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Narrow-linewidth operation of folded 1178nm VECSEL with twisted-mode cavity

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Abstract: A vertical external-cavity surface-emitting laser (VECSEL) with a twisted-mode configuration is demonstrated. This architecture is particularly advantageous for power scaling of single-frequency VECSELs employing multiple gain mirrors in folded cavities. In such a configuration, some of the gain mirrors are inherently at the fold, and the lasing spectrum becomes unstable. This is caused by four waves interfering, destabilizing the standing wave pattern at the quantum wells. We show that the lasing spectrum can be narrowed by employing a twisted-mode configuration, which stabilizes the standing-wave pattern at the gain mirror. Furthermore, single-frequency output of more than 10 W at 1178 nm is demonstrated for a VECSEL employing two gain mirrors in a standing-wave cavity. In comparison, the output power for operation with one gain mirror only was 7.4 W when operating in single frequency. The choice of wavelength for the work reported in this paper is motivated by the opportunity to demonstrate compact VECSEL-based guide star lasers for adaptive optics via frequency doubling to the sodium D_2 resonance at 589 nm.

1. Introduction

Vertical external cavity surface emitting lasers (VECSELs) operating at 1178 nm are attractive solutions for the development of laser guide star technology because of their simplicity [1,2] compared to alternate guide star technologies; a solid-state-laser approach [3] (sum-mixing between Nd:YAG lasers at 1064 nm and 1319 nm) has shown scalability but requires two separate lasers to be controlled. The fiber amplifier approach [4-6] yields substantial power at 1178 nm, which can be directly doubled to 589 nm, but requires an amplifier design that suppresses the stimulated Brillouin scattering that limits the output power in single frequency.

Target specifications for laser guide stars require the wavelength to match the sodium D_{2a} line, which translates to a wavelength of 589 nm at a linewidth less than 1 GHz. Desired power levels exceed 20 W [5,6]. To date VECSELs have demonstrated the ability to meet these targets yet they are still far from being adopted as guide star technology. Some of the most relevant experiments towards this goal are the demonstration of single-frequency operation with >20 W of output power at 1013 nm [7], demonstration of 20 W emission at 590 nm wavelength range using intra-cavity SHG [8], and the recent power record of 72 W for emission at 1180 nm [9] using an intracavity diamond heatsink; although this last result concerns multimode operation, it demonstrates the maturity of the gain-mirror technology for this wavelength range.

In general, the output power of VECSELs can be scaled to multiple tens of watts and beyond by enlarging the spot size, so called "lateral scaling" [10], or then by using multiple gain mirrors in one cavity, so called "longitudinal scaling" [11]. Longitudinal scaling distributes the heat dissipation over multiple devices, reducing the requirement for heat removal for the individual devices. In the case of longitudinal scaling, at least one VECSEL

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device must be at a fold of the cavity. This can cause issues in longitudinal mode stability due to spatial hole burning in the plane of the quantum wells created by the four-wave interference between the fields arriving from different directions. In this paper, we present a technique to alleviate occurrence of such instability by implementing a twisted-mode configuration [11]. A similar configuration has been analyzed for a solid-state disk laser [13] while single-frequency Q-switched operation has also been demonstrated [14]. Using this design, we experimentally demonstrate its effectiveness in ensuring single-frequency operation with more than 10 W of total output power. Single-frequency operation indeed exceeds the linewidth requirement of guide star application, and also opens up the opportunity of efficient external resonant frequency doubling.

2. Standing wave pattern and twisted-mode configuration

The use of resonant periodic gain (RPG) media in VECSELs, in which the quantum wells are located at the antinodes of the standing wave pattern, makes them immune to spatial hole burning when the device is placed at the end of a standing-wave cavity at normal incidence. In this configuration, the positions of the antinodes of the standing wave patterns of different longitudinal modes are very close, and there are just two waves interfering; the magnitudes of the standing wave patterns of different longitudinal modes are essentially the same. This allows single-frequency operation in the first longitudinal mode to exceed the threshold, the one with the lowest cavity loss, which saturates all the gain available. On the other hand, a gain mirror placed in the middle of the cavity, at a fold, carries a standing wave pattern formed by four beams; forward propagating incident and reflected, as well as backward propagating incident and reflected. This situation is schematically shown in Fig. 1. The beam width and angle of incidence are exaggerated for the purpose of presentation (w = 3 λ, AOI = 15 degrees, both within the gain medium), and the wavefront is assumed to be planar throughout. In an actual cavity, the beam width is approximately 160 μm in radius, or more than 450 λ within the semiconductor material, and the angle of incidence is 5 degrees in air, which becomes just 1.4 degrees in the gain medium. The locations of the quantum wells are indicated by red lines. The plot in the middle shows the intensity distribution on the first quantum well with three different phase relationships between the forward and backward beams, denoted as ϕ. The distribution is similar for all the other wells.

