Modeling Impact of Oxide Island on the Lasing of ARROW-VCSEL

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***Abstract*—We analyze the impact of a low-refractive antiresonant oxide island buried in a top VCSEL mirror on the lasing conditions of lateral modes of different orders. By performing comprehensive thermal, electrical, and optical numerical analysis of the VCSEL device, we show the impact of the size and location of the oxide island on the current crowding effect and compute threshold currents for various lateral modes. We demonstrate that if the island is placed close to the cavity, the threshold shows strong oscillations, which for moderate island distances can be tuned to increase the side mode discrimination.**

***Index Terms*—ARROW-VCSEL, resonance, single-mode, oxidation, modal transfer method**

Designing high-power vertical-cavity surface-emitting lasers (VCSELs) that operate on a single lateral optical mode is still a challenge. A common way to achieve single-mode emission is to make a relatively small electrical aperture. However, it limits the laser output power to less than 1 mW. Various approaches have been considered to overcome this limitation, like use of graphene-bubble dielectric distributed Bragg reflectors (DBRs) [1], double cavities [2], shallow relief [3] zinc-diffusion with oxide-relief [4], and grating couplers [5]. One of the promising possibilities is the application of antiresonant reflecting optical waveguides (ARROWs) within the VCSEL structure [6], [7], [8], [9]. Several such approaches have been successful, including a simplified version of the ARROW structure (S-ARROW) containing a low-index core surrounded by a single high-index ring. With this structure, substantial mode discrimination has been observed for 980 nm VCSELs with a core diameter of 8–12 µm [10], [11], [12], [13], [14], [15].

Previously [16], we presented an S-ARROW structure directly into the VCSEL cavity, inside the device aperture (i. e. on its axis), in the form of an oxide island manufactured with a planar oxidation technology [17], [18]. We showed that such an oxide island can have a strong impact on the lateral modes in the VCSEL. Their optical losses do not change monotonically with the island size, but are of an oscillatory nature. We proved that these oscillations are caused by the distorting effect of the island, which has a low-refractive-index, on the spatial profiles of the modes. For low island sizes, the modes have a tendency to focus on the high-effective-index region outside its radius, while with larger islands they are confined within it.

The main drawback of that analysis was the fact that it was a purely cold-cavity analysis, which did not consider the impact of the oxide island on the current flow. Now, we address this gap by investigating not only the optical modes but also the current flow and the resulting temperature distribution inside the laser structure [19].

We determine threshold currents for lateral modes of different orders for various island diameters and positions. We performed a similar analysis in a previous study for a cold cavity [20], and demonstrated strong oscillations in the optical losses, mainly in the HE_{11} and HE_{12} modes. Although the structure was slightly different than that considered in here—the oxide island was located inside the cavity (instead of in the top DBR) and the top DBR was dielectric—the physical mechanism causing these oscillations (the changing of the mode profiles due the differently sized islands) remains the same. We can therefore expect similar behavior in the current structure. However, this time we take a step further and consider the overlap between the gain and the optical mode profile which is distorted by the island, as well as the impact of the thermal heating caused by the current flow.

A good estimate of these effects is the threshold current, which is computed for each mode separately. We compute the threshold current for the dominant modes (namely LP_{01}, LP_{02}, LP_{11}, and LP_{21}) in the case of an island located around the 12^{th} DBR pair. As can clearly be seen in Figure 1, the modal behavior strongly depends on the distance of the oxide island from the cavity. When it is positioned below the 12^{th} DBR pair, there are strong oscillations in the threshold current which increase with the island diameter. For more distant island locations, these oscillation are strongly suppressed and almost disappear.

