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Spectral narrowing and stabilization of interband cascade laser by volume Bragg grating

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A volume Bragg grating recorded in photo-thermo-refractive glass was used to spectrally lock the emission from an 18-μm-wide interband cascade laser ridge to a wavelength of 3.12 μm. The spectral width of emission into the resonant mode is narrowed by more than 300 times, and the thermal wavelength shift is reduced by 60 times. While the power loss penalty is about 30%, the spectral brightness increases by 200 times.

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1. INTRODUCTION

The increasing importance of optical systems operating in the mid-IR ($\lambda = 3$–6 μm) spectral region has motivated intensive research to develop emitters and other optical components for this band. An especially promising mid-IR source is the interband cascade laser (ICL), which was first proposed 20 years ago [1,2] and now provides continuous-wave (CW) output powers of up to 500 mW at room temperature [3,4]. Typical spectral widths for narrow-ridge ICLs without distributed feedback (DFB) gratings are 20–40 nm, with a thermal shift of about 2 nm/K. It would be beneficial to develop a means for further scaling the output power, while also increasing the spatial and spectral brightness of the emission.

The spectral locking of semiconductor, solid-state, and fiber lasers emitting in the near-IR and visible spectral regions has progressed substantially through the application of volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass (see [5] for a recent survey). It was demonstrated for all of the above laser classes that the emission could be narrowed and positioned anywhere within the luminescence band of the gain medium. If the spectral width of a VBG is much wider than the distance between adjacent longitudinal modes, the spectral width of the laser emission is usually comparable to that of the VBG. However, if the spectral width of the VBG is comparable to or smaller than the longitudinal mode spacing, the laser switches to a single-frequency regime and emits a line that could be orders of magnitude narrower than the spectral width of the VBG. Moreover, multiple spectrally narrowed and stabilized beams can be spectrally or coherently combined by a sequence of VBGs, or by multiplexed VBGs.

While PTR glass is quite suitable for visible and near-IR applications, its absorption beyond 2.7 μm presents an obstacle to expanding the operation at longer wavelengths [6]. The absorption is relatively weak up to about 4 μm, however, which is attributable to the absorption bands of hydroxyl and molecular water that are introduced during preparation of the glass [7]. It has been determined that the typical hydroxyl concentration in PTR glass is about 30 ppm, which can be reduced by dehydration during the glass fabrication [8]. While improvement of the glass for mid-IR applications remains a work in progress, the present investigation has taken the first step toward our ultimate goal of developing single-mode high-brightness mid-IR ICLs in VBG cavities. In particular, we explore the potential for using a VBG to spectrally lock and narrow the output from an ICL, even though the PTR glass employed in this work is far from optimal for the purpose.

2. EXPERIMENTAL

The ICL with seven active stages was grown by molecular beam epitaxy on a GaSb substrate, to a design similar to those described previously [9]. To determine natural thermal shift of

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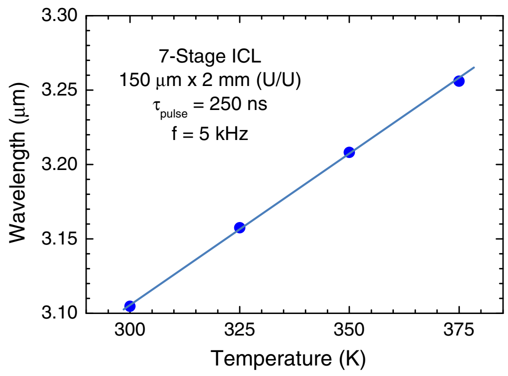

Fig. 1. Dependence of the centroid emission wavelength on temperature for a broad area ICL processed from the seven-stage wafer used to fabricate the narrow ridge. The dimensions are 150 μm × 2000 μm and the facets are uncoated.

emission wavelength, broad ridge (150 μm × 2000 μm) lasers with uncoated facets that were processed from the same wafer exhibited a threshold current density of 230 A/cm^2 and slope efficiency of 640 mW/A when operated in pulsed mode at 300 K. Figure 1 plots the dependence of centroid emission wavelength on temperature. The shift from 3.10 μm at 300 K to 3.26 μm at 375 K corresponds to a thermal coefficient of 2.1 nm/K. The spectral width of emission from the broad-ridge devices operating in pulsed mode is about 25 nm. For experiments with spectral locking, the narrow-ridge waveguide with dimensions 18 μm × 4500 μm and high-reflection (HR)/antireflection (AR) facet coatings was processed by methods described in [4], and soldered epitaxial side down on a C-mount. For free running at 25°C, the laser's threshold current is about 0.2 A, while at a CW pumping current of 1 A, the laser emits 315 mW.

