14

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Coupled Resonator Vertical Cavity Laser

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ABSTRACT

The monolithic integration of coupled resonators within a vertical cavity laser opens up new possibilities due to the unique ability to tailor the interaction between the cavities. We report the first electrically injected coupled resonator vertical-cavity laser diode and demonstrate novel characteristics arising from the cavity coupling, including methods for external modulation of the laser. A coupled mode theory is used model the output modulation of the coupled resonator vertical cavity laser.

Keywords: vertical cavity surface emitting lasers, coupled resonator, coupled cavity

1. INTRODUCTION

Cleaved coupled-cavity (C^3) devices have been employed to achieve mode suppression and frequency stabilization in edge-emitting lasers [1]. Using composite resonators within a vertical cavity surface emitting laser opens up new possibilities due to the unique ability to: (i) tailor the coupling between the monolithic cavities; (ii) dynamically modify the cavity interaction; and (iii) incorporate passive or active resonators which are spectrally degenerate or detuned. Composite resonators can be utilized to influence the spectral and temporal properties within a vertical cavity laser. Previous photopumping studies of coupled vertical cavity laser structures have demonstrated three mode coupling (two photonic and one excitonic) [2], dual wavelength emission [3], and short pulse generation [4].

We report the first electrically injected coupled resonator vertical-cavity laser (CRVCL) diode. Our simulations show that CRVCLs can be utilized to control spectral as well as temporal properties within the laser. Experimentally we demonstrate novel characteristics arising from cavity coupling, including two methods for external modulation of the laser.

2. THEORY

Fig. 1 shows a schematic of a CRVCL. To analyze this structure, the laser field is written as a linear superposition of the passive coupled cavity eigenmodes [5]. To solve for these eigenmodes, we model the coupling mirror (middle distributed Bragg reflector (DBR) mirror in Fig. 1) with a dielectric "bump" so that the dielectric permittivity is:

$$\varepsilon(z) = \varepsilon_o\,[1 + (\eta/k)\,\delta(z)] \tag{1}$$

where $\eta = 2\sqrt{(1-T)/T}$, T is the coupling mirror transmission, and k is the magnitude of the coupled cavity wave vector. The eigenmodes u(z) are determined by solving

$$\frac{d^2}{dz^2} = -\mu_o \varepsilon(z)\,\Omega^2 u(z) \tag{2}$$

where Ω is the eigenfrequency . The boundary conditions are

$$u(-L_A) = u(L_B) = 0$$

$$u(0^+) = u(0^-)$$

$$\frac{d}{dz}u(0^+) - \frac{d}{dz}u(0^-) = -\eta\, k\, u(0).$$

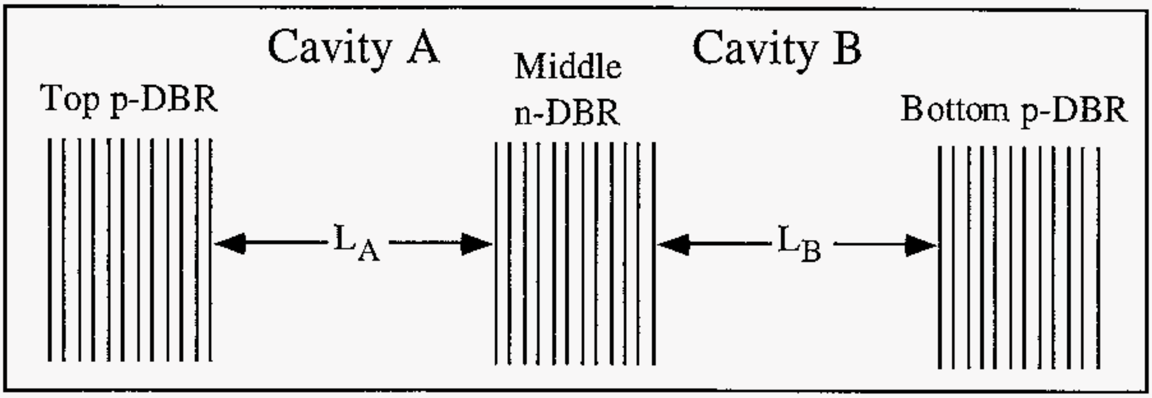

Figure 1. Schematic of coupled resonator vertical cavity laser (CRVCL).

