Q-switched Operation of a Coupled-Resonator Vertical-Cavity Laser Diode

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FEB 24 2000
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Abstract

We report Q-switched operation from an electrically-injected monolithic coupled-resonator structure which consists of an active cavity with InGaAs quantum wells optically coupled to a passive cavity. The passive cavity contains a bulk GaAs region which is reverse-biased to provide variable absorption at the lasing wavelength of 990 nm. Cavity coupling is utilized to effect large changes in output intensity with only very small changes in passive cavity absorption. The device is shown to produce pulses as short as 150 ps at repetition rates as high as 4 GHz. A rate equation approach is used to model the Q-switched operation yielding good agreement between the experimental and theoretical pulse shape. Small-signal frequency response measurements also show a transition from a slower (~ 300 MHz) forward-biased modulation regime to a faster (~ 2 GHz) modulation regime under reverse-bias operation.

Keywords: Vertical-Cavity Surface-Emitting Laser, VCSEL, Coupled-Cavity, Q-switching.

The ability to generate optical pulses from vertical-cavity surface-emitting lasers (VCSELs) is of great importance in the development of high speed optical data links, where very short pulses at high repetition rates are required in a small, economical package. In addition to the many other advantages of VCSELs, such as low cost, straight forward fabrication of 2D arrays, and wafer-level testing, VCSELs, with their small mode volume, have been shown to be very fast, with small-signal modulation bandwidths in excess of 20 GHz [1]. High repetition, short pulse operation of VCSELs has been achieved through a variety of methods including mode-locking [2], gain-switching [3], and Q-switching [4,5]. Mode-locking can produce very short pulses at high repetition rates, but the pulses are typically low power and fabrication of an external cavity is required which adds complexity. Gain-switching is a very useful technique for the production of short pulses, but the pulses usually have a very large chirp due to the rapidly changing carrier density as the pulse is emitted. Q-switched operation, while typically yielding longer pulses, has the potential benefit of producing pulses at higher powers with lower chirp. In this paper, Q-switched operation is achieved by using the unique properties of a coupled-resonator vertical-cavity laser [6,7] to produce large changes in the cavity Q with only very small changes in absorption.

Photo-pumped coupled-resonator vertical-cavity lasers have been investigated and have demonstrated picosecond pulse generation [8]. The picosecond pulses in Ref. 8 were generated by optically pumping the coupled-cavity structure with 100 fs pulses to produce gain-switched operation. Here, we demonstrate short pulse operation of a coupled-cavity laser diode using electrical injection where current can be independently injected into either cavity. High speed probe contacts have been fabricated on the top surface to facilitate high speed testing and optical pulse generation. Cavity coupling produces a lasing mode which is extended throughout the structure producing a high field amplitude in both the active and the passive cavities [6,9].

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Under these conditions only a small change in intracavity absorption is required to significantly change the Q factor of the composite resonator. As shown below, the small change in absorption provided at 990 nm (the lasing wavelength) by reverse biasing the GaAs passive cavity is sufficient to produce Q-switched pulses. Previously, Q-switched operation in a vertical-cavity structure has been achieved by positioning absorbing quantum well (QW) layers at some position in the top distributed Bragg reflector (DBR) which is well away from the peak cavity field amplitude [4,5]. For these devices, the overlap of the electric field with the absorber is smaller so that a larger absorption is required to produce Q-switched pulses. By using a coupled-cavity structure, the interaction between the absorbing layer and the cavity field can be increased significantly.

As shown in Fig. 1a, the coupled resonator is composed of a bottom n-type DBR with 33 periods, a middle n-type DBR with 11.5 periods, and a top p-type DBR with 21 periods. The bottom one wavelength active cavity contains three 8 nm $\text{In}_x\text{Ga}_{1-x}\text{As}$ QWs while the top passive cavity has a half wavelength GaAs layer. The device was fabricated using a two-tier etch with two metal ring contacts on the top as well as a back side contact so that current can be independently injected into either cavity. High speed probe contacts were added to the upper passive cavity to provide efficient current injection at high frequencies. This allows the active cavity to be operated with constant current and the top cavity to be used as a modulator. Fig 1b shows a schematic of the electric field intensity inside coupled resonator where the intensity is peaked at the GaAs absorbing layer for efficient absorption modulation.

The experiments were performed by applying a CW current just above threshold to the active cavity to generate laser emission. The passive cavity was then modulated with an RF sine wave centered around - 4 volts so that it is reverse-biased through the full period of the applied RF. Pulses were measured using a streak camera system in synchroscan mode with a 10 ps

resolution. The streak camera was triggered at 80 MHz using a second, synchronized RF generator. Using this scheme, the passive cavity must always be modulated at a frequency which is an integer multiple of 80 MHz. For the frequency response measurements, an RF sweep generator connected to a scalar network analyzer was used to characterize the coupled-cavity devices.

Figure 2 shows Q-switched operation of the coupled resonator device plotted for several different RF power levels applied to the passive cavity. The inset of the figure shows the full-width-half-maximum (FWHM) of the Q-switched pulses as a function of RF power level. The pulse width decreases with increasing RF power up to the limit of the RF generator used for these experiments. The minimum pulse width observed was 150 ps FWHM using an RF power of + 20 dBm with pulsed operation possible up to ~ 4 GHz. The repetition rate for the data shown in Fig. 2 (and Fig. 3) was 0.88 GHz. This frequency was chosen to show the largest change in the FWHM of the pulse relative to the FWHM of the applied RF signal (570 ps @ 0.88 GHz) while still showing two pulses in the streak camera's 1.8 ns window. Thus, for the 150 ps pulse shown in Fig. 2, the pulse is compressed 3.8 times over that of the applied RF 'pulse'. The maximum achievable compression ratio was about 10.

