Lateral Integration of VCSEL and Amplifier with Resonant Wavelength Detuning Design

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Abstract We propose and demonstrate the lateral integration of a VCSEL and a slow-light VCSEL amplifier with in-plane resonant wavelength detuning design, enabling the unidirectional coupling and stable single-mode operation with good beam quality. The modelling and simulation result of the wavelength detuning and unidirectional coupling is shown. A slow light laterally coupled from the VCSEL to the amplifier can be amplified uniformly when the amplifier is pumped above the threshold current. We also present the experimental data of the beam quality, output power and spectrum. The measured data show the increased single-mode output power with good beam quality in comparison with conventional VCSELs. A record single-mode power (40 mW) with narrow beam divergence (<0.6°) is presented.

key words: VCSELs, Slow Light, Unidirectional Coupling, Amplifier

Classification: Integrated optoelectronics

1. Introduction

VCSEL has been widely used as a light source in cost-effective high-speed data center and short-reach networks [1-4]. These days, the applications of VCSELs have been extended into high power applications such as laser manufacturing and optical sensing. [5-8] However, the single-mode output power of VCSELs is limited by its small active region volume. Thus, increasing the output power of VCSELs emerges as a critical issue for high power applications. Although two-dimensional VCSEL arrays offer kW-class output power, but there still remains difficulties in their poor beam quality [9-12].

In our group, we proposed the slow light VCSEL amplifier to realize high output power and good beam quality at the same time [13-16]. In the proposal an input light is coupled through a lensed fiber to a lateral propagation mode with a small group velocity so-called “slow light”. By injecting a current above the threshold of the amplifier VCSEL, slow light can be amplified. In this case, the amplified output is proportional to the amplifier length and the beam divergence is getting smaller and smaller with increasing the length. Over 3 W single-mode operation with high-beam quality for 3 mm a long VCSEL amplifier is reported in [15]. We then proposed and demonstrated the taper-shaped oxide aperture lateral integration platform of a VCSEL and amplifier, avoiding an external laser source. The laterally integrated device exhibited a single mode output power over 10 mW [17]. However, there still remains difficulties in achieving unidirectional lateral coupling to avoid instability in mutually coupling and further increasing the stable single-mode output power.

In this paper, we present a structure of lateral integration of a VCSEL and amplifier with in-plane resonant wavelength detuning design showing the stable unidirectional coupling and a record single-mode power of 40 mW.

2. Device structure and Modelling

The schematic structure of an amplifier integrated VCSEL with a top dielectric DBR and wavelength detuning design is illustrated in Fig.1. Firstly, proton implantation is carried out between the VCSEL and amplifier section on the half-VCSEL structure for electrical isolation. Then the top phase control layer of the VCSEL section is partly etched to form a resonant wavelength detuning of the VCSEL and amplifier sections. Then a SiO\(_2\)/Ta_2O_5 dielectric DBR is evaporated on the top of the half-VCSEL [18-20]. Since the resonant wavelength is proportional to the effective cavity length of VCSELs [21-23], the resonant wavelength of the VCSEL is shorter than that of the amplifier section due to the thickness differences between the two cavities as shown in Fig. 1(b).

As we already stated in [24], we are able to achieve unidirectional coupling from the VCSEL to the amplifier, because a longer wavelength light cannot be coupled from the amplifier section to the VCSEL. Thus, we could still keep the single-mode operation of the small aperture VCSEL. Figure1(c) shows the top view of a fabricated device, the oxide aperture of the VCSEL is around 4x4 \( \mu m \) and amplifier section is at a length of 900 \( \mu m \). The end of the amplifier is taper-shaped to reduce the back reflection from the end.

Compared with our former design, in which the resonant wavelength difference is much less than 1 nm through a
difference in the oxide aperture width between the VCSEL and amplifier [17], the new structure offers a larger detuning wavelength (> 10nm), resulting in stable unidirectional coupling. Thus, high output and stable lateral coupling can be expected. We calculated the wavelength detuning by using a transfer matrix method [25-27]. A structure of a VCSEL with 4-pairs top semiconductor DBR and 980 nm center wavelength is assumed. The calculated results are shown in Fig. 2(a). When the contact layer of the VCSEL is etched by 60 nm, a wavelength detuning of 15nm between the two cavities is achieved.

