Bistability in Bipolar Cascade VCSELs

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Measurement results on the formation of bistability loops in the light versus current and current versus voltage characteristics of two-stage bipolar cascade VCSELs are presented. It is observed that the bistable behavior is the more pronounced the more the cavity resonance is blue-shifted with respect to the gain maximum of the quantum wells. Additionally, the slope efficiency increases by more than a factor of 1.5 compared to conventional VCSELs due to carrier recycling.

1. Introduction

Bistability in vertical-cavity surface-emitting lasers (VCSELs) offers attractive applications in the area of high density optical memory and signal processing such as optical switching. Several mechanisms have been reported which favor bistable output behavior in VCSELs, such as polarization state changes [1], [2], index variations under optical injection [3], [4], transverse mode hopping [5], and saturable absorption [5], [6], [7]. For the first time to our knowledge, in this article, measurement results are reported on the bistable behavior of bipolar cascade VCSELs, exploiting the saturable absorption effect. Bipolar cascade VCSELs, in general, have been successfully demonstrated to overcome the bottleneck of limited roundtrip gain in vertical laser resonators due to carrier recycling [8]. However, since the active regions in cascade lasers are electrically coupled, current spreading in the cavity leads to non-homogeneously pumped stages which can favor bistable behavior. It is observed that bistability loops continuously expand with increased detuning between cavity resonance and gain maximum.

2. Device Structure

Figure 1 shows a schematic cross-section of an investigated selectively oxidized two-stage bipolar cascade VCSEL grown by molecular beam epitaxy (MBE).

The design consists of two densely stacked active pn-junctions, each of which comprises three undoped 8 nm thick In$_{0.2}$Ga$_{0.8}$As quantum wells separated by 10 nm thick GaAs barriers. Both active regions are placed in the antinodes of the standing wave pattern and are electrically coupled by a highly doped reverse-biased GaAs tunnel junction in between. The p-type top and n-type bottom Bragg reflector stacks consist of 19 and 32.5 Al$_{0.9}$Ga$_{0.1}$As/GaAs layer pairs, respectively. Current confinement is achieved by mesa
etching and subsequent selective oxidation of a 30 nm thick AlAs layer incorporated in the node of the standing wave pattern above the upper active region. For the p- and n-type doping we use C and Si, respectively. Finally, a ring contact deposited on the mesa allows for top surface emission.

3. Experimental Results

For research purposes we have chosen a substrate position in the MBE chamber which yields a strong gradient in layer thicknesses and therefore a shift of the cavity resonance of almost 80 nm between the center and edge of a two-inch wafer. The gain maximum, on the other hand, shifts only by about 3 nm as measured from edge-emitting lasers fabricated from the VCSEL material. Thus, such a wafer allows to investigate the device performance with respect to the detuning between cavity resonance and gain maximum. The oxide aperture of the devices under test is about 3 to 4 \mu m in diameter, resulting in single-mode emission. All presented measurement data are obtained from continuous wave operation at room temperature.

Figure 2 shows light versus current (L–I) characteristics of two-stage cascade VCSELs with different emission wavelengths. The lasers are driven in 1 \mu A steps by a precision current source which also monitors the voltage. It is clearly seen that bistable behavior is more and more pronounced in shorter wavelength devices, where no hysteresis loops are found at wavelengths longer than 980 nm. The observed hysteresis width ranges up to about 0.57 mA in current with an optical power discontinuity of more than 960 \mu W at the turn-on switching point at 938 nm wavelength. This bistable behavior can be explained by the wavelength and carrier density dependent absorption coefficient of the active stages. Firstly, due to only one oxide aperture, current spreading is present in the
Fig. 2: Emission wavelength dependent formation of $L-I$ bistability loops. The gain maximum is fixed at about 973 nm.

cavity which leads to a reduced carrier density in the bottom compared to the top stage. Thus, the bottom active region acts like a tunable absorber in the first place. Secondly, the wavelength dependent absorption coefficient decreases with longer wavelength, in particular at the long wavelength side of the gain maximum ($\lambda \geq 973$ nm here), which explains the disappearance of bistability.

Fig. 3: Bistable $L-I$ and $I-V$ characteristics of the 964 nm wavelength bipolar cascade VCSEL from Fig. 2.

All optical bistability loops shown in Fig. 2 are accompanied by a corresponding hysteresis in the current versus voltage ($I-V$) characteristic. This observation is explicitly shown in Fig. 3 for the device emitting at 964 nm wavelength. Here, the hysteresis width and output power discontinuity are 11 $\mu$A and 510 $\mu$W, respectively. The corresponding voltage discontinuity of about 17 mV occurs at the switching points and can be explained by the sudden change in carrier density in the active regions due to the abrupt optical turn-on and turn-off behavior.
As a direct effect of carrier recycling the investigated single-mode cascade devices exhibit slope efficiencies of about 33 to 38% that are significantly higher than those measured for conventional one-stage reference VCSELs (21 to 23%). For comparison, Fig. 4 shows the typical $L-I$ characteristic of a conventional one-stage VCSEL and of a two-stage bipolar cascade VCSEL at about 972 nm emission wavelength. The increase in differential quantum efficiency indicates that both active regions in the cascade VCSELs contribute to lasing. Thus, the presented design can combine bistability and increased roundtrip gain.

4. Conclusion

We have presented data on bipolar cascade VCSELs which exhibit optical and electrical bistability loops due to saturable absorption. The bistability strongly depends on the detuning between resonance wavelength and gain maximum that is attributed to the wavelength and carrier density dependent absorption coefficient. Moreover, the presented cascade VCSELs also provide additional roundtrip gain compared to conventional one-stage lasers. Therefore, applications such as optical switching and optical memory may also arise for bipolar cascade VCSELs. In future, we will investigate the bistability loops with respect to temperature as well as cascade VCSEL design variations.
References


