Coupled-Waveguides for Dispersion Compensation in Semiconductor Lasers

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A dual waveguide for intracavity dispersion compensation in semiconductor lasers is presented and applied to a short mid-infrared wavelength quantum cascade laser operating in the first atmospheric window ($\lambda \approx 4.6 \ \mu m$). As a result, stable comb operation on the full multi-mode dynamical range is achieved in this device. Unlike previously proposed schemes, the dual waveguide approach can be applied to various types of semiconductor lasers and material systems. In particular, it could enable efficient group velocity dispersion compensation at near-infrared wavelengths where semiconductor materials exhibit a large value of that parameter.

1. Introduction

The generation of optical frequency combs via direct electrical pumping of semiconductor lasers[1–5] is an attractive alternative to the well-established mode-locked laser sources in terms of compactness, robustness and integrability. Recently, novel sensing methods based on optical frequency combs[6] have attracted much attention. In particular, the dual comb configuration of optical frequency combs[5,8,9] enabling the realization of compact mid-infrared dual-comb spectrometers in the second atmospheric window and at terahertz wavelengths.[10–12] The signal over noise ratio of such devices is improved compared to other schemes. In particular, quantum cascade lasers (QCLs) can operate as optical frequency combs when using the QCLs intracavity dispersion compensation for the improvement of the comb’s bandwidth and operation stability.[13,14] However, dispersion compensation by waveguide engineering[15–17] is preferable in terms of its capability to correct for large amounts of dispersion, as well as its reliability and cost. Moreover, intracavity dispersion compensation enables the possibility to scale the device to arbitrary lengths.

In a coupled-waveguide system, the wavelength dependence of the inter-waveguide coupling through the evanescent tails of the individual modes may lead to a significant change of its propagation vector. In turn, the modes of coupled-waveguides can exhibit an additional dispersion that exceeds the one of bulk materials.[18] In a previous work, we found that the coupling of the laser fundamental mode to a plasmonic resonance engineered in the lasers top cladding can lead to efficient dispersion compensation in long ($\lambda \approx 7 \ \mu m$) mid-infrared wavelength QCLs.[19,20] This approach cannot be applied to shorter wavelengths where dispersion is particularly high due to the proximity of the bandgap.[21] This is due to the difficulty to scale the plasma frequency accordingly (see Supplementary Figure 1) and to the introduction of unavoidable free carrier losses.

2. Results

In the present work, we demonstrate dispersion compensation by coupling the optical mode to a passive dielectric waveguide engineered in the device top cladding. We fabricated a QCL based on a diagonal three quantum well design for emission at $4.6 \ \mu m$.[22,23] As seen in Figure 1a, the device integrates a passive InGaAs waveguide close to the active region. A Scanning Electron Micrograph (SEM) image of the device front facet is displayed in Figure 1b.

The active region of the device was grown by molecular beam epitaxy using the InGaAs/AlInAs material system on an InP:Si (2 $\times 10^{17}$ cm$^{-3}$) substrate. The active layers were placed between two 100 nm thick layers of Si-doped InGaAs ($6 \times 10^{16}$ cm$^{-3}$). The exact layers sequence of the QCL is detailed in ref.[22]. The device was processed to a buried heterostructure QCL. A 4.4 $\mu m$ wide ridge was etched by wet-etching technique and a lateral InP:Fe insulating layer was grown by metalorganic vapour phase epitaxy (MOVPE). The top cladding layers were then grown by MOVPE and include an InGaAs waveguiding layer. The top cladding layers sequence is 0.5 $\mu m$ InP:Si $1 \times 10^{17}$ cm$^{-3}$, 1.2 $\mu m$ InP:Si $1 \times 10^{16}$ cm$^{-3}$, 1 $\mu m$ InGaAs:Si $1 \times 10^{16}$ cm$^{-3}$, 1.6 $\mu m$ InP:Si $1 \times 10^{16}$ cm$^{-3}$, 0.4 $\mu m$ InP:Si $2 \times 10^{17}$ cm$^{-3}$, 0.4 $\mu m$ InP:Si $3 \times 10^{16}$ cm$^{-3}$. A second 6.7 $\mu m$ wide ridge was etched in the cladding by wet-etching and a lateral InP:Fe insulating layer was grown by MOVPE. Devices were mounted epide side down on AlN submounts.

