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GAIN COUPLING OF CLASS A SEMICONDUCTOR LASERS (POSTPRINT)

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14. ABSTRACT We report on the development of a gain-coupled class A semiconductor laser for dual-wavelength generation via optical switching. A vertical external cavity surface emitting laser (VECSEL) structure is used, because it provides a flexible platform for high-power, high-brightness output in the near-IR and visible ranges. For the first time (to our knowledge), two VECSEL cavities sharing a common gain region are studied. Because the cavities are in competition for common carriers, birefringent filters in the external cavity control the laser cavity thresholds; this configuration demonstrates the possibility of switching between the two cavities, which can operate at different wavelengths. However, in this Letter we also show, numerically and experimentally, that with the consideration of spontaneous emission, it is possible to maintain simultaneous lasing in each cavity at a different wavelength.						
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Gain coupling of class A semiconductor lasers

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We report on the development of a gain-coupled class A semiconductor laser for dual-wavelength generation via optical switching. A vertical external cavity surface emitting laser (VECSEL) structure is used, because it provides a flexible platform for high-power, high-brightness output in the near-IR and visible ranges. For the first time (to our knowledge), two VECSEL cavities sharing a common gain region are studied. Because the cavities are in competition for common carriers, birefringent filters in the external cavity control the laser cavity thresholds; this configuration demonstrates the possibility of switching between the two cavities, which can operate at different wavelengths. However, in this Letter we also show, numerically and experimentally, that with the consideration of spontaneous emission, it is possible to maintain simultaneous lasing in each cavity at a different wavelength. © 2010 Optical Society of America

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High-power semiconductor lasers with wavelength switching capability are of great interest in a range of applications including optical communication. Optically pumped vertical external cavity surface emitting lasers (VECSELs) have proven to be very reliable in achieving multiwatt high-brightness emission [1–3]. The insertion of a birefringent filter (BF) in a VECSEL cavity allows a narrow-linewidth, widely tunable emission [2,4,5]. In this Letter we report gain coupling, switching, and dual-wavelength operation in VECSELs by combining a linear and a v-shaped cavity VECSEL sharing the same gain region. We present unique behaviors such as high-power optical switching and tunable dual-wavelength emission. Experimental results and supporting modeling results are reported.

The novel design, shown in Fig. 1, is the simplest dual-cavity gain-coupled configuration consisting of a linear cavity (cavity 1) and a v-shaped cavity (cavity 2) coupled by sharing a common VECSEL quantum-well gain material. This design is unique in that each cavity oscillates at its own frequency, while the BFs eliminate optical coupling between the laser cavities, which may occur due to scattering. Unlike other dual-wavelength VECSELs that employ a single external cavity with either quantum wells designed for different wavelengths [6] or polarization optics that split the mode into spatially separated regions on the gain chip [7,8], this configuration relies on the naturally broad semiconductor gain and provides control over each cavity independently. This dual-cavity design allows us to potentially avoid instabilities [9,10] due to photon interaction between the two cavities while maintaining the ability to simultaneously control the output of each.

The VECSEL gain chip used in the experiment is designed for emission around 975 nm. The active region consists of 14 InGaAs compressive strained quantum wells 8 nm thick surrounded by GaAsP strain compensation layers and AlGaAs pump-absorbing barriers. A 99.9% distributed Bragg reflector stack made of 25 pairs of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{AlAs}$ is grown on the top of the active region, and a single-layer quarter-wave low-reflection

coating of SiO_2 is applied to the surface of the chip to enhance the 975 nm signal.

The geometry, cavity lengths, and reflectivities are shown in Fig. 1. The output power of cavity 1 can be controlled by rotating the BF in cavity 2, and vice versa. For example, if a constant pump power is maintained and the BF in cavity 1 remains fixed, tuning the BF in cavity 2 creates regions where only cavity 1 lases and regions where only cavity 2 lases. In this case, the lasing wavelength of cavity 1 is essentially constant at the wavelength selected by the BF in cavity 1.

A map of the output power for each cavity as a function of wavelength of each of the two cavities is shown in Fig. 2, as measured using a thermopile detector. Figure 2(a) shows the output power of cavity 1 over the entire tuning range of the chip, while Fig. 2(b) shows the output power of cavity 2. Figure 2 is given for a fixed pump power of ~ 15 W, and the two axes represent the tuning of each cavity with respect to the wavelength corresponding to minimum uncoupled cavity threshold. $\Delta\lambda_{1,2}$ are the offsets with respect to this minimum uncoupled threshold of each respective cavity.

