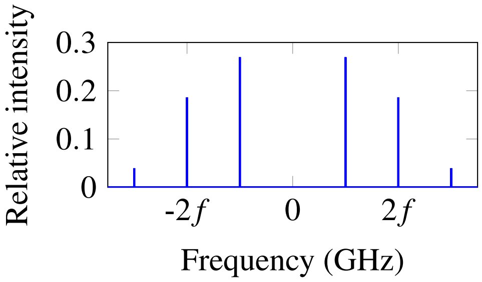

Figure 1: Output for reverse direction at modulation frequency f.

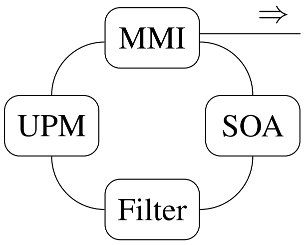

Figure 2: Schematic of unidirectional laser without optical coupling.

if there is any optical coupling between the two. This coupling will be minimized using the presented design such that only parasitic coupling will remain. It is to this reduced coupling that the reduced feedback sensitivity is attributed.

Most methods of enforcing unidirectional operation introduce some form of optical coupling between the CW and CCW modes, but this is no option in this laser as they all lead to enhanced feedback sensitivity. This coupling is not introduced by the optical isolator demonstrated in [2].

One can think of this optical isolator as consisting of two parts: a unidirectional phase modulator (UPM) and a wavelength selective filter. The UPM ideally does not influence light propagating in the forward direction in any way, while it converts light propagating in the reverse direction to other wavelengths as shown in figure 1. When the filter is designed to allow the original wavelength to pass, while at the same time blocking the converted wavelengths, the combination acts as a narrowband isolator.

For the design of the UPM, various trade-offs were made. First of all increasing the RF operating frequency of the UPM decreases the length of the UPM, increases the filter length and increases the required electrical frequencies. For our laser an operating frequency of $f = 5\,\mathrm{GHz}$ was selected. This results in a total length of the UPM of approximately 8 mm. Four asymmetric Mach-Zehnder interferometers (AMZIs) placed in series were used as an intra-cavity filter, with a total unbalance of approximately 13 mm. Higher unbalances were considered undesirable because of losses. Also, the electro-optic phase modulators (EOPMs) are expected to operate with sufficient efficiency at this frequency.

Finally, care has to be taken that the laser will operate in a single longitudinal mode. The four-stage filter ensures this is the case. When adding a semiconductor optical amplifier (SOA) for gain and a multi-mode interferometer (MMI) as an output-coupler, the schematic representation of figure 2 is obtained.

Analytical model

In order to understand the behavior of the laser with the proposed design better, it was modeled by using a set of rate equations. We use the slowly varying envelope approximation for the cavity-averaged values for the various variables. We assume only one CW and one CCW mode are relevant and all other modes can be neglected, which is valid when the other modes are suppressed by the filter. Furthermore the gain is linearized around the threshold carrier density and the EOF is modeled as a time-delayed injection from the CW

into the CCW mode. The coupling is only in one direction because only light from the CW mode will reach the external reflector.
The analytical model then reads as follows:

$$\dot{E}_{\mathrm{cw}} = \frac{1}{2}\xi(1+i\alpha)NE_{\mathrm{cw}} \tag{1a}$$

$$\dot{E}_{\mathrm{ccw}} = \frac{1}{2}\xi(1+i\alpha)NE_{\mathrm{ccw}} - \frac{\Delta\Gamma}{2}E_{\mathrm{ccw}} + \frac{\gamma}{2}\exp(j\omega_0\tau)E_{\mathrm{cw}}(t-\tau) \tag{1b}$$

$$\dot{N} = J - \frac{N}{T} - (\Gamma+\xi N)|E_{\mathrm{cw}}+E_{\mathrm{ccw}}|^2 \tag{1c}$$

Here ξ is the differential gain, α is the line width enhancement factor, N is the number of carriers minus the number at threshold, E_{cw} is the electric field strength in the CW direction, E_{ccw} is the electric field strength in the CCW direction, $\Delta\Gamma$ is the gain difference introduced by the combination of the UPM and the filter, γ is a measure for the amount of EOF, ω_0 is the natural angular frequency of the laser at threshold, τ is the time delay before EOF returns to the cavity, J is the carrier injection rate relative to threshold, T is the carrier life time and Γ accounts for the optical loss.
We can define an optical power and phase as $E_{\mathrm{a}} = \sqrt{P_{\mathrm{a}}}\exp(i\phi_{\mathrm{a}})$ for a equal to CW and CCW. Equations 1 can then be expanded into equations for the optical power and phase by separating their real and imaginary parts. Assuming the laser will reach a steady state, a relation between the phase of the CW mode at time $t-\tau$ and the phase of the CCW mode at time t can then be derived and from this result we can then determine that

$$\frac{P_{\mathrm{ccw}}}{P_{\mathrm{cw}}} \approx \frac{\gamma^2}{\Delta\Gamma^2} \tag{2}$$

