Wavelength Bistability in Two-Section Mode-Locked Quantum-Dot Diode Lasers

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***Abstract*—We report a two-section mode-locked quantum-dot laser with an emission wavelength that is bistable with respect to applied bias on the saturable absorber region. The two stable lasing wavelengths for this device are about 1173 and 1166 nm with a power contrast ratio of over 30 dB. The largest switchable wavelength range is 7.7 nm. The optical power and pulsewidth (6.5 ps) are almost identical in the two lasing modes under optimized conditions. The operation of this laser can be explained by the interplay of the spectral-hole burning and the quantum-confined Stark effect.**

***Index Terms*—Diode laser, mode-locked, quantum dot (QD), wavelength bistability..**

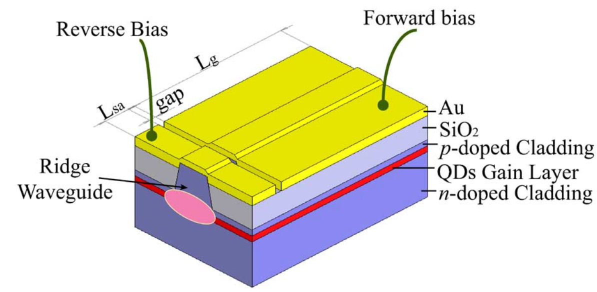

Fig. 1. Aschematic of the two-section QD diode laser. Waveguide width = 6 μm; $L_g = 5.5$ mm; $L_{\rm sa} = 0.3$ mm.

I. Introduction

OPTICAL bistability has many important applications in optical communications and photonic switching, and has been demonstrated in a wide variety of active and passive components. Most studies to date concerning optical bistability have featured polarization and power bistability [1], [3], [4]. Wavelength bistability has been more elusive, although there has been some work based on two-mode competition in semiconductor optical amplifiers [5]. A component exhibiting wavelength bistability could function as a flip-flop memory with the output wavelength indicating the logic state of the device. To be practical in future all-optical networks, such a device must support high-speed data transmission and be switchable on a time-scales of the shortest data packet lengths. In this letter, we report a two-section mode-locked diode laser based on self-assembled quantum dots (QDs) that exhibits wavelength bistability. The structure is monolithic, and therefore, extremely compact and simple, and operates at a repetition rate of 7.9 GHz. A closely related effect, wavelength switching, has been demonstrated before in two-section QD laser diodes [6], [7]. The main differences between this and previous work are the large parameter space where two branches of stable operation exist and the very high contrast between the two modes.

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II. Experiments and Results

The mode-locked QD laser has a structure similar to those already reported in the literature [3], [4], [6], [7]. A schematic of the two-section laser is shown in Fig. 1. The laser consists of a two-section ridge waveguide where one section is electrically pumped while the other section is reverse biased as a saturable absorber. The active region consists of a tenfold stack of InGaAs QDs layers embedded in a GaAs waveguide, which is sandwiched between AlGaAs cladding layers. Our QDs have a ground state transition of 1173 nm and an excited state transition of 1045 nm, determined from the electroluminescence spectrum (not shown). The waveguide was fabricated by standard photolithography and wet etching. A 6-μm-wide waveguide was etched in the top cladding layer followed by the removal of a small section of the heavily doped cap layer to provide isolation between the two sections. The lengths of the gain section (L_g) and the absorber section ($L_{\rm sa}$) are 5.5 and 0.3 mm, respectively, and the resistance between the two sections is $96k\Omega$. P- and n-type ohmic contacts were established with Ti–Au and Ni–AuGe–Ni–Au, respectively. No coating was applied to the cleaved facets. The device was mounted p-side up on a copper heat sink that was thermoelectrically temperature controlled.

The optical spectrum and output power of the QD laser were measured with current injection into the gain section and a reverse bias voltage applied to the absorber section. The operating temperature was 12 °C. With the absorber region floating, the threshold current is 45 mA and the lasing wavelength is 1173 nm. With a fixed reverse bias on the absorber, the laser exhibits a hysteresis loop in the power-current characteristics [3], [4]. Stable mode-locking can be achieved over a wide range of injection levels.

