Bias-controlled wavelength switching in coupled-cavity $In_{0.4}Ga_{0.6}As/GaAs$ self-organized quantum dot lasers

Weidong Zhou, Omar Qasaimeh, Jamie Phillips, Sanjay Krishna, and Pallab Bhattacharya[a]
Solid-State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

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Efficient wavelength switching is demonstrated in an $In_{0.4}Ga_{0.6}As/GaAs$ self-organized quantum dot laser with an intracavity absorber section. A wavelength shift of ~15 nm, believed to be caused by a shift of lasing between the bound states of the quantum dot, is obtained for a bias change of 6 V.
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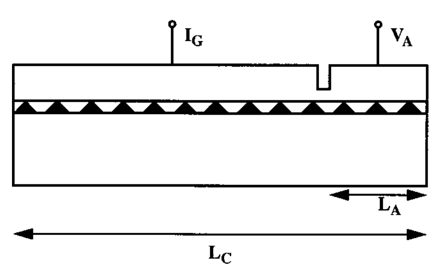
Solid-state light-emitting devices with the capability of electrically controlled wavelength switching may become important for read and write operations, chip-to-chip interconnects, and wavelength-division multiplexing.[1–5] There have been extensive studies of optical bistability in semiconductor lasers with intracavity saturable absorbers.[6,7] Such devices have been successfully used as memory elements in optical communication systems using time-division multiplexing. Because the bistability in these devices corresponds to the laser on and off states, however, the ultimate switching speed is limited by the spontaneous carrier lifetime in the active region, which is of the order of a few nanoseconds. One approach to improving the switching speed of bistable semiconductor lasers is to make use of two-mode bistability,[8] where the two states correspond to two modes of the laser having different wavelengths, polarization, or directional orientation. Because the two states correspond to two cavity modes, the changes in carrier populations can be minimal if there is substantial overlap between the modes. In addition, because one mode is always lasing, carrier lifetimes are shortened appreciably by stimulated emission.

Self-organized (In, Ga)As/(Al, Ga)As quantum dots generally exhibit two distinct peaks in the room- or low-temperature photoluminescence (PL) spectra, separated by 50–80 meV, depending on the dot heterostructure.[9] It is believed that ground- and excited-state transitions in the dots are responsible for these peaks. An important aspect of the bound states is that the conduction-band ground state is twofold degenerate, whereas the first excited states are almost fourfold degenerate.[10] Therefore, it is possible to switch the lasing from the ground state to the excited state by increasing the injection current or by varying the cavity loss in a laser. It is important to note that such distinctly separated levels are generally not encountered in quantum well lasers. An elegant way to investigate the switching behavior is to characterize a coupled-cavity system, made with quantum dot active regions, in which two sections are separately biased. By changing the bias across the absorbing region, the overall cavity loss can be made high enough so that the ground state gain can be made zero or negative and the excited-state gain remains positive. In this letter, we present a demonstration of bias-controlled wavelength switching in an edge-emitting quantum dot laser with an integrated intracavity saturable absorber formed with the same quantum dots.

An $In_{0.4}Ga_{0.6}As/GaAs$ multilayer quantum dot (QD) laser heterostructure [shown in Fig. 1(a)] was grown by molecular beam epitaxy (MBE). Details of such growth have been described elsewhere.[11] The InGaAs QD regions, grown in the three-dimensional Stranski–Krastanow (SK) growth mode, are separated by 15 Å of GaAs barriers. The dot density, as measured by atomic force microscopy (AFM), is $\sim 5\times 10^{10}\,cm^{-2}$. The near-pyramidal dots are 14 nm in base length and 7 nm in height. The separate confine heterostructure (SCH) laser consists of appropriate inner and outer cladding layers and contact regions.