![Fig. 1](image1.png)

*Fig. 1* (a) Top view of the proposed TCC VCSEL; (b) Cross view of the proposed device; (c) Top view of a fabricated device

Also, the simulation of lateral coupling is carried out using the film mode matching method [28-30] as shown in Fig. 2. We assume the same structure in Fig. 2(a). When there is an input light at the resonant wavelength in the VCSEL, strong lateral coupling from the VCSEL to the amplifier can be seen. However, when there is an input light at the resonant wavelength in the amplifier section which is 15 nm longer than that of the VCSEL, coupling from the amplifier to the VCSEL can be avoided. The unidirectional behavior of our device is helpful for the stable operation of the seed single-mode VCSEL.

![Fig. 2](image2.png)

*Fig. 2* (a) Resonant wavelength of laser and amplifier when 60nm of the top layer of laser side is etched; (b) Calculated intensity distribution in unidirectional coupling when there is a wavelength detuning

3. Experimental Results and discussions

Figure 3(a) shows the experimental measurement of the resonant wavelength when the phase control layer of the VCSEL section is partly wet-etched. The device has the same structure as we assumed in the modelling as shown in Fig. 2 (a). The oxidized VCSEL aperture is around 4x4 μm. The amplifier length is 900 μm, which is over 200 times longer than the VCSEL. As we can see from the figure, when the phase control layer is etched by 60 nm in the VCSEL section, the resonant wavelength of the VCSEL (981nm) is about 15nm shorter than that (996nm) of the amplifier section. The experimental data is in agreement with our simulation.

Figure 3 (b) shows the near field pattern (NFP) when the VCSEL and amplifier is pumped separately. As shown in the top figure, a rather large amount of light is coupled from the VCSEL into the amplifier section when VCSEL is pumped. On the other hand, as shown in the bottom figure, very little light is coupled from the amplifier section into the VCSEL. The experimental results agree with the simulation. Obviously, there is no optical isolator function included in the device. The unidirectional coupling takes place due to the difference in resonant wavelengths at each cavity. In particular, the unidirectional coupling behavior is a great help in reducing instabilities for the lateral integration of a VCSEL and amplifier which functions as another large VCSEL. The mode control of the VCSEL amplifier can be realized thanks to the seed light from the single-mode VCSEL.

![Fig. 3](image3.png)

*Fig. 3* (a) Measured Spectrum; (b) Experimental NFP

Figures 4 (a)-(c) shows the amplification behavior of the integrated device with an amplifier length of 900 μm. Figure 4 (a) shows the measured FFP with pumping both the amplifier section and VCSEL, showing a narrow beam divergence at FFP angle of around 27°. With pumping the amplifier with 100mA CW current, we could get a single-peak narrow beam divergence of 0.06°, which is close to the diffraction limit (0.06°) of the 900 μm long amplifier. Figure 4 (b) shows the measured L/I under pulsed operation when the amplifier is pumped with a coupling from the VCSEL. The photodiode is tilted from the vertical axis by 30° so that the vertical lasing power of the amplifier is not captured. An output power of 40mW with 750mA pulse current at pulse width of 1 μs was achieved. We also measured the spectrum of the amplifier output as shown in Fig. 4 (c). Single mode operation at the wavelength of the coupled light from the VCSEL is clearly observed with side mode suppression ration (SMSR) of over 30 dB.
promising to be used as cost-effective light source for various applications such as optical 3D sensing, laser manufacturing, LiDAR system and so on.

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References


Fig. 4 (a) FFP with and without amplification; (b) I/L of the device with a seed light from the VCSEL (c) Spectrum of the amplifier output under pulsed operation.

4. Conclusion

In conclusion, we present the modelling and experiments of an amplifier-integrated VCSEL. We carried out the lateral integration design of a VCSEL and amplifier with a resonant wavelength detuning. The unidirectional coupling from the VCSEL to the long amplifier is realized. A record single mode power of 40 mW with SMSR and nearly-diffraction limited beam quality is achieved. Through optimizing the design and fabrication processes, further improvements of the single mode power over 100 mW can be expected by increasing the amplifier length. Our integrated device is