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Naturally, each waveguide has a frequency-dependent propagation vector. The waveguides are designed such that these two propagation vectors are equal for a resonant frequency $\omega_0$. At this frequency, if the two optical modes have equal group velocity dispersion (GVD), these couple to form a symmetric and an anti-symmetric supermode. Since, due to the coupling, the supermodes are switching from a branch with higher (respectively lower) group velocity to a branch with lower (respectively higher) group velocity, these feature a resonantly depressed (respectively enhanced) GVD that can then be used for dispersion compensation.\(^{[18]}\) Applying directly such approach to a laser system leads to a fundamental difficulty: Since at resonance the supermodes are equally distributed in both waveguides, lasing can occur on the high and low GVD supermodes simultaneously.

We therefore considered a system where the two modes of the individual waveguides have a different GVD. In that case, using coupled mode theory, the induced GVD ($\Delta \text{GVD}$) writes as (see Supplementary materials for the derivation):

$$
\Delta \text{GVD}_{+/-} \simeq \pm \frac{\kappa}{\delta \omega} \left( \tilde{\omega}^2 + 1 \right)^{1/2} \left( 1 + \alpha \tilde{\omega} \right)
$$

for the symmetric (+) and anti-symmetric (−) modes, where $\kappa$ is the coupling strength, $\tilde{\omega} = (\omega - \omega_0)/\delta \omega$ is the normalised frequency, $\delta \omega = 2\kappa \left| \frac{1}{v_1} - \frac{1}{v_2} \right|$ the resonance bandwidth and

$$
\alpha = 6 \kappa \tilde{\omega} \left( D_1 - D_2 \right) \left( \frac{1}{v_1} - \frac{1}{v_2} \right)^{-2}
$$

the asymmetry factor. In the last expressions, $v_i$ are the group velocities and $D_i$ the GVDs of the decoupled active region ($i = 1$) and passive waveguide ($i = 2$) modes. For $\alpha$ different from zero, the GVD difference between the two waveguides $D_1 - D_2$ induces a shift of the GVD maxima. In turn, dispersion compensation can be achieved without requiring that the two optical modes are in resonance. The resulting asymmetry in the overlap factor of the two supermodes with the active region enables the laser to naturally select one of the two and remain monomode. This method allows to correct for GVD values up to a few thousand fs$^2$ mm$^{-1}$. Varying the geometry, the peak GVD can be increased at the cost of a reduced spectral bandwidth.

We simulated the optical modes for various geometries using a two-dimensional finite element solver and targeted zero GVD at the central laser wavelength. The refractive index profile along the growth axis of the fabricated device is displayed in Figure 1c. The computed electric field profile of the anti-symmetric (blue line) and symmetric (red line) modes are also displayed, while the full two dimensional intensity profiles of these modes are reported in Figure 1d,e. These two modes result from the coupling of the two distinct active region and passive waveguide optical modes. The dispersion curves of the two uncoupled modes are reported in Figure 2a with dashed lines while the dispersion...
of the coupled modes are reported with full lines. From supplementary Eq. 3 we deduce a coupling strength $\kappa = 82 \text{ cm}^{-1}$ at 2200 cm$^{-1}$. Note that since the two uncoupled modes have dissimilar GVDs $D_1 = 1140 \text{ fs}^2 \text{ mm}^{-1}$ and $D_2 = 2600 \text{ fs}^2 \text{ mm}^{-1}$, their dispersion curves never actually cross. Our simulation predicts a minimum of the GVD close to zero at the laser operation wavelength for the anti-symmetric mode (see Figure 2c). The latter has as a result a much larger overlap shaded area and an overlap with the active region equal to 0.7 (see Figure 2c). The latter has as a result a much larger overlap with the active region ($\Gamma_{AR}$) than the symmetric mode which is localized in the passive waveguide. This induces a strong mode selection mechanism which ensures that the device operates with high efficiency on the low GVD anti-symmetric mode since the computed $\Gamma_{AR}$ of the device without coupled waveguide is only slightly higher 0.77 while no additional losses are introduced at the laser wavelength (see Supplementary Figure 2).

To confirm that the laser operates on the anti-symmetric mode, we measured its farfield emission profile in pulsed operation at rollover. These experimental data (see Figure 3a) are compared to the farfield computed from the supermodes nearfield obtained from our 2D mode simulation that are displayed in Figure 3b,c. The difference between the measured (Figure 3a) and computed (Figure 3c) farfield can be attributed to the presence of loss and gain in the passive waveguide and active region, respectively, which is not taken into account by our model (see Supplementary material).