Contact Layer	p+	GaAs	0.1 μm	
Outer Cladding	p	$Al_{0.3}Ga_{0.7}As$	1 μm	
Buffer Layer	i	$Al_{0.3}Ga_{0.7}As$	10 nm	
Inner Cladding	i	GaAs	0.1 μm	
4 ML $In_{0.4}Ga_{0.6}As$ QDs				x (N-1)
Spacer		GaAs	15 Å	x (N-1)
7 ML $In_{0.4}Ga_{0.6}As$ QDs				
Inner Cladding	i	GaAs	0.1 μm	
Buffer Layer	i	$Al_{0.3}Ga_{0.7}As$	10 nm	
Outer Cladding	p	$Al_{0.3}Ga_{0.7}As$	1 μm	
Contact Layer	p+	GaAs	0.1 μm	
S.I. (100) GaAs Substrate				

(a)



(b)

FIG. 1. (a) Heterostructure for quantum dot laser and intracavity saturable absorber grown by molecular beam epitaxy; (b) schematic of the laser structure with integrated intracavity saturable absorber.

[a]Electronic mail: pkb@eecs.umich.edu

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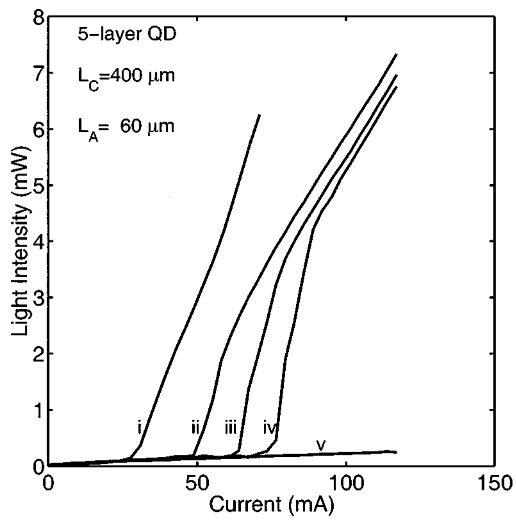

FIG. 2. Measured light–current ($L-I$) characteristics of the laser with different saturable absorber biasing voltage V_A: (i) V_A shorted to gain region voltage; (ii) $V_A=1.5$ V; (iii) $V_A=1.3$ V; (iv) $V_A=1.0$ V; and (v) $V_A=0$ V.

The laser and the intracavity saturable absorber (SA) device were fabricated in the ground–signal–ground (GSG) configuration by using standard photolithography and lift-off techniques and a combination of dry and wet etching. The device is shown schematically in Fig. 1(b). The gap between the gain and SA region is 10 μm in width and extends almost to the inner cladding layer just above the quantum dot active region. The laser and absorber single-mode waveguides are etched to almost the same depth. The deep etch in the gap ensures a resistance larger than 2 KΩ between the two sections. The width of the waveguide is 3 μm and the lengths L_C and L_A, as indicated in Fig. 1(b), vary from 400 to 1200 μm and 15 to 100 μm, respectively. After forming the *p*- and *n*-type contacts, a thick SiO_2 layer is deposited for device passivation and isolation. 1.4 μm Ti/Al/Ti/Au was finally evaporated to form the interconnects. The data reported here are from three- and five-layer QD lasers with $L_C=920\,\mu$m, $L_A=100\,\mu$m, and $L_C=400\,\mu$m, $L_A=30$, 60 μm, respectively. The laser and SA end facets are not coated.

Measured light–current ($L-I$) characteristics of the coupled-cavity device, for different values of saturable absorber bias V_A, are shown in Fig. 2. The light exiting from the SA end is measured. There are two significant features in the data. First, the threshold current linearly increases from the lowest value of 18 mA (where the gain and SA regions are shorted) as the SA bias is tuned to increase the cavity losses. Second, a distinct discontinuity is observed in the $L-I$ characteristics at higher output powers. These two features are attributed, respectively, to nonsaturable and saturable losses in the SA.[12]