When the laser is operated with fixed injection current to the gain region and a varying bias on the absorber region, more

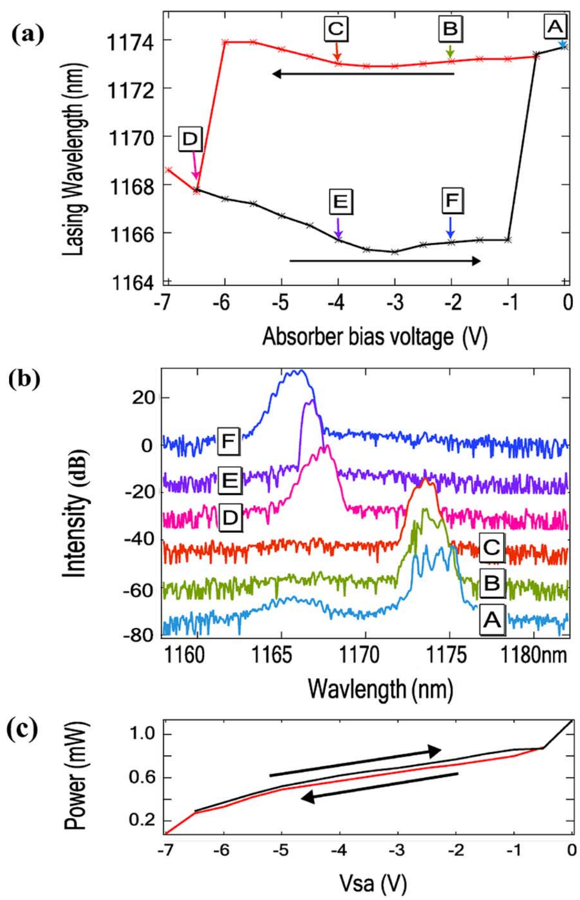

Fig. 2. (a) Wavelength of the laser emission as a function of absorber bias (V_{sa}) at a fixed gain section current of 55 mA. The dark (top red) trace is taken with the bias ramped up (down). (b) Optical spectra at various positions in the above hysteresis curve (the curves are offset for clarity). (c) Optical power as a function of V_{sa}.

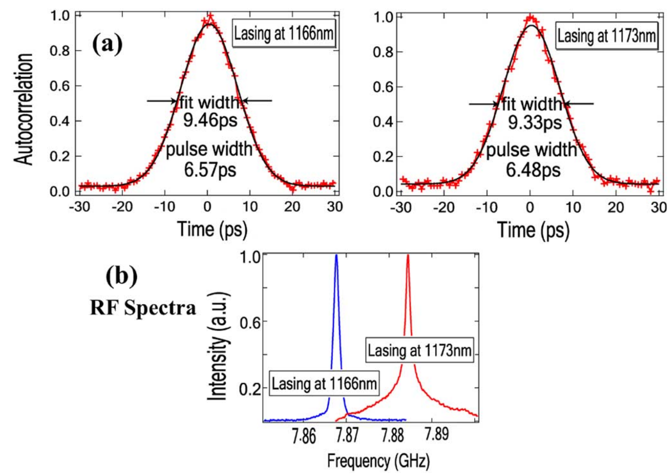

Fig. 3. (a) Intensity autocorrelation for the mode-locked pulses on different branches of the hysteresis curve, both at -4-V reverse bias. (b) Corresponding radio-frequency spectra.

interesting characteristics are observed, as shown in Fig. 2(a). Hysteresis and bistability are observed in the lasing wavelength upon varying the reverse bias voltage on the absorber. With the laser current at 50 mA and the absorber bias V_{sa} at 0 V, the laser mode-locks stably at about 1173 nm. As the absorber reverse bias is increased, this continues to be the case until the emission wavelength jumps abruptly to 1168 nm at -6.5-V bias. When the absorber reverse bias is then decreased, the laser remains mode-locked around 1166 nm until approximately -0.5 V, when the laser returns to the original wavelength and is still mode-locked. As evident from Fig. 2(b), the two modes are well separated and the power contrast between them is over 30 dB. Through the absorber bias V_{sa} range of -1 to -6.5 V, the laser is bistable and can be switched between two distinct wavelengths by applying the appropriate voltage pulse. Both lasing wavelengths are in the ground state. The largest switchable wavelength range is 7.7 nm when $V_{\mathrm{sa}} = -3$ V. Moreover, the power in each of the two lasing modes is almost identical, as shown in Fig. 2(c). At $V_{\mathrm{sa}} = -4$ V, for example, the power ratio between 1173 nm (0.57 mW) and 1166 nm (0.62 mW) is 0.92.

We also measured the pulse characteristics of the laser output in the two branches of the loop in Fig. 2. They are displayed in Fig. 3 with $V_{\mathrm{sa}} = -4$ V. The pulsewidth was measured with a background-free autocorrelator [Fig. 3(a)]. The corresponding pulsewidth is about 6.5 ps, assuming a Gaussian shape, and is essentially identical in both branches. The pulse could be shortened by increasing the reverse bias, and the shortest value obtained is 3 ps at -6 V. Fig. 3(b) shows the radio-frequency spectra of the device and shows a repetition rate around 7.9 GHz. The difference in frequency between the two branches is approximately 15 MHz, with the longer wavelength branch at higher frequency, as expected from the normal dispersion in the predominantly GaAs waveguide. We have measured numerous laser chips, and many show similar bistable behavior, although the regions of wavelength bistability and the separation between the two stable modes vary. It appears that the key to bistable operation in these structures is the correct ratio between the lengths of the gain and absorber regions.