Solutions of (2) satisfying the boundary conditions are

$$\begin{aligned} u(z) &= A \sin[k(z+L_A)], && \text{for } -L_A \le z \le 0 \\ &= B \sin[k(z-L_B)], && \text{for } \quad 0 \le z \le L_B \end{aligned} \tag{3}$$

where the wave vectors satisfy the equation

$$\sin[k(L_A+L_B)] = \eta/2 \{\cos[k(L_A-L_B)] - \cos[k(L_A+L_B)]\} \tag{4}$$

Continuity at the coupling mirror requires

$$\frac{A}{B} = -\frac{\sin(kL_B)}{\sin(kL_A)} \tag{5}$$

The solutions of (2) show the interaction between the resonators can be controlled by the transmission of the shared middle DBR mirror as well as variations in the optical path lengths of the cavities. Both of these parameters can be dynamically modified using current injection to depress the refractive index. For example, small changes in the optical path length of one resonator will modify its eigenfunction as shown in Fig. 2. Thus as the optical path of one cavity changes, the amplitude in that cavity will also change; if we extract light from that cavity, the laser output will be modulated. Note that with the proper choice of coupling between the resonators, the sensitivity of the output on path length variations can be optimized. Moreover, the mode amplitude in the active cavity and its frequency can be designed to have negligible change, the latter enabling chirpless modulation of the laser.

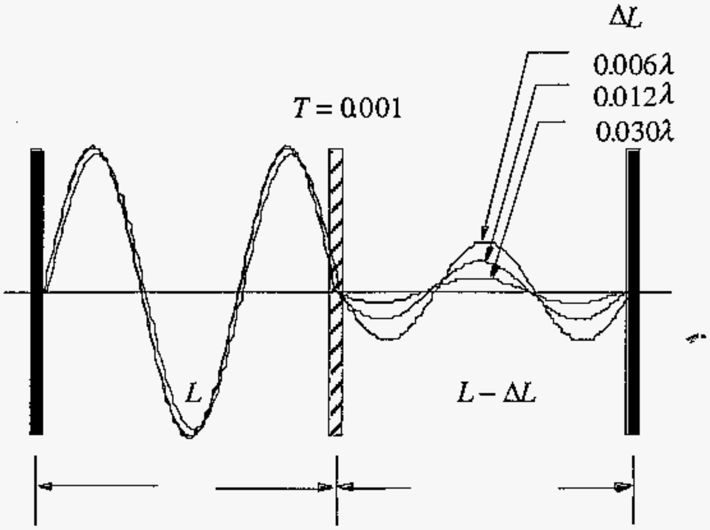

Figure 2. Composite resonator eigenfunctions arising from small reduction of the optical path length in one cavity.

3. FABRICATION

Fig. 3 shows a top view and side sketch of the CRVCL which consists of a lower 1-λ thick active resonator containing 3 InGaAs quantum wells and a passive upper resonator composed of 1-λ thick GaAs. In the bottom active cavity we employ selective oxidation of AlGaAs to form buried oxide layers for efficient electrical and optical confinement [6]. Separate electrical contacts to each cavity provide independent current injection into the two resonators (concentric ring contacts in Fig. 3), thus producing a three terminal optoelectronic source.

4. DEVICE CHARACTERISTICS

The coupling between the resonators is controlled by the transmission of the shared middle DBR sketched in Fig. 3. Fig. 4(a) shows the cavity resonances as a function of periods in the middle DBR. As the DBR reflectivity decreases, the resonance splitting and thus cavity coupling increases. The resonances shift in opposite directions in Fig. 4(a) which may be important for frequency tuning applications. In Fig. 4(b) we show the measured reflectance of a CRVCL with a 11.5 period middle DBR: the two cavity resonances are 14 nm apart in Fig. 4(b), in agreement with our calculations in Fig. 4(a).