The measured spectral switching characteristics are displayed in Fig. 3(a) for a coupled-cavity device with quantum dot layers in the active region. The laser current is kept constant at 114.4 mA when the SA voltage V_A is changed from -4 to 2 V, and the output switches from 0.992 to 1.008 μm. The shift corresponds to almost 20 meV. This switching behavior is observed from both three- and five-dot layer samples. It was also observed that the discrete wavelength switching becomes easier and more pronounced when the

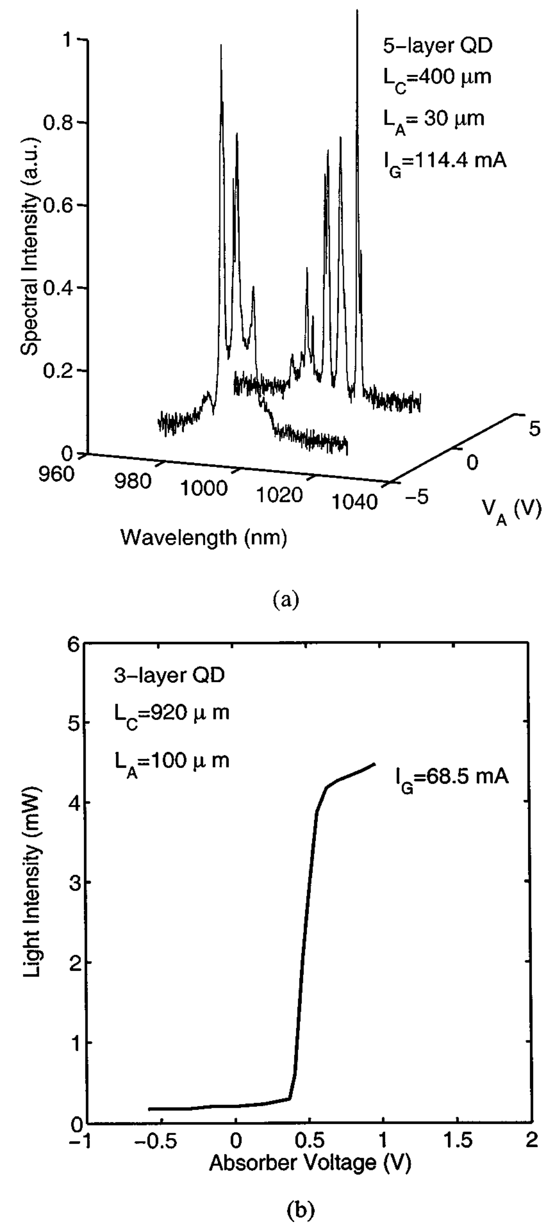

FIG. 3. (a) Lasing wavelengths at two different saturable absorber biasing voltages; (b) modulation of ground-state laser emission with saturable absorber biasing voltage change.

ratio of L_A/L_C increases. The multiple peaks in the output spectra, which are separated by energies larger than the longitudinal-mode separation, are characteristic of quantum dot laser outputs. They are believed to originate from interference effects caused by waveguide leakage into the substrate.[13]

The discrete nature of the wavelength switching indicates that lasing shifts from one bound state to another. The question is why the energy difference is only 16–20 meV and not ~50 meV. While we do not fully understand this discrepancy, which is under investigation, the results may indicate that the bound states of the dots are made up of contributions from the various dot sizes and switching occurs from the ground state of larger dots to those of smaller dots, and not from ground to excited states. Another possibility is that we see switching from the uppermost ground states to the lowermost excited states of the dots, the spread in each subband being caused by the 15%–25% size nonuniformity.

It is also evident that the coupled-cavity device can be operated as an efficient light modulator, with emission from the ground-state transitions. As the SA voltage decreases, the light output at $\sim 1\ \mu$m switches from high to low intensity for an increment of only 0.2 V in the SA voltage. This is illustrated in Fig. 3(b).

In conclusion, we report the demonstration of wavelength switching and light intensity modulation in InGaAs/GaAs quantum dot lasers with integrated intracavity saturable absorbers. The output can be switched by $\sim$20 meV and amplitude switching is achieved with a voltage change on the saturable absorber of only 0.2 V.

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