Comparison of Wavelength Splitting for Selectively Oxidized, Ion Implanted, and Hybrid Vertical-Cavity Surface-Emitting Lasers

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***Abstract*—The wavelength splitting between the LP_{01} and LP_{11} modes of selectively oxidized, ion implanted, and hybrid ion implanted/selectively oxidized vertical-cavity surface-emitting lasers is studied by experiment and theory. Measured splittings at threshold show marked differences between the different laser structures due to the effects of index guiding and thermal lensing. Theoretical results were obtained using a vector optical mode solver and show good agreement with experimental results. The hybrid lasers exhibited behavior intermediate between the ion implanted and selectively oxidized lasers and could be optimized for high power single transverse mode emission.**

***Index Terms*—Laser modes, vertical-cavity surface-emitting laser (VCSEL).**

I. INTRODUCTION

HIGH-POWER single-mode operation is greatly desired for use in such applications as optical imaging and scanning, as well as data communications over single-mode fiber. Due to the extremely short cavity length, vertical-cavity surface-emitting lasers (VCSELs) lase in only one longitudinal mode. However, because of the relatively large transverse dimensions of the optical cavity, they may lase in multiple transverse modes. This is especially true for selectively oxidized VCSELs due to their strong inherent index confinement. One can decrease the number of lasing modes by decreasing the cross-sectional area by making smaller oxide apertures. However, this also decreases the active volume, and thus reduces the output optical power. Another way to achieve single-mode operation is to increase the loss to the higher order modes. However, this can also increase the loss to the fundamental mode. Therefore, achieving high-power single-mode operation from a selectively oxidized VCSEL has been somewhat problematic.

There are many different approaches that have been pursued to achieve high power single-mode operation in selectively oxidized VCSELs. Some introduce loss to the higher order modes, such as surface relief etching [1]. Areas of the first few layers of the top distributed Bragg reflector (DBR) where higher order modes exhibit high intensity are etched away, reducing the reflectivity for these modes. Thus, the fundamental mode experiences less loss than the higher order modes, and is the preferential lasing mode. One drawback to this approach is that the etched top DBR also increases the scattering losses to the fundamental mode, reducing the power. Another method is to lengthen the optical cavity to increase the diffraction losses for the higher order modes [2]. However, though lasing in a single transverse mode is achieved, multiple longitudinal modes will lase if the cavity is made too long. In addition, extending the longitudinal cavity of a VCSEL can increase the optical loss significantly. High-power single-mode operation can also be realized by increasing the gain of the fundamental mode [3]. Ion-implantation-induced disorder in the active region can spatially define the laser gain. Thus, there is a preferential gain window which pumps the fundamental mode. There are also methods involving external mirrors [4] and coupled cavities [5]. These techniques have provided the highest single-mode powers, but add considerable complexity. Recently, we reported high-power single-fundamental mode operation of an 850-nm vertical-cavity laser using a hybrid ion implanted/selectively oxidized structure [6]. By using two types of apertures, the current can be selectively injected through a smaller implant aperture into the fundamental optical mode defined by the larger oxide apertures, producing lasing in a single transverse mode. By implementing both oxide and implant apertures, we seek to separate the effects of transverse optical confinement and electrical confinement, respectively.

In this paper, we characterize the transverse optical mode behavior of three device structures fabricated from the same wafer: implant, oxidized, and hybrid VCSELs. Oxide-confined and implanted VCSELs have exhibited dramatically different optical properties [7]. A particularly sensitive method to elucidate the degree of transverse optical confinement for small device diameters is to examine the spectral splitting between the fundamental and first higher order modes [8] at threshold. The wavelength splitting between the fundamental mode (LP_{01}) and the first higher order mode (LP_{11}) at threshold is determined experimentally and compared to results calculated using a vector optical solver based on the numerical mode-matching method (NMM) [9]. In this manner, the degree of index confinement of these structures is characterized, and using this analysis, single fundamental mode operation can be optimized.

Manuscript received October 1, 2002; revised January 24, 2003.