Figure 2 shows there are broad operating regimes where either cavity 1 or cavity 2 is lasing. These regions result directly from gain competition between the two cavities. By adjusting the BF we alter the resonant periodic mode overlap enhancement [11,12], which in turn

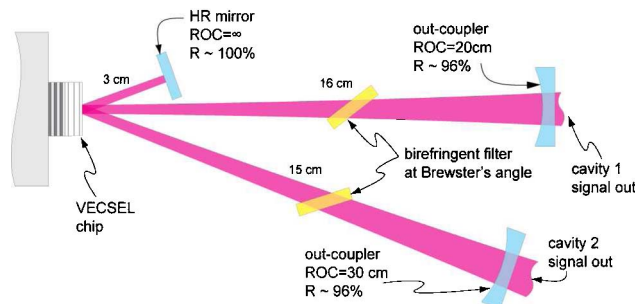


Fig. 1. (Color online) Schematic of coupled VECSEL system. The BFs are used to tune each cavity-respective wavelength within the semiconductor gain bandwidth. The linear cavity (cavity 1) passes once through the chip in a round trip, while the v-shaped cavity (cavity 2) passes twice.

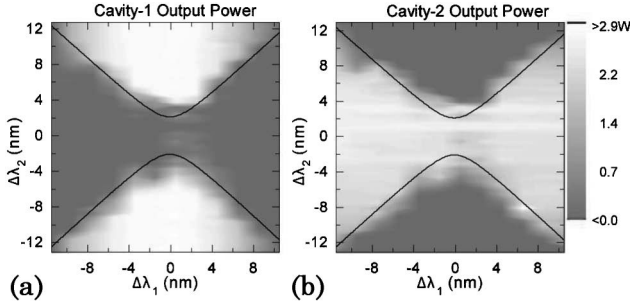


Fig. 2. Map of the output power for each cavity as a function of the wavelength with (a) the linear cavity (1) and (b) the v-shaped cavity (2) for cavity wavelengths at a fixed pump power of ~ 15 W. Gray-scale changes from completely off (dark), to completely on (light). The lines in (a) and (b) show the positions of the equal uncoupled threshold, indicating areas where both cavities operate simultaneously. $\Delta\lambda_{1,2}$ is the offset with respect to the wavelength of the minimum uncoupled threshold.

controls the threshold of the uncoupled cavities. We experimentally confirm this by measuring the threshold of each uncoupled cavity individually as a function of wavelength. Because the gain essentially “clamps” at threshold, the laser with the lowest threshold lases first, thereby inhibiting the ability of the other cavity to reach the threshold. By comparing the values of the threshold for each uncoupled cavity, we plot the regions of equal threshold where the laser switches from one cavity output to the other. For most operating regimes, the relative threshold of the uncoupled cavities is sufficient to indicate which of the two laser cavities will be on when the two cavities are coupled together. The boundary between each cavity lasing occurs where the uncoupled cavity thresholds are equal.

To understand this laser system, we first introduce a set of simplified rate equations, ignoring barrier absorption and spontaneous emission, patterned after a single-cavity case [13]:

$$\frac{dN}{dt} = \frac{P\Omega}{V_a \hbar \omega_p} - \frac{N}{\tau} - v_g g [\Gamma_{r1} S_1 + 2\Gamma_{r2} S_2], \quad (1)$$

$$\frac{dS_1}{dt} = -\frac{S_1}{\tau_{p1}} + v_g \Gamma_{1g} S_1, \quad (2)$$

$$\frac{dS_2}{dt} = -\frac{S_2}{\tau_{p2}} + 2v_g \Gamma_{2g} S_2. \quad (3)$$

In Eqs. (1)–(3), N is the carrier density, $S_{1,2}$ are the photon densities in the linear and the v cavities (1 and 2, respectively), P is the incident pump power, Ω is the pump absorption efficiency, ω_p is the angular frequency of the pump, τ is the carrier lifetime, v_g is the group velocity, $\Gamma_{r1,r2}$ is the resonant periodic gain enhancement factor in each cavity, g is the gain, $\tau_{p1,p2}$ are the photon lifetimes in each cavity, $\Gamma_{1,2}$ are the total overlap integrals, and V_a is the volume of the active region. The factor of 2 in front of the S_2 term in Eq. (1) accounts for the chip being a fold of the cavity; a round-trip of cavity 2 consists of twice the number of passes through the gain as cavity 1. There is no explicit photon coupling, so the

two cavities are solely coupled through the carrier density in the gain element.

We explain the cavity competition by analyzing the steady states of Eqs. (1)–(3). It becomes immediately evident that, for all cases where the uncoupled thresholds are not identical, either S_1 or S_2 will be zero. The cavity with the lowest losses lases first, preventing photons from building up in the other cavity. Fitting the threshold of cavity 1 without the influence of cavity 2 across the tuning range of the BF confirms this. We assume a logarithmic gain function $g(\lambda; N) = g_0 \ln(N/N_{tr}(\lambda))$, explicitly ignoring the shift-carrier density typically included [14]. In this case, the constant coefficient g_0 and the function $N_{tr}(\lambda)$, allowed to vary linearly with wavelength, are used as fitting parameters. This functional form was determined to be suitable over the tuning range and approximate carrier densities present in this laser system by using commercially available many-body software [15]. We then use these values to calculate the cavity 2 threshold over the same wavelength range. By comparing the predicted thresholds of the two cavities, we determine the boundaries indicated by the lines in Fig. 2.