Figure 2 illustrates the configuration employed for spectrally locking the ICL in a VBG external resonator. The laser emission was collimated with an aspheric lens (ThorLabs: C037TME-E) with $f = 1.873$ mm, $NA = 0.85$, and AR coating for 3–5 μm. A reflecting VBG with thickness of 2.8 mm and an aperture of 8 mm × 6 mm was used as a narrowband output coupler. The simulated reflection spectrum of this VBG is shown in Fig. 3. At the resonant wavelength of 3120 nm, the VBG without an AR coating is projected to have a diffraction efficiency of 30%, with a spectral width of 1.2 nm FWHM. Since the grating vector is tilted in our case by 1° from the normal to the PTR glass plate surface, Fresnel reflections from the grating surfaces contribute additional losses in the resonator, affecting the external-cavity feedback efficiency and also degrading the spectral contrast of the locking. The reflection of

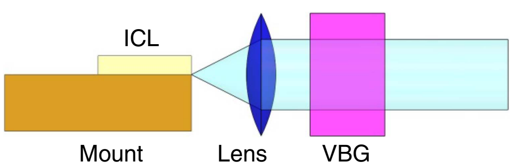

Fig. 2. Optical scheme for spectral locking of ICL by a VBG as an output coupler in an external resonator.

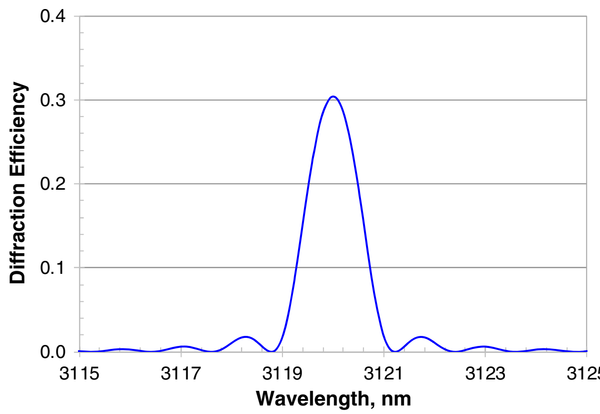

Fig. 3. Simulated reflection spectrum for a VBG recorded in PTR glass. The thickness is 2.8 mm, aperture dimensions are 8 mm × 6 mm, diffraction efficiency is 30%, central wavelength is 3120 nm, and spectral width is (FWHM) 1.2 nm.

1%–2% for the single-layer AR coating on the ICL front facet is also too high for optimal performance, since external-cavity ICLs tend to exhibit lasing in parasitic Fabry–Perot modes when only a small amount of feedback is present [10]. It was shown [11] that increasing reflectivity of a VBG output coupler facilitates spectral locking while also increasing power penalty. For these reasons, the diffraction efficiency of 30% for this VBG is too high compared to optimal feedback in the ICL resonator. Nonetheless, the present experiments provide a proof of concept for ICL spectral locking using a grating recorded in the PTR glass. We have compared the output characteristics of the ICL in the VBG resonator to those for the same ridge in a free-running configuration without any external feedback.

3. RESULTS

Figure 4 shows the dependence of the CW output power on pumping current for the ICL ridge in both free-running (blue) and external Bragg resonator (red) geometries at 25°C. The spectral locking induces a small decrease of the lasing threshold, as expected since the external VBG coupler provides additional

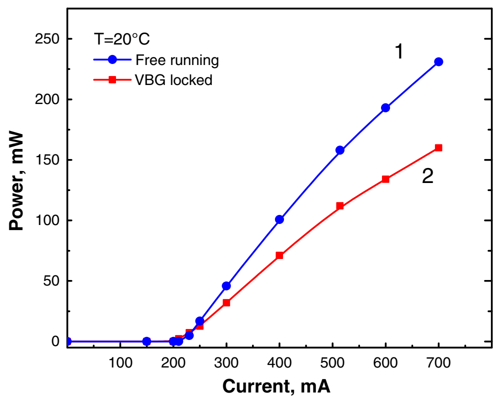

Fig. 4. Comparison of the *L-I* characteristics for the free-running ICL (curve 1) with those of the ICL in an external Bragg resonator (curve 2).

feedback. This is accompanied by a roughly 30% reduction of the output power (at 700 mA). The small decrease of lasing threshold resulting from a significant increase of the feedback and high power penalty may be attributed to absorption in the non-optimal VBG (16.3%), reflection losses at the uncoated grating surfaces (7.8%), and excessive feedback in the resonator (associated with residual reflections at the front facet of the ICL waveguide and 30% reflection from the VBG). We anticipate that dehydration of the PTR glass to reduce the mid-IR absorption, AR coatings on the grating surfaces, a better AR coating on the ICL front facet (≤0.1%), and optimization of the feedback in accordance with the gain coefficient in the active waveguide would reduce the net loss of power and efficiency to no more than 1%–5%. Losses in this range were demonstrated previously for analogous near-IR semiconductor lasers coupled to VBG external resonators [5].