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Digital Object Identifier 10.1109/JQE.2003.810264

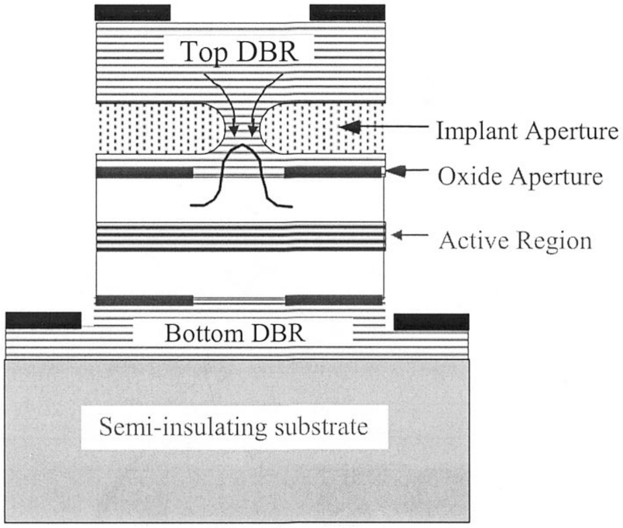
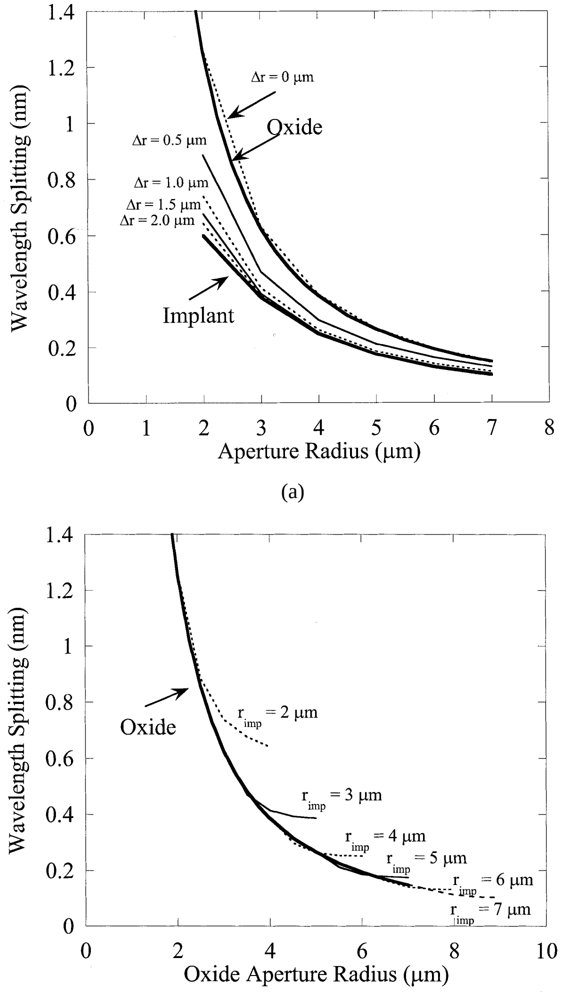


Fig. 1. Side view sketch of hybrid implant/oxide VCSEL.

II. THEORY AND MODELLING

In our hybrid single-mode structure, the implant aperture is located above the active region and oxide apertures, as shown in Fig. 1. The purpose of having two apertures in this structure is to separate the effects of the current confinement and the optical confinement. The implant aperture is used to confine the current flow, while the oxide aperture defines the optical cavity. By making the implant aperture smaller than the oxide aperture, the current is funnelled into the center of the optical cavity, preferentially pumping the fundamental mode over higher order modes. The unpumped quantum wells around the periphery of the implant aperture also provide greater loss to the higher order modes through absorption. Due to the implant aperture, a thermal lens can also arise [10]. Thus, single-mode operation in these hybrid VCSELs will be due to a combination of selective carrier injection, thermal lensing, and peripheral optical loss.