Figure 2 and the description in the preceding paragraph explain the behavior of the coupled system everywhere except near the boundary when the BFs are tuned such that both uncoupled cavities have similar thresholds. In this boundary regime, a close inspection of Fig. 2 reveals regions where both S_1 and S_2 are nonzero, a scenario not predicted by solving Eqs. (1)–(3), except at the boundary $\frac{\Gamma_{12}}{\tau_{p1}} = \frac{\Gamma_{21}}{\tau_{p2}}$. This unstable point is not achievable in practice owing to noises in real systems. However, we see operating conditions near the boundary allow both lasers to be on, even at differences in wavelengths of 17 nm and 22 nm in the second and fourth quadrants of Fig. 2, respectively.

By chopping one of the cavities and using a 200 MHz detector, the temporal aspects of the switching action are observed. Figure 3(a) represents a region in Fig. 2, well away from the boundary, where cavity 1 is completely on and cavity 2 is completely off. We first block cavity 1, and then suddenly unblock the cavity, turning it on. Cavity 2 tends to zero symmetrically in this case, as the uncoupled threshold of cavity 1 is lower than that of the uncoupled cavity 2. Photons build up in cavity 1, dropping cavity 2

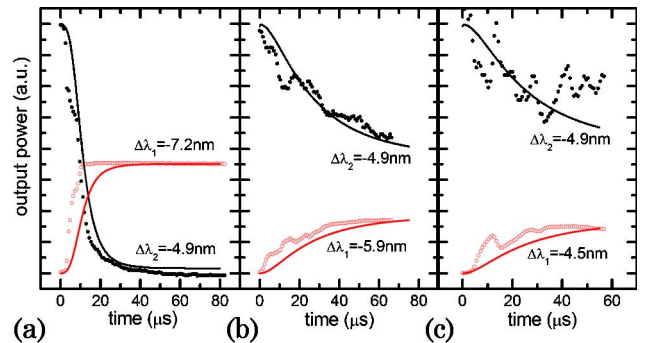


Fig. 3. (Color online) Plot of output power versus time for different cavity tunings. The linear cavity was chopped in the dual-cavity configuration. (a) Cavity tuned such that cavity switches from completely on to completely off. (b), (c) Various tuning such that the switching is less complete. Simulated results are shown as solid curves.

below the threshold; this result closely matches what is seen by chopping a single cavity. As we adjust the BF to tune closer to the regions of equal threshold, we see in Figs. 3(b) and 3(c) that the cavities begin to lase at the same time.

To account for the case of simultaneous lasing, the effect of spontaneous emission must be included in Eqs. (2) and (3) by appropriately adding a $\beta_{1,2}BN^2$ term, where B is the spontaneous emission coefficient and $\beta_{1,2}$ is the coupling of this emission to each cavity mode. When spontaneous emission is included, the gain coupling prevents one cavity from running away and the other from shutting off completely. Consider the case shown in Figs. 3(b) and 3(c), where cavities 1 and 2 are very near the areas of equal threshold. Cavity 1 begins blocked and is unblocked at time $t = 0$. The uncoupled threshold of cavity 1 is initially slightly lower, and the photon density increases at the expense of the photon density of cavity 2. As the photon density of cavity 2 drops, the relative contribution of the spontaneous emission increases. Because spontaneous emission is an additive term to the photon equation, it can be considered as a mechanism for reducing the threshold gain of cavity 2, thus lowering the uncoupled threshold of cavity 2 below that of cavity 1 and effectively reducing the photon density of cavity 1. This cycle is damped by the photon lifetime, allowing both cavities to operate simultaneously. This effective reduction in the threshold is, of course, very small, which is why this effect is important only when the two uncoupled thresholds are very close.

We confirm this effect by solving Eqs. (1)–(3) with the aforementioned spontaneous emission term included. In the model, we adjust $\Gamma_{r1,r2}$ in order to simulate the tuning of the BF. It takes less than a 1% change in the resonant periodic gain to account for the difference between Figs. 3(a) and 3(c). The calculated effect, shown as solid curves in Fig. 3, nicely predicts the overall shape of the curves. The experimental fluctuations seen in Figs. 3(b) and 3(c) are not fully understood, but they are believed to result from mechanical vibrations in the VECSEL experiment, which becomes very sensitive when the two cavities have nominally identical thresholds. Numerical investigations reveal that the switching time is primarily limited to the photon buildup of class A lasers [16], where the lifetime is a function of the sum of the uncoupled photon lifetimes.

The dual-cavity design allows for gain coupling of the VECSEL cavities. We examined the simplest case that employs a linear and a v cavity that are gain coupled. This coupling allows not only optical switching between two cavities operating at different wavelengths but also the simultaneous generation of different wavelengths from a common gain medium, at wavelengths anywhere near the boundary where the two laser thresholds are similar.

A fundamental set of rate equations is used to define an operation map where the areas of simultaneous operation and switching regions are plotted. We have numerically and experimentally identified and explained the boundary lines between linear and v-cavity dominance, defining the tuning capabilities of the dual-wavelength generation. In addition, it may be possible to expand the system to include several cavities centered on a common gain medium to allow for even more flexibility.

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