We measured the light and voltage versus current characteristics of the device while operated under continuous wave operation at $-15 \text{ }^\circ\text{C}$. The threshold current is 530 mA and the output power reached 75 mW at rollover (see Figure 3d). For the reference device, the thresholded current is 420 mA and the output power reaches 158 mW at 690 mA (see Supplementary Figure 4). The decrease of performance for the coupled waveguide device can be attributed to additional scattering losses and to the reduction of the thermal conductance due to the presence of the 1 $\mu$m thick InGaAs layer between the active region and the heatsink. This is not a fundamental limit of the coupled waveguide scheme. Exchanging the roles of the InGaAs passive and active region cores would allow to efficiently extract the heat dissipated by the device in the epi-down soldering geometry used. We deduced the GVD from the subthreshold emissionspectrum measured at a current of 450 mA at $-15 \text{ }^\circ\text{C}$. Because the two supermodes have very different refractive indices, their dispersion can be retrieved from the interferogram independently. However, since the $\Gamma_{AR}$ of the symmetric mode is just 0.07, only the emission from the anti-symmetric could be measured. The GVD is displayed in Figure 3e (red line). For comparison, a measurement performed on a 4.5 mm long reference device without the additional passive waveguide is also displayed (blue line). The top cladding layers sequence of the reference device is: 0.42 $\mu$m InP:Si $1 \times 10^{16}$ cm$^{-3}$, 2.5 $\mu$m InP:Si $1 \times 10^{16}$ cm$^{-3}$, 0.85 $\mu$m InP:Si $1 \times 10^{18}$ cm$^{-3}$. For the reference device, a GVD as large as 740 $\text{ fs}^2 \text{ mm}^{-1}$ is deduced at 2200 cm$^{-1}$, while for the device including the passive waveguide a GVD of only 50 $\text{ fs}^2 \text{ mm}^{-1}$ is deduced at 2200 cm$^{-1}$. This confirms that the coupling to the passive waveguide reduced the dispersion of the device ($\Delta \text{GVD} = -690 \text{ fs}^2 \text{ mm}^{-1}$).

To characterize the coherence of the optical spectrum we measured the intermode beatnote of the device directly from the laser bias current using a RF spectrum analyzer with a resolution
bandwidth (RBW) of 500 Hz. For the reference device, the intermode beatnote reaches up to 16 kHz (see Supplementary Figure 5). This suggests that the reference device is not operating in a low-noise comb state. For the coupled waveguide device, narrow beatnotes with full width at half maximum (FWHM) less than 500 Hz were measured on the whole multi-mode dynamical range (see Figure 3f and Supplementary Figure 6). The intermode beatnote frequency tuned smoothly with current at a rate of \( -0.13 \text{ GHz A}^{-1} \), similar to values reported in ref. [19]. At a current of 830 mA the intermode beatnote has a FWHM \( \approx 411 \text{ Hz} \) (Figure 3g) and the optical spectrum spans 40 cm\(^{-1}\) (see Figure 3h). Such narrow and stable beatnotes have up to now always been observed in QCLs operating in comb regime.

Nevertheless, to demonstrate that the devices actually operate as frequency combs, we measured the multiheterodyne beating spectrum of two HR coated 4 mm devices at \( -20 \) °C. The first device current was set to 600 mA while the second device current was set to 460 mA. The optical beams were combined and focused on a MCT detector and the time trace was recorded using an oscilloscope. The total acquisition time was 40 ms and the signal was averaged with a single acquisition time of 3.3 \( \mu \text{s} \) using the noise cancellation method detailed in ref. [10]. The resulting spectrum is displayed in Figure 3i. Ninety three (93) distinct comb lines are observed. Since the free spectral range of the combs is approximately 0.39 cm\(^{-1}\), this corresponds to an optical span of 38 cm\(^{-1}\) and demonstrates that the devices operate as frequency combs on the whole spectral bandwidth. The FWHM of one line is 1.26 MHz (see Figure 3j), this directly shows the suitability of these devices for dual-comb spectrometers in the first atmospheric window.

3. Conclusion

In conclusion, we presented a dual coupled-waveguide design for dispersion compensation in semiconductor lasers and demonstrated its application to a quantum cascade laser. The fabricated devices operate as frequency combs on the whole spectral bandwidth and multi-mode dynamical range. Unlike previously demonstrated integrated dispersion compensation methods, the dual waveguide scheme can be applied to various types of semiconductor lasers and material systems. Moreover, it allows to correct for GVD values up to a few thousand fs\(^2\) mm\(^{-1}\). This suggests that this design strategy could enable the development of high performance semiconductor laser based optical frequency combs from the long mid-infrared to the near-infrared wavelengths ranges. Actually, an interband laser waveguide design that is computed to be dispersion compensated at 1.3 \( \mu \text{m} \) is proposed in the supplementary material.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

dispersion compensation, frequency comb, quantum cascade lasers

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