An optical solver using NMM is used to model each VCSEL's characteristics [9] at threshold. Given the VCSEL structure, the model calculates the threshold gain (which includes the effect of material absorption and oxide diffraction losses) for a given transverse mode. Selectively oxidized VCSELs are simulated by including an oxide aperture in the structure. Implant aperture devices are modeled by inserting a thermal lens in the structure from the active region to the implant aperture in the top DBR for each aperture radius. This is achieved through an increase in the refractive index of 0.012 corresponding to $\Delta T = 30$ K [11] within the implant radius. The thermal lens' refractive index is linearly graded down to its ambient value 0.2 μm beyond the aperture radius. For implant aperture devices, the value of the change in the refractive index in the thermal lens is constant but the spatial extent of the thermal lens varies with implant aperture size. Hybrid VCSEL simulations implement both the oxide aperture and the thermal lens.



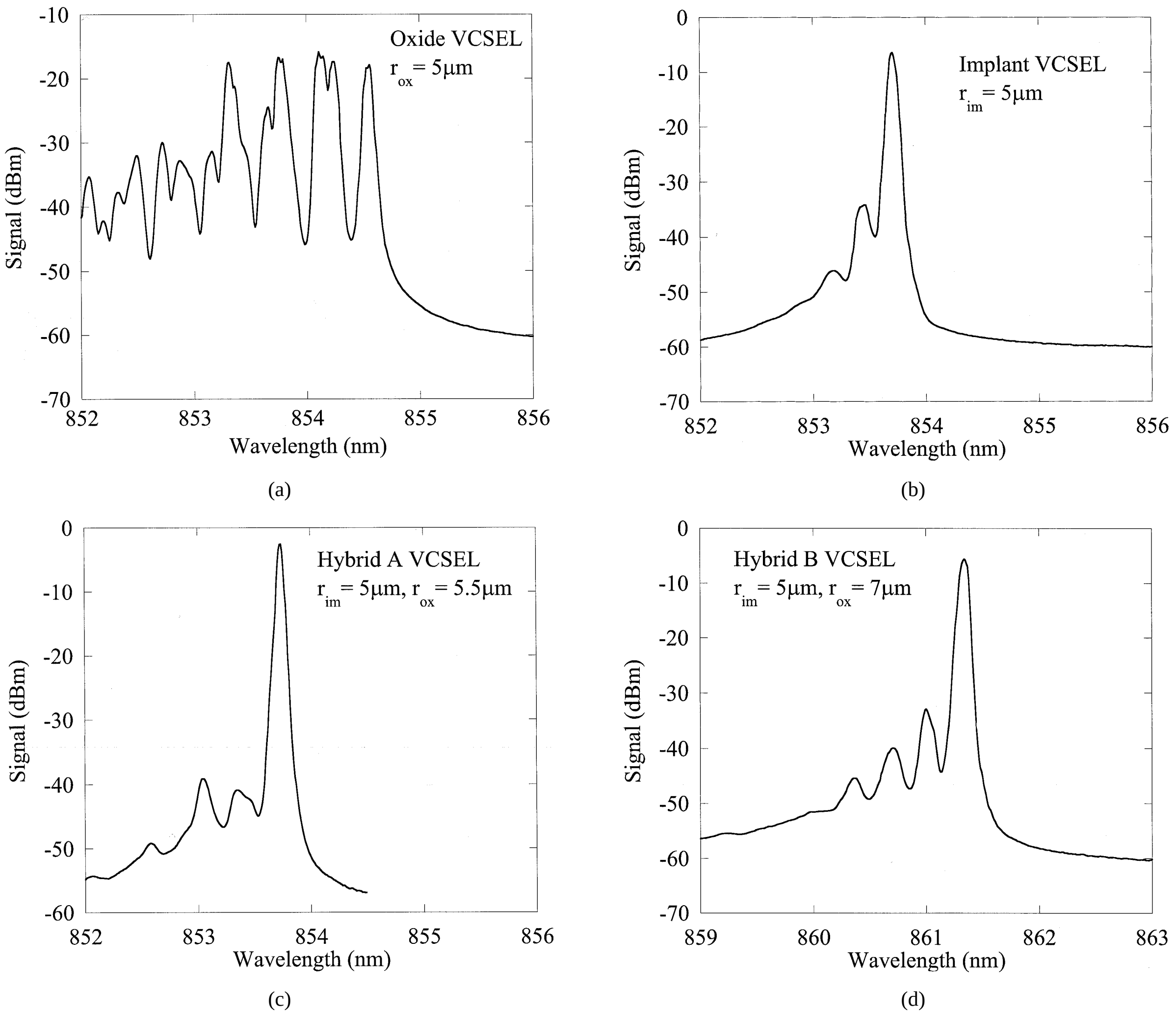
(a)