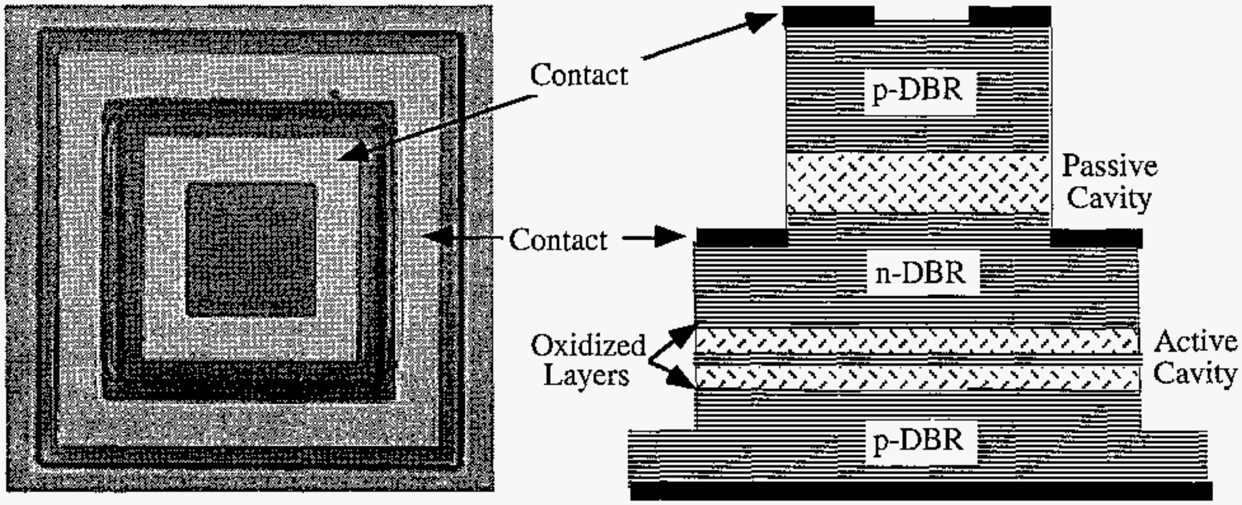

Figure 3. Top view and side sketch of CRVCL.