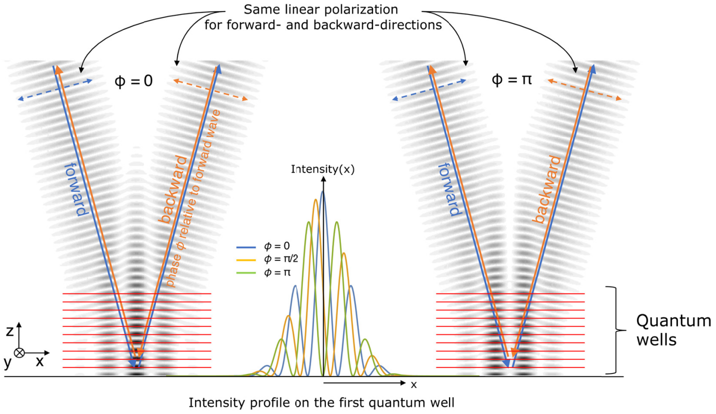

Fig. 1. Standing wave pattern at the fold, with different phase relationship in the forward and backward beams. The plot in the middle shows the intensity distribution on the first quantum well.

With non-zero angle of incidence, the transverse components of the k-vectors for forward and backward beams are opposite. A fringe pattern develops that is oriented laterally (in the plane of incidence) where, as illustrated in Fig. 1, the positions of the peaks depend on ϕ, which is itself a function of mode number. Different longitudinal modes therefore have different intensity distributions, which leads to the same effect as spatial hole burning in solid-state lasers, i.e. no single mode saturates the gain of the quantum wells. This makes single frequency operation more difficult than the case of a VECSEL device at the end of the cavity at normal incidence. The longitudinal modes of such a VECSEL therefore become unstable.

In order to overcome this limitation, we implement a "twisted-mode" configuration [12,14] with quarter-wave plates (QWP) inside the VECSEL cavity. Because the forward and backward beams with opposite transverse components of the k-vectors are in orthogonal polarizations, they do not interfere; therefore no transverse fringe forms even for non-normal incidence. The anticipated standing wave pattern in such a configuration is shown in Fig. 2, with the intensity distribution on the quantum wells in the plot in the middle. Because of the lack of interference, the distribution remains the same regardless of the phase relationship between the forward and backward waves, and therefore holds for all longitudinal modes. By decoupling the forward and reverse beams, the VECSEL behaves in the same way as it would in normal incidence at the end of the cavity: the single longitudinal mode to oscillate is the one that saturates all the gain available from the quantum wells. This relation holds in the entire section between the two QWPs. We believe therefore that multiple devices can be placed at folds without suffering from instability in longitudinal modes.

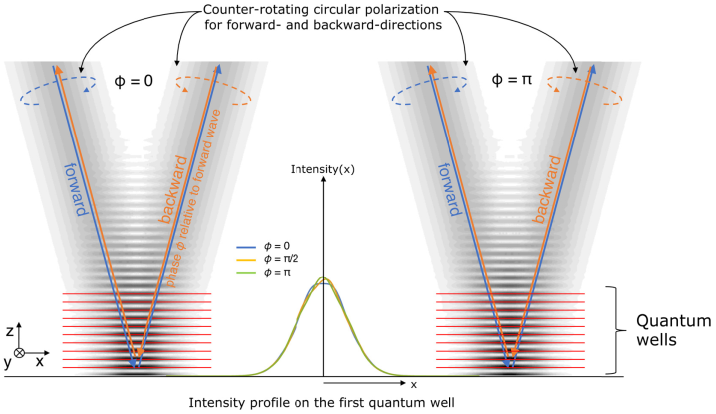

Fig. 2. Standing wave pattern at the fold, with twisted-mode configuration.

3. Experiment

Figure 3 shows the schematic of the VECSEL cavity we used in the experiment. The gain mirror comprises ten GaInNAs quantum wells, with the gain peak designed to be near 1178 nm, and a highly reflective distributed Bragg mirror. In this experiment, we have chosen not to use an intracavity heatsink for two reasons, 1) to avoid any etalon effects of the heatsink, and 2) to prevent residual birefringence of the heatsink from affecting the polarization in the cavity. The VECSEL tended to lase in the range of 1170-1176 nm when no spectral filter was inserted in the cavity. The cavity has a Z-fold architecture, with the gain mirror at one of the folds. The other fold mirror and the other end mirror are curved so that the cavity mode has similar mode sizes of approximately 160 μm radius at the VECSEL and at the flat end mirror. Both the folding mirror and two end mirrors are highly reflecting at 1178 nm. The distances between the flat mirror and the 200 mm concave mirror and between that mirror and the gain mirror are both 175 mm. The gain mirror and the 300 mm concave mirror are 285 mm apart. The angle of incidence on the gain mirror is 5 degrees, and that on the 200 mm concave mirror is 10 degrees. We note that in this design, the flat dielectric end mirror can be easily replaced with another gain mirror for the longitudinal scaling experiment. The pump light is incident on the VECSEL in the horizontal plane (the plane of the resonator) at an angle of approximately 10 degrees, and has a nominal spot size of 150 µm in radius. Because of the fairly small angle of incidence, the pump spot is only slightly elliptic (longer in the horizontal direction).