(b)

Fig. 2. Theoretical calculation of the wavelength splitting between the LP_{01} and LP_{11} modes at threshold for oxide, implant, and various hybrid VCSELs plotted versus (a) the implant aperture size and (b) the oxide aperture size.

Fig. 2 shows theoretical calculations of the wavelength splitting between the LP_{01} and LP_{11} modes for the various device structures. Fig. 2(a) plots the results versus the size of the implant aperture (or oxide aperture for the oxide-confined VCSELs). The thick curves correspond to the oxide-confined VCSELs and the implant VCSELs, while the other curves represent hybrid VCSELs with varying differences between the size of the implant and oxide apertures, with the implant aperture always being smaller than the oxide aperture $(\Delta r = r_{\mathrm{oxide}} - r_{\mathrm{implant}} > 0)$. From this figure, it is clear that the spectral splitting of the implant and oxide-confined VCSELs differ significantly with decreasing aperture diameter. From Fig. 2(a), we see that when the oxide and implant apertures of the hybrid VCSELs are the same size $(\Delta r = 0)$, the expected wavelength splitting is essentially that found for an oxide aperture. As the oxide aperture becomes much bigger than the implant aperture (Δr increases), the wavelength splitting approaches that of the implanted VCSEL case. Thus, when the oxide aperture is much larger than the implant aperture, the effective aperture is the implant aperture (or the size of the thermal lens).

Fig. 2(b) plots the same data versus the size of the oxide aperture. The thick line represents the oxide-only VCSELs, while the other six lines represent hybrid VCSELs with different sized implant apertures. The first two points of the hybrid curves, corresponding to aperture size differences of $\Delta r = 0$ and 0.5 μm, respectively, line up well with the oxide-only solution. Thus, we



(a) (b) (c) (d)

Fig. 3. Measured spectra at 10-mA bias for VCSELs with: (a) 10-μm oxide aperture, (b) 10-μm implant aperture, (c) 10-μm implant aperture with 11-μm oxide aperture, and (d) 10-μm implant aperture with 14-μm oxide aperture.