For islands positions where oscillations occur, the strongest increase of the threshold current can be observed with diameters of around 10 µm, which is exactly the diameter of the outer oxidation located in the cavity. There are two possible reasons for this: an increase in the optical modal loss, or a decrease in the overlap between the light and the gain. However, as can be seen from Figure 2a, there is no expected negative correlation between the overlap factor and the threshold. At the 10 µm island (where the threshold is highest), the overlap not only does not decrease but increases visibly to double the size of the overlap for the 15 µm island (for which the threshold is the lowest). This happens for all the analyzed modes. Hence, we conclude that for the analyzed island distances (9^{th}–15^{th}

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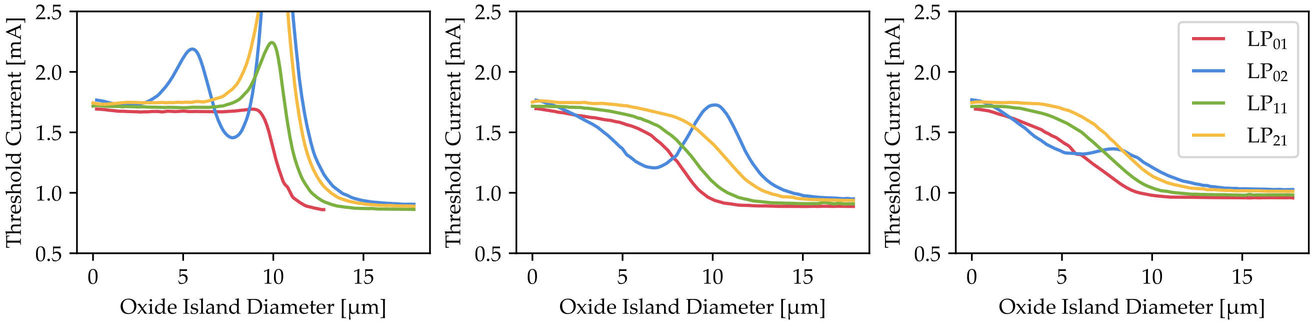
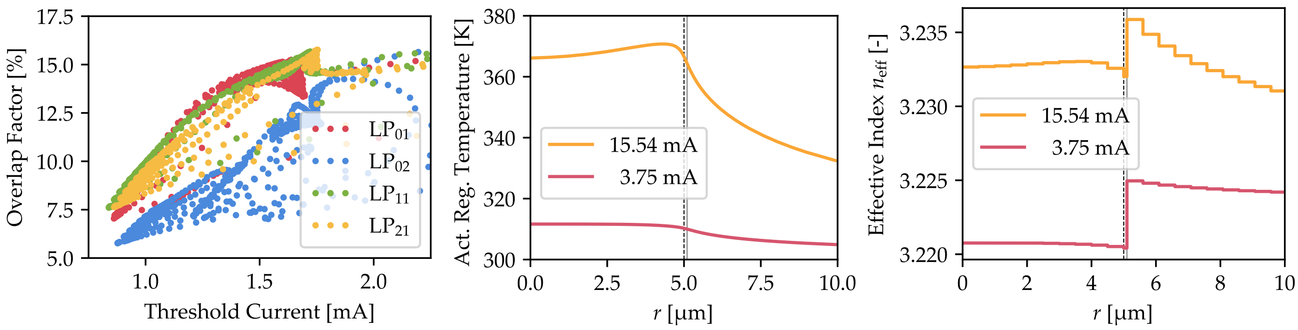


(a) island in the 10th DBR (b) island in the 12th DBR (c) island in 15th DBR

Fig. 1. Dependence of threshold current on the size of the oxide island for several locations in the DBR layers. The position of the island has a strong impact the qualitative behavior of the modes. Below the 12th pair, strong oscillations are visible. A rapid increase in threshold current can be observed for critical island diameters (10 µm and around 5 µm for the LP_{02} mode).



(a) (b) (c)

Fig. 2. The correlation between the overlap factor and the threshold current (a), temperature profile (b) and effective index distribution (c) in the active region for input currents of 3.75 mA and 15.54 mA.

DBR pairs) the overlap between the optical mode and the gain has a negligible impact on the threshold current. The origin of the threshold variations is match or mismatch of the modal profile with the anti-resonant oxide aperture.

In order to maintain a single-mode regime, the impact of the oxide island on the optical properties of the laser must be larger than the thermal lensing effect. Up to the input current of 3.75 mA this is indeed the case, as the heating is not significant: around 12 K over ambient temperature of 300 K, as shown in Figure 2b. In consequence the radial effective index distribution of the VCSEL shows a strong change only at the island radius (Figure 2c). For comparison, at 15.54 mA, where the laser heats by 70 K, the thermal lensing is strong and the effect of the oxide aperture is reduced.

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