Figure 5 shows the emission spectra for the free-running ICL (curve 1) and the ICL coupled to the external VBG resonator (curve 2) for three currents ranging from 205–700 mA. Note that, at the lowest current [Fig. 5(a)], the free-running device has not yet reached threshold and produces amplified spontaneous emission over a broad spectrum (≈60 nm FWHM). However, at the same pumping level, the additional feedback provided by the external cavity leads to emission in a narrow lasing line at the 3120 nm resonant wavelength of the VBG (see Fig. 3). When the pump current is increased, the free-running ICL first emits a few narrow lines in the vicinity of the spontaneous emission spectrum and then broadens to comprise numerous lateral as well as longitudinal lasing modes that form a complex shape with total width of about 25 nm [Fig. 5(b)]. At the maximum applied CW current of 700 mA [Fig. 5(c)], the free-running ICL emits several wide bands spanning about 40 nm. The centroid wavelength shifts to the red, due to heating of the active waveguide. In contrast, at the intermediate pumping current of 514 mA [Fig. 5(b)], the main power of the ICL coupled to the external Bragg resonator still concentrates in a narrow line determined by the VBG, although at this point weaker parasitic lines also appear. It is apparent from the spectra at 700 mA [Fig. 5(c)] that these lines tend to occur at wavelengths for which the free-running laser also exhibits spectral peaks (although much broader). This implies that the parasitic lines may result mostly from Fabry–Perot lasing within the ICL waveguide, via feedback from the 1%–2% reflection at the front facet. Fresnel reflection from the uncoated grating surfaces may also provide sufficient feedback for lasing outside the VBG spectrum.

Figure 6 shows emission spectra of the VBG-locked ICL at four pumping currents ranging from 230 to 700 mA. The main emission lobe's linewidth of about 0.1 nm for all currents represents an upper bound imposed by the spectral resolution of our spectrometer (Thermo Nicolet 6700 FT-IR). Note that this spectral width is at least 1 order of magnitude narrower than the VBG resonance illustrated in Fig. 3. In comparison, the spectral width of near-IR diode lasers locked by similar VBGs is usually comparable with the spectral width of an output coupler VBG. This implies that the ICL is switched to a single-frequency regime. An estimated longitudinal mode spacing in our external Bragg resonator is about 0.25 nm, meaning