Under Q-switched operation, the higher power pulses appear later in time, whereas for gain-switched operation, the higher power pulses are emitted at earlier times since the gain builds up faster with stronger pumping. In these experiments, we are modulating the loss in the passive cavity while the electrical pumping to the active cavity is fixed. Pulses are emitted when the absorption in the passive cavity falls below some critical level and the cavity Q rises enough for the device to be above the lasing threshold. When higher RF powers are applied to the passive cavity, the device stays below threshold longer allowing the gain to build in the active region. When the Q of the device is restored and threshold is reduced, the emitted pulse has a

higher peak power and appears at a later time. As shown in Fig. 1b, the standing wave pattern in the coupled-cavity system acts to maximize the influence of the absorption in the passive cavity. In addition to this cavity enhanced absorption, the associated changes in the index of refraction in the passive cavity are large enough to cause a change in the standing wave pattern such that more (or less) of the electric field overlaps the absorbing layer. This coupled-cavity modulation mechanism has been previously demonstrated [7]. The absorption and the index will change together, but their relative importance for Q-switching is unknown. The combination of absorption and index modulation causes a change large enough to induce Q-switched operation.

Figure 3 shows a comparison between the experimental data and a simulation using the following set of rate equations:

$$\frac{dn}{dt} = (g - \Gamma_c - \Gamma_b \sin^2(\Omega t)) n \quad (1)$$

$$\frac{dN}{dt} = P - \gamma N - gn \quad (2)$$

where n and N are the photon and carrier densities. We approximate the modal gain by

$$g = \Gamma A (N - N_0) \quad (3)$$

where Γ is the mode confinement factor, and, for the InGaAs QWs, we use the gain coefficient $A \approx 4.4 \times 10^{-5} \text{ cm}^3/\text{s}$ and transparency carrier density $N_0 \approx 1.15 \times 10^{18} \text{ cm}^{-3}$ [10]. In the above equations, $\Gamma_c = 10^{12} \text{ s}^{-1}$ is the photon decay rate in the cavity, $\Gamma_b = 1 \times 10^{13} \text{ s}^{-1}$ is the amplitude of the modification of the cavity decay rate due to the reverse-bias, Ω is the modulation frequency, P is the pumping rate, and $\gamma = 10^9 \text{ s}^{-1}$ is the carrier decay rate. The optical pulse calculated using this rate equation approach very closely matches the experimental data in Fig. 3. The calculated carrier density shown in Fig. 3 is out of phase with the optical pulse. As expected, the carrier

density increases while the cavity Q is low, and, when the cavity Q becomes high, an optical pulse is switched out of the resonator which depletes the carriers.

As shown in Fig. 4, frequency response measurements for the coupled-cavity vertical-cavity laser diode were performed at several different passive cavity bias voltages. These measurements were performed by applying a CW current to the active cavity and using the passive cavity as a modulator. A bias voltage was applied to the passive cavity together with a small-signal RF modulation. As the passive cavity diode begins to turn on (near 2 Volts), the recombination lifetime in the passive cavity limits the speed of the modulation. This can be understood as follows. Under forward-bias operation of the GaAs passive cavity, there is spontaneous emission at 870 nm, but no stimulated emission at 870 nm since the device lases at 990 nm. Because the net carrier recombination lifetime without stimulated emission is rather long (a few ns), the carrier density cannot be modulated at high speeds and the frequency response curve is peaked at low frequencies (~ 300 MHz). However, under reverse-bias operation there is no current flow through the passive cavity and the modulation is due only to changes in the applied field. The field can be modulated at a much higher rate which is limited by the parasitic capacitance of the device. Thus, under reverse-bias operation, the frequency response curve is peaked at higher frequencies. The transition between these two regimes occurs at about 2 volts which is the turn-on of the passive diode. The inset shows the intensity at 2 GHz modulation of the passive cavity as a function of passive cavity DC bias voltage which clearly shows a sharp drop at about 2 volts. The large size of the upper passive cavity mesa ($50 \times 50 \mu\text{m}$) and the conducting substrate both act to limit the speed of the device.

In summary, we have demonstrated Q-switched operation of a coupled-resonator vertical-cavity laser diode. With high speed probe contacts attached to the passive cavity, we have observed Q-switched pulses as short as 150 ps (FWHM) at repetition rates as high as 4 GHz. A

rate equation model for the Q-switched operation accurately reproduces the experimental data. Frequency response measurements show a transition from slow operation under forward-bias modulation to high speed operation with the passive cavity reverse-biased. Increasing the absorption in the upper cavity, for example by incorporating the appropriate quantum wells, should lead to improved Q-switched operation.

This research was performed at Sandia National Laboratories, a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy under contract No. DE-AC04-94AL85000.

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Figure Captions:

Fig. 1 : (a) Schematic of a coupled-resonator vertical cavity laser. (b) Electric field intensity as a function of position inside the coupled resonator. Note that the intracavity field is peaked at the position of the GaAs absorbing layer.

Fig. 2 : Q-switched pulses from a coupled-cavity plotted for several different RF power levels applied to the passive cavity. The inset shows the change in pulse width as a function of RF power at 0.88 GHz. + 0 dB corresponds to an incident power of + 20 dBm.

Fig. 3 : Calculated Q-switched pulses together with experimental data. The dashed line shows the carrier density as a function of time. The active cavity was supplied with 14 mA CW, while the passive cavity was supplied with a - 4 V bias and + 20 dBm of RF power at 0.88GHz.

Fig. 4 : Frequency response data plotted for two different passive cavity bias voltages. The inset shows the intensity at 2 GHz plotted as a function of passive cavity bias voltage. Note that the high frequency components begin to disappear as the passive cavity diode turns on.

Figure 1

Figure 2

Figure 3

Figure 4