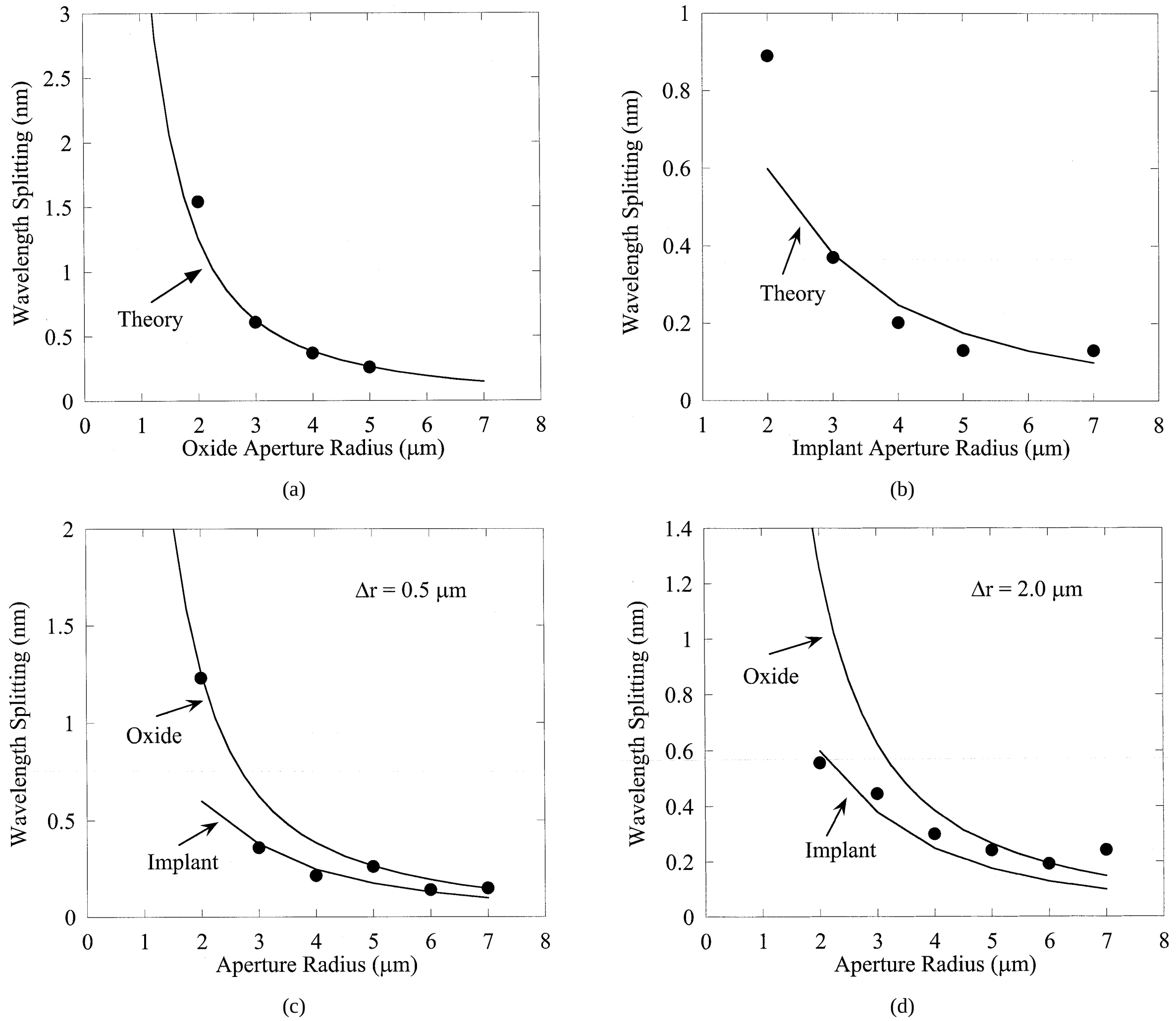
conclude that for small aperture differences the effective aperture of the hybrid VCSEL is the oxide aperture. Also, as illustrated by the 6- and 7-μm implant cases, large implant aperture VCSELs give nearly the same result as oxide-only VCSELs. Thus, for very large implant apertures, the effective aperture of the hybrid VCSEL is defined by the oxide aperture.

III. EXPERIMENT

A cross section of the hybrid VCSEL structure is shown in Fig. 1. The 850-nm VCSEL wafer is grown using metal organic vapor phase epitaxy on a semi-insulating substrate. The top and bottom DBRs consist of 21 and 35 mirror pairs, respectively. Current confining implant apertures are fabricated through a 300-keV proton implantation, and range from 2 to 14 μm in diameter. The VCSEL mesas are reactive ion etched, and are selectively oxidized in a furnace at 400 °C for 40 min to form the square oxide apertures, varying in size from 2 to 18 μm in length [12]. Coplanar contact pads are deposited.

The wafer is placed on top of a copper heatsink that is temperature controlled by a thermoelectric cooler to maintain a temperature of 25 °C. Light from the VCSELs is directly coupled into a cleaved 62.5-μm multimode fiber. The spectra are measured using an HP 71451 B optical spectrum analyzer (OSA) with a 0.08-nm resolution bandwidth.