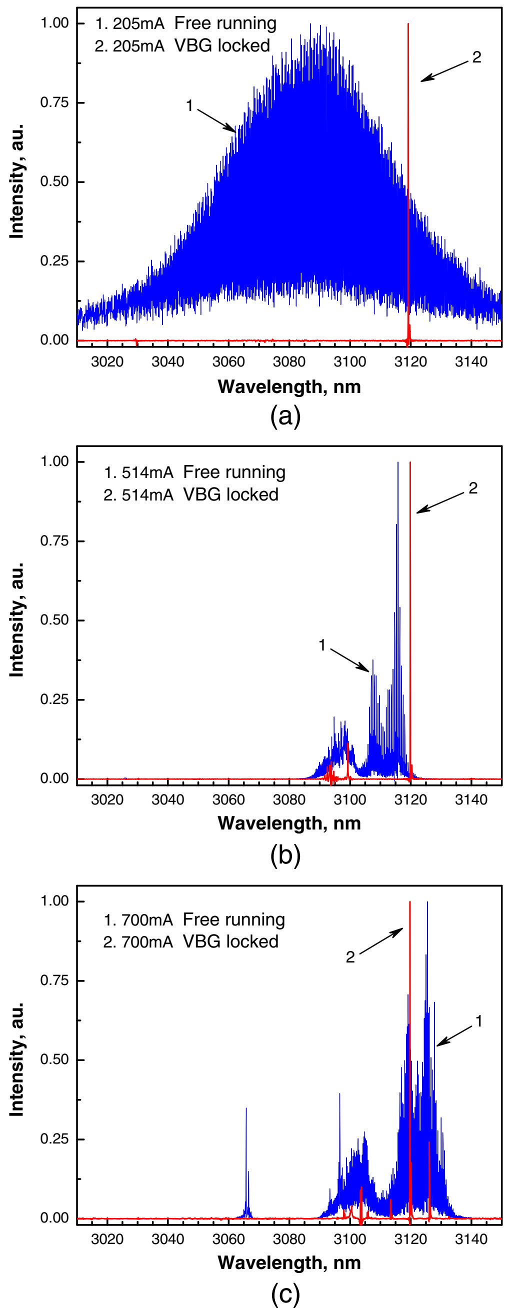

Fig. 5. Emission spectra of the ICL in the free-running regime (curve 1) and in the external Bragg resonator (curve 2) for three pumping currents of (a) 205, (b) 514, and (c) 700 mA.

that there is enough discrimination between the adjacent modes based on the VBG reflectivity spectrum shown in Fig. 3. Consequently, it is not surprising that the VBG-locked ICL can exhibit single-frequency operation. A more detailed analysis based on higher resolution spectral measurements will require further investigation. It should be emphasized that the ICL's spectral width is narrowed by more than 300 times. This means that, even with high residual reflection from the front facet and the non-optimal grating efficiency, the spectral brightness of the VBG-locked ICL is about 200 times higher than that for a bare laser.

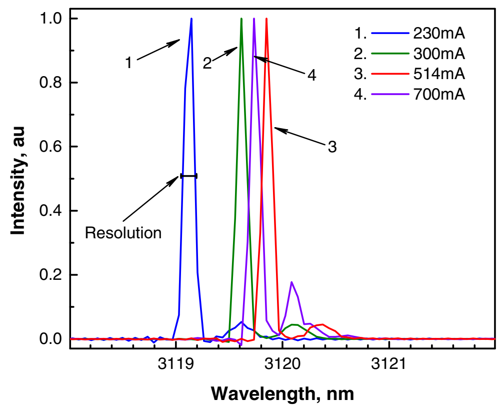

Fig. 6. Emission spectra of the VBG locked ICL at different pumping currents. Curve 1, 230 mA; curve 2, 300 mA; curve 3, 514 mA; and curve 4, 700 mA.

Figure 6 also shows a tendency of a redshift of the emission wavelength with increasing current. The maximum shift is about 0.8 nm for the pumping current of 514 mA. However, further increasing the pumping current to 700 mA leads to a blueshift for 0.2 nm. Changes of emission spectra caused by increased pumping current, which were observed for near-IR laser diodes locked by similar VBGs, show that the shift of the emission wavelength is gradual, because it is controlled by heating of VBGs by laser radiation. In our case, the total observed shift (0.8 nm) is larger than the distance between adjacent longitudinal modes (0.25 nm) but smaller than the spectral width of the VBG (1.2 nm). Therefore, while the average shift of the emitting wavelength is determined by heating of the VBG by laser radiation, the exact position of the longitudinal mode with the highest gain can fluctuate in the vicinity of the VBG's reflection maximum. This mode hopping could explain the nonmonotonic behavior of the emission wavelength in the studied ICL. It is known [6] that the thermal shift of the Bragg wavelength in a PTR glass is determined by its thermal expansion, which for 3 μm it is about 0.03 nm/K. Therefore, the maximum wavelength shift of 0.8 nm corresponds to a VBG heating of about 25 K. Since the natural thermal shift of the ICL gain peak is 2.1 nm/K (Fig. 1), spectral locking with the VBG has decreased the thermally induced wavelength shift by more than 60 times.

4. CONCLUSIONS

Thus, we have used a VBG recorded in PTR glass to spectrally lock the emission from an 18-μm-wide ICL ridge to a wavelength of 3.12 μm. The spectral width of emission into the resonant mode is narrowed by more than 300 times, and the thermal wavelength shift is reduced by 60 times. While the power loss penalty is about 30%, the spectral brightness increases by 200 times. The power loss results primarily from mid-IR absorption in the PTR glass that was developed previously for visible and near-IR applications, as well as from the absence of AR coatings on the VBG surfaces. While at pumping currents ≤514 mA, the ICL emitted mostly at the VBG resonance wavelength, full spectral locking does not occur at higher pumping currents due to the competition with feedback from the ICL's front facet. Future work should focus on the development of PTR glasses that do not absorb in the mid-IR, as well as on the spectral beam combining of ICL outputs that are spectrally narrowed with VBGs.

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