High-Speed Dynamics of GaAsSb Vertical-Cavity Lasers

D. C. Kilper, F. Quochi, J. E. Cunningham, and M. Dinu

***Abstract*—The intensity noise spectrum is measured for antimonide based 1.3 μ vertical-cavity surface emitting lasers. Analysis of the noise spectra indicates a modulation bandwidth of 5.7 GHz with an intrinsic maximum frequency response that exceeds 28 GHz. A discontinuity in the relaxation oscillation resonance frequency is observed, which suggests that the lasing behavior at threshold is assisted by nonlinearities in the gain medium.**

***Index Terms*—Optical communication, quantum-well lasers, semiconductor epitaxial layers, surface-emitting lasers.**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) with emission at long wavelengths (1.3–1.5 μ) have many advantages for use in fiber optic communications. Low cost, high speed, and wafer scale integration are some of the key attributes of VCSELs that have led to their widespread acceptance in short reach applications. The challenges associated with developing long wavelength VCSELs have received much attention [1]–[4]. Novel material systems such as GaAsSb and GaInNAs, which can be grown on GaAs substrates, produce some of the most promising devices [1]–[5]. By incorporating compressively strained GaAsSb quantum wells (QWs) with AlGaAs mirror technology, VCSELs were recently demonstrated with room temperature, continuous-wave (CW) lasing up to 0.7 mW at a 1.28-μ wavelength [5]. Although CW lasing is observed in electrically pumped devices [2], [4], the optically pumped lasers have shown substantially better performance, including differential efficiencies above 14% [5]. The greater control afforded by optical pumping is also well suited for investigating the intrinsic lasing behavior in order to evaluate the potential of these devices. In this letter, we report on the high-speed dynamics of optically pumped antimonide-based VCSELs through measurements of the relative intensity noise (RIN) spectrum. These first measurements of RIN spectra from long wavelength VCSELs demonstrate that these devices are rapidly approaching maturity. The noise spectra are analyzed using a single-mode quantum Langevin theory and a differential gain of $dg/dN = 0.8 \times 10^{-16}$ cm^2 is extracted assuming an internal efficiency of 0.75. pump power dependence of the relaxation oscillation resonance and the damping rate indicate an intrinsic modulation bandwidth of 5.7 GHz for operation at 1.49 times threshold and a maximum 3-dB bandwidth greater than 28 GHz (K factor $= 0.32$ ns). Detailed measurements also show that the lasing behavior exhibits a nonlinear jump at threshold indicating that the performance is enhanced by a nonlinear mechanism such as self-focusing or saturable absorption.

The GaAsSb VCSELs used in this experiment are similar to those reported previously [5]. Three pairs of 6-nm GaAsSb QWs are situated at the antinodes of a 2 λ cavity. The output mirror is a 27 pair λ/4 AlGaAs stack and the device is pumped through an 11 pair SiO_2–TiO_2 dielectric distributed Bragg reflector (DBR) on the back side. The reflectivities of the top and bottom mirrors are nominally equal. A 674-nm MOPA laser is used as the pump source. The pump laser power is varied with an ND filter wheel and the pump laser spot size is carefully adjusted on the sample. Continuous-wave lasing is only obtained for a narrow range of spots sizes around 6 μm in diameter. Smaller spot sizes increase the spontaneous emission for very low pump powers, as expected, but threshold is never achieved.

The collimated output of the VCSEL is sent through a polarization insensitive optical isolator and then coupled into a multimode optical fiber. The optical fiber is connected to a TEK SA-42 high-speed photodetector, an HP 70951A optical spectrum analyzer, or a power meter depending on the measurement. Care was taken to guard against optical feedback to the VCSEL. The output of the photodetector was amplified by 43 dB with a low noise amplifier (MITEQ AFS44 18 GHz) and analyzed on an HP 70908A 22 GHz rf spectrum analyzer. A 3-dB pad was inserted between the detector and amplifier to reduce ripple in the rf spectrum. The response of the detector and electronics was calibrated using an SLED with a flat, broadband noise spectrum.

The VCSEL studied in this experiment has a threshold pump power of 19.0-mW incident on the laser chip. Assuming an absorption coefficient of 2×10^4 cm^{-1} in GaAs, the pump absorption is 78%. Using the nominal pump spot size of 6 μm, the equivalent threshold current density is $J_{\rm th} = 28$ kA/cm^2 (14.8-mW threshold power). The laser emission is highly single mode (~40-dB sidemode suppression) from threshold up to a pump rate $(R = (P/P_{\rm th}) - 1)$ of 0.49, above which one or more higher order spatial modes begin to lase in addition to the fundamental mode. A maximum output power of 0.519 mW at the output mirror is achieved at a pump rate of 0.89 and a lasing wavelength of 1.28 μ.

The relative intensity noise (RIN) spectra at pump rates of 0.017 (circles) and 0.49 (squares) are shown in Fig. 1 (spectrum analyzer settings: RBW 3 MHz, VB 10 kHz). The spectra have been corrected for the thermal noise and the response of the photodetection electronics. Direct measurement of the pump laser intensity noise revealed that the intensity noise below the

Manuscript received September 18, 2001; revised December 10, 2001.
The authors are with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733 USA (e-mail: dkilper@lucent.com).
Publisher Item Identifier S 1041-1135(02)01853-0.

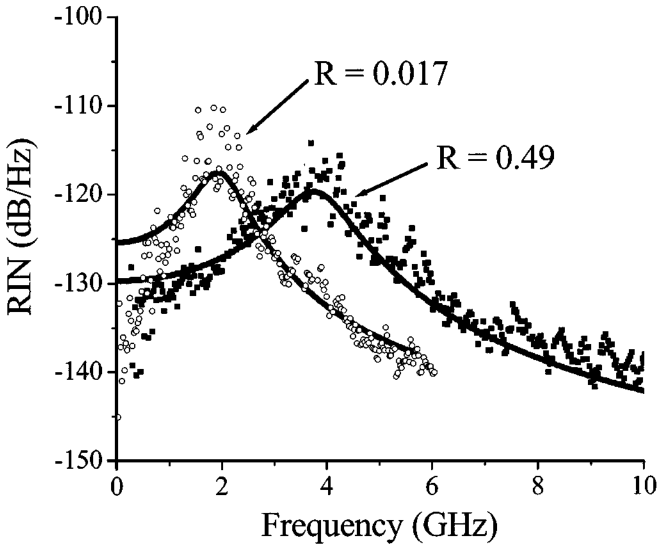

Fig. 1. Relative intensity noise spectra for two laser pump rates ($R = (P/P_{\rm th}) - 1$), 0.017 (circles) and 0.49 (squares). The solid curves are fits generated using a single-mode quantum Langevin theory.