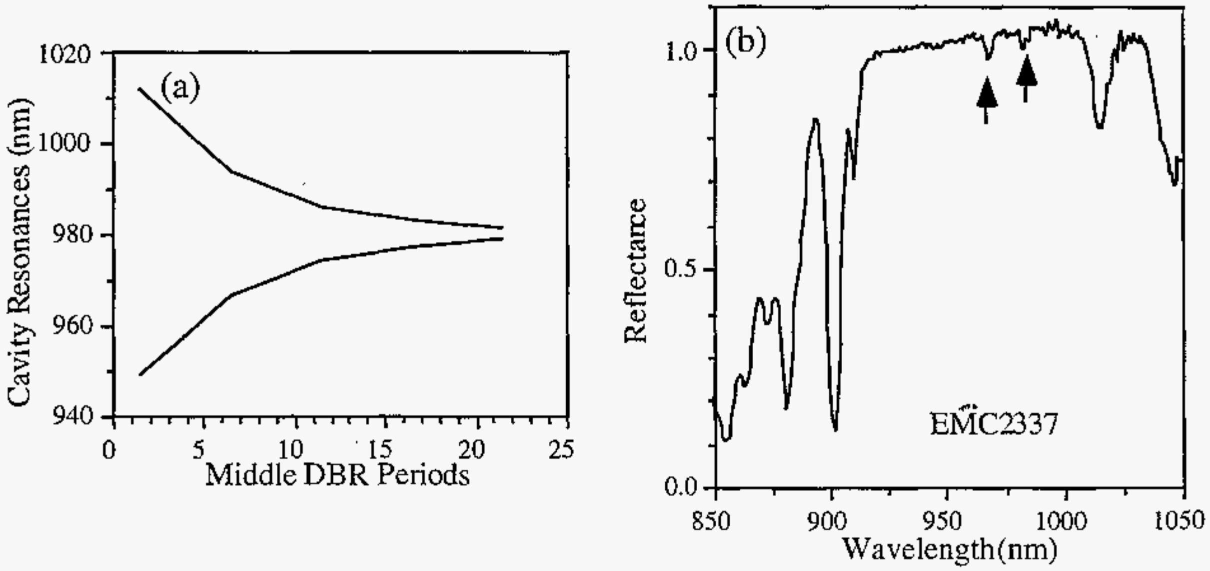

Figure 4. (a) Tunable resonances of CRVCL by varying the coupling of the middle DBR. (b) Measured reflectance of CRVCL which has 11.5 period middle DBR. The arrows denote the cavity resonances.

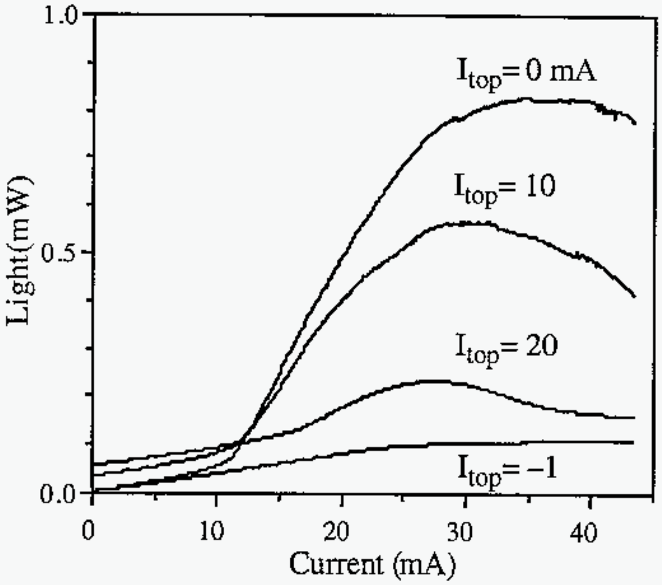

Figure 5. Light from the CRVCL with current injection to the top (passive) cavity.

In Fig. 5 we show the cw light output from a large aperture (20 x 20 μm) CRVCL with injection current into the lower active cavity. A single lasing emission at 997 nm corresponding to the longer resonance in Fig. 4(b) is observed. Lasing emission from only the eigenmode of the lower active cavity is apparent, since the upper passive cavity eigenmode is not adequately pumped even with current injection into the passive resonator (although increased spontaneous emission is observed). Below lasing threshold in Fig. 5, the output increases with current injection into the passive cavity due to increased spontaneous emission. However above lasing threshold, current injection into the passive cavity depresses the index and thus optical path length in the passive cavity leading to a decrease in light output, consistent with the simulation in Fig. 2. Thus the behavior in Fig. 5 conclusively demonstrates that a coupled resonator effect is responsible for the reduction of light output above lasing threshold. The most efficient modulation using forward injection current into the passive cavity is achieved when the active cavity is biased at its maximum power.

A second method of modulation can be accomplished by slightly reverse biasing the top cavity. This leads to complete extinction of the lasing due to cavity enhanced absorption in the top cavity. Using this effect, 50 MHz large signal modulation of the CRVCL has been achieved (limited by measurement apparatus). Note with the bottom active cavity maintained above threshold and employing coupled cavity effects for modulation, chirp-free high speed modulation is possible.

5. CONCLUSIONS

The first electrically injected composite resonator vertical cavity laser is reported. Using an active/passive configuration, we have achieved "external" modulation of the CRVCL using two methods. Forward injection of current into the passive cavity leads to a modification of the optical path length which decreases the light output. Furthermore reverse biasing the passive cavity also enables large signal modulation due to cavity enhanced optical absorption. Other characteristics of the laser can also be modified using coupled cavity phenomena, such as frequency tuning, gain switching, and high speed modulation, which are under investigation.

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