For wavelength filtering, we inserted a 3 mm thick uncoated quartz birefringent filter and a 0.5 mm thick uncoated fused silica etalon inside the cavity. We added an uncoated silica plate as an adjustable Brewster's window to use as a variable output coupler. With up to 30 W of pump power at 808 nm, we observed 3.7 W of single-ended output, resulting in 7.4 W total single frequency output in two beams. The output coupling was estimated to be about 3%.

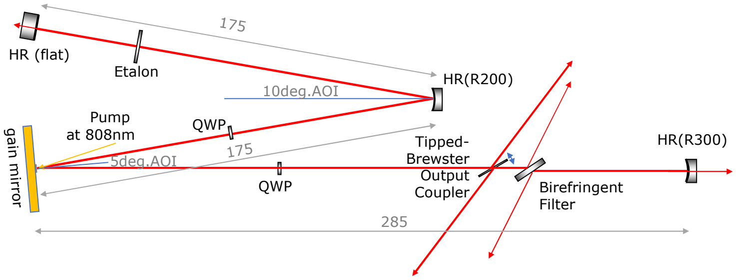

Fig. 3. Schematic of the folded VECSEL cavity with twisted-mode configuration. Letters in gray indicate the nominal dimensions.

Figure 4 illustrates the effectiveness of the technique. The mode structure is shown as observed with a scanning confocal Fabry-Perot interferometer (THORLABS SA210-8B, FSR = 10 GHz, finesse >150) in the twisted-mode configuration (Fig. 4a), with the QWP rotated so that the mode is not twisted (Fig. 4b), and QWPs taken out of the cavity (Fig. 4c). These screenshots were taken without averaging on the oscilloscope. With no QWPs, the mode structure is uncontrolled. With the incorrectly oriented QWPs, the structure is not improved, but output is greatly reduced. By contrast, in the twisted-mode configuration, the linewidth is below the resolution of the interferometer, which is 67 MHz.

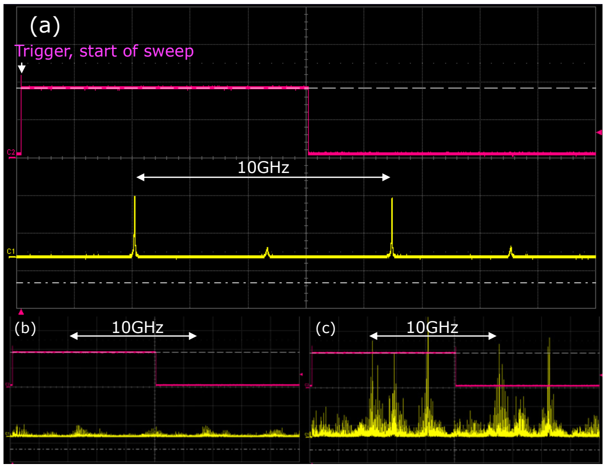

Fig. 4. Longitudinal mode observation on a scanning Fabry-Perot interferometer with 10 GHz FSR and 67 MHz resolution. (a) twisted-mode cavity, (b) QWP rotated, (c) no QWP in cavity.

In the longitudinal scaling experiment, the flat end mirror was replaced with another VECSEL device. This second device experiences only two-wave interference so the standing wave pattern is that of a normal VECSEL with a single device at the end. The longitudinal mode behavior is therefore unaffected. With two gain mirrors in the cavity, pumped at the same power 30 W at 808 nm, we have observed a total output power of 10.1 W in single frequency at 1178 nm. The lasing spectrum of the two-device VECSEL is shown in Fig. 5.

The laser operates in single frequency, and the spectral linewidth in Fig. 5 is again limited by the resolution of the spectrum analyzer.

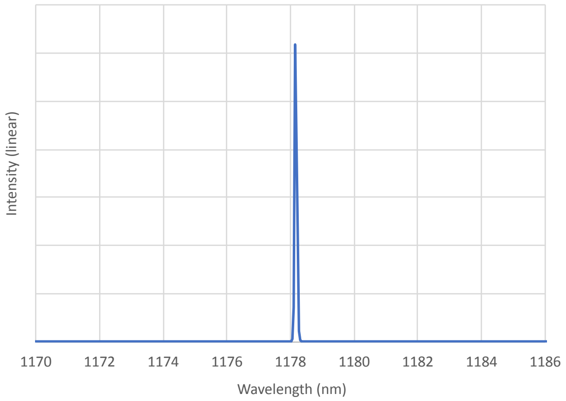

Fig. 5. Lasing spectrum of 2-devices VECSEL at 1178 nm.

4. Summary

We have presented longitudinal power scaling of a VECSEL with twisted-mode configuration, and demonstrated 10.1 W single frequency output at 1178 nm with a two-gain mirror VECSEL. One gain mirror was placed at the fold and the other at the end of the cavity. By contrast, the output power from a cavity with only one device at the fold was measured as 7.4 W in single frequency. The effectiveness of mode-twisting combined with longitudinal scaling was clearly demonstrated by rotating the QWP and observing the single-mode behavior with a scanning Fabry-Perot interferometer.

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