Four aperture combinations in the VCSELs are studied: oxide aperture only, implant aperture only, and two different hybrid aperture combinations. For the hybrid VCSELs studied, the implant aperture is always made smaller than the oxide aperture to promote single-mode operation [6]. In one case, the radial difference Δr between the two apertures is 0.5 μm (hybrid A), while the other case uses a larger $\Delta r = 2$ μm (hybrid B). For each combination, spectra are measured for several aperture sizes at many different currents. Fig. 3 shows spectra from the four cases studied. Fig. 3(a) is the spectra from a 10-μm oxide aperture VCSEL biased at 10 mA. It shows highly multimoded behavior as expected from the strong index confinement. Fig. 3(b) shows the spectra of a 10-μm implant aperture VCSEL biased at 10 mA. Under these conditions, it is lasing primarily in a single transverse mode as expected from the effects of thermal lensing. Fig. 3(c) and (d) shows spectra of hybrid VCSELs biased at 10 mA with a 10-μm implant aperture and 11- and 14-μm oxide apertures, respectively. Both are lasing in a single transverse mode. However, LP_{11} is also noticeably suppressed in Fig. 3(c) (side-mode suppression ratio $(\mathrm{SMSR}) > 35$ dB) as compared to Fig. 3(b) and (d) $(\mathrm{SMSR} \simeq 27\ \mathrm{dB})$. It is also worth



(a) (b) (c) (d)

Fig. 4. Comparison of theoretical calculations with measured results at threshold bias for: (a) oxide, (b) implant, (c) hybrid A, and (d) hybrid B VCSELs.

noting that the higher order modes are more clearly defined in the spectra from the hybrid VCSELs than those from the implant VCSEL. The devices characterized in Fig. 3(a)–(c) are located near the central region of the wafer, while hybrid B in Fig. 3(d) is near the edge, which accounts for the shift of wavelength. However, this wavelength discrepancy is small enough to avoid gain dependant transverse mode effects [13]. In our measurements, the highest single-mode power in a hybrid VCSEL is produced from a laser incorporating a 6-μm implant aperture and an 8-μm oxide aperture.

IV. COMPARISON OF THEORY AND EXPERIMENT

Fig. 4 shows comparisons of experiment and simulation for the spectral splittings between the fundamental and first higher order mode at lasing threshold. In many cases, there is greater than 30-dB side-mode suppression between the fundamental and first higher order mode. The measured splitting for the selectively oxidized VCSELs in Fig. 4(a) exhibit good agreement with our simulation. The implanted VCSELs are depicted in Fig. 4(b) and also show good agreement between experiment and theory. For either structure, at large (> 8 μm diameter) apertures, the splitting is very small, as expected. The comparisons in Fig. 4(a) and (b) validate our model used in our simulation. Fig. 4(c) shows the comparison of the hybrid A VCSELs with $\Delta r = 0.5$ μm plotted versus the implant aperture radius. For the smallest aperture, the hybrid VCSEL behaves similar to the oxide VCSEL. The comparison for the hybrid B VCSELs with $\Delta r = 2$ μm is shown in Fig. 4(d). The behavior of these VCSELs more closely resembles that of the implant rather than the oxide VCSELs. This behavior is due to the refractive index step seen by the modes in the VCSEL. For hybrid VCSELs with small oxide apertures, the LP_{01} and LP_{11} modes are influenced by the oxide index step, while for the hybrid VCSELs with larger oxide apertures, the modes are influenced by the index difference of the thermal lens.

V. CONCLUSIONS

We have measured and compared the wavelength splitting of the LP_{01} and LP_{11} modes for selectively oxidized, ion implanted, and hybrid ion implanted/selectively oxidized VCSELs. The wavelength splittings were also compared to theory, and show good agreement. For hybrid VCSELs with small oxide apertures, the LP_{01} and LP_{11} modes are influenced by the oxide index step, while for the hybrid VCSELs with larger oxide apertures, the modes are influenced by the index difference of the thermal lens. The observed modal dependence on the relative sizes of the implant/oxide aperture is consistent with our findings of single-mode operation [6]. Of the VCSELs measured, hybrid VCSELs with an implant aperture slightly smaller that the oxide aperture (hybrid A) had the largest SMSR. Through optimization of the size of the smaller implant aperture to the large oxide aperture, it should be possible to increase the modal discrimination to achieve high power fundamental mode operation.

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