The wavelength hysteresis loop for QD diode laser could be used for applications that require switching between wavelengths on a picosecond time scale. For instance, when the absorber is biased in the middle of the hysteresis loop, the output wavelength could be switched by an ultrafast electrical pulse of the required polarity. Since no current is injected to the absorber region, the modification of the absorber region that selects the lasing mode should be as fast as the pulse injected. Therefore, the switching time of the optical bistability for a two-section diode laser is determined by the saturation recovery time of the absorber section, as in [1]. In QDs, the carrier recovery time can be subpicosecond [8]. In our case, the output of the diode laser is a pulse train, and a minimum of one round-trip time is needed for the next lasing state to be established. So the wavelength switching time is limited by the round-trip time of the diode laser. For our laser, the repetition rate is 7.9 GHz, so the switching time can be as short as 120 ps. For a shorter cavity, a shorter switching time could be achieved.

We attribute the wavelength bistability of this device to the interplay between two separate properties of the QD saturable absorber region, the quantum-confined Stark effect (QCSE) and

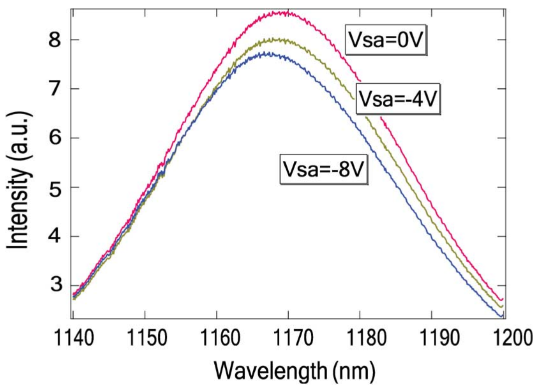

Fig. 4. Electroluminescence spectra taken from a sample similar to the laser, but with an antireflection coating to inhibit lasing. The light was extracted from the facet adjacent to the absorber region. V_{sa} is the bias voltage of the absorber region.

spectral hole burning (saturation) [4]. The QCSE manifests itself as a strong red-shift of the QD absorption peak in an applied electric field. The effect on the overall laser cavity (absorber plus gain region) is to shift the peak gain to shorter wavelengths. To test this, we measured the electroluminescence spectrum as a function of absorber bias from the same laser sample except that one of the facets was antireflection-coated to inhibit lasing. The result is shown in Fig. 4. The light was extracted from the facet adjacent to the absorber region. Although not a quantitative measure of the gain spectrum in our laser cavity, it is clear that the effect of the increased bias is not only to reduce the over all gain but to shift the peak. This alone would not explain the wavelength bistability observed here, as the emission wavelength of the laser would simply favor the mode with the most gain.

III. Discussion and Conclusion

To explain the wavelength bistability, we consider the competition between the two potential lasing modes in the cavity. The two-mode coupled rate equations must be solved including the effects of self- and cross-saturation in both the gain and absorbing regions. A detailed analysis is beyond the scope of this work, but general understanding can be gleaned from the discussions in [9]. Lin and Ku conclude that the region for bistability for these coupled modes is largest when cross-saturation is maximized in the gain region, but minimized in the absorber region. Stable single-mode operation then occurs when the unsaturated gain of one of the lasing modes is sufficiently higher than the other. In our case, the QCSE makes the relative gain of the two modes bias-dependent.

Considering the argument above, a two-section QD device would appear to be ideal for generating wavelength bistability. For one, cross-relaxation in the absorber region has been shown to be negligible for the wavelength separations seen here [10]. This is due to the strong three-dimensional confinement present in InGaAs QDs and is in stark contrast to what is seen in structures of higher dimensionality. The situation is different in the gain section, where the carrier density is extremely high. Here cross-saturation is much more efficient, as it can occur due to depletion of carriers in the states that supply the QDs or through an increase in homogeneous linewidth due to very efficient carrier–carrier scattering [11]. In addition, especially near the peak of the ground-state transition, QDs have a relatively flat gain profile, allowing two well-separated modes to see similar amounts of gain.

In conclusion, wavelength bistability is demonstrated in a two-section QD laser. Hysteresis and bistability in lasing wavelength are observed upon varying the reverse bias voltage on the absorber. The largest switchable wavelength range is 7.7 nm, from about 1173 to 1166 nm, with a power contrast ratio of over 30 dB. The wavelength bistability mechanism is based on the interplay of saturation and the QCSE in the laser.

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