This equation allows to determine the gain difference needed to obtain $P_{\mathrm{ccw}}/P_{\mathrm{cw}}$ for a given feedback rate γ.
$\Delta\Gamma$ can be expressed in the single pass isolation $T_{\mathrm{UPM}} = T_{\mathrm{reverse}}/T_{\mathrm{forward}}$ to facilitate design of the laser. Since the round-trip gain for the lasing CW mode is unity, the roundtrip gain for the CCW mode equals T_{UPM}. The loss difference per unit of time will therefore be $\Delta\Gamma = \sqrt{1-T_{\mathrm{UPM}}}/\tau_{\mathrm{R}}$, where τ_{R} is the cavity round trip time. When assuming an output coupler that couples out half of the light, and assuming that the light from the feedback passes through the UPM before entering the SOA, the feedback rate is $\gamma = \sqrt{RT_{\mathrm{UPM}}}/(2\tau_{\mathrm{R}})$ where R is the power reflectivity of an external reflection making

$$\frac{P_{\mathrm{ccw}}}{P_{\mathrm{cw}}} \approx \frac{RT_{\mathrm{UPM}}}{4(1-T_{\mathrm{UPM}})} \tag{3}$$

This predicts a suppression of the CCW mode of 30 dB relative to the CW mode for $T_{\mathrm{UPM}} = 20\,\%$ which can be proven to influence the power in the lasing mode by less than 30 dB. This is assumed to sufficiently reduce the effect of the EOF.
It can be shown that the power in the side frequencies of figure 1 can be expressed as $P_n = J_n(2A)^2$ where P_n is the power at the side frequency, J_n is the bessel function of the first kind, n^{th} order and A is the modulation amplitude of the modulating electrical signal expressed in radians of phase shift. Maximally 91 % of the optical power will be in the first two side peaks and non-linearities will likely reduce this number by less than 10 %[2], which totals to slightly more than the desired 80 % suppression. It will therefore be sufficient to only suppress the first and second side frequencies.

Numerical Model

Numerical device simulations have been performed using a commercial time domain traveling wave circuit simulator (PICWave). In this simulator, similar to the analytical model, it is assumed that only one transverse mode is supported by the waveguide. The simulated structures are discretized along the longitudinal direction and in the time domain. During a simulation, the simulator steps through time with the desired accuracy while computing the changes to the various quantities (electric field, carrier concentration etc.) at every time step. In the simulations that were run for this project, the circuit of figure 2 was implemented using an ideal power splitter as an output coupler, an SOA that showed realistic characteristics, a UPM consisting of two phase modulators and a filter consisting of four serially placed asymmetric Mach-Zehnder interferometers (AMZIs). The AMZIs had free spectral ranges of 10 GHz, 20 GHz, 200 GHz and 2 THz respectively. Together with the gain profile, this provided more than 40 dB of side-mode suppression in the simulation. Next, compliance with the analytical model was studied. To this end, the laser output was connected to a time delay element that introduced $\tau \approx 3.3\,\mathrm{ns}$ of delay and a reflector with power reflectivity R. A number of simulations has been run for values of R ranging from 0 to 1. For each of the simulations, the laser was allowed to stabilize after which the ratio between the CW and CCW modes, central wavelength, line width and RIN number were determined. It was found that the ratio between the CCW mode and CW mode was approximately 25 dB at $R = 1\,\%$ (30 dB was predicted by the analytical model), and a linear fit of this ratio with respect to R resulted in a relative error of less than 1.5×10^{-3} , which agrees well with the predictions from the analytical model. The deviations can be explained by differences in the modeling of the UPM and filter. Furthermore, the central wavelength, line width and RIN number were found to be unaffected up to the simulation accuracy for R up to 1 (linewidth and central wavelength accurate up to 4 MHz, RIN up to 4 %). The average output power was constant for $R < 3\,\%$, after which it declined by about 1 % for $R = 1$.

Conclusion

We have presented a proposal for a laser that we expect to be highly insensitive to EOF. This is attributed mainly to the decoupling of the lasing mode from the mode to which the EOF returns. The final robustness of the laser for up to 3 % of EOF is obtained by keeping the mode that collects the EOF sufficiently far below threshold to reduce variations in the carrier density. We will proceed with the fabrication of a photonic integrated circuit to compare these predictions against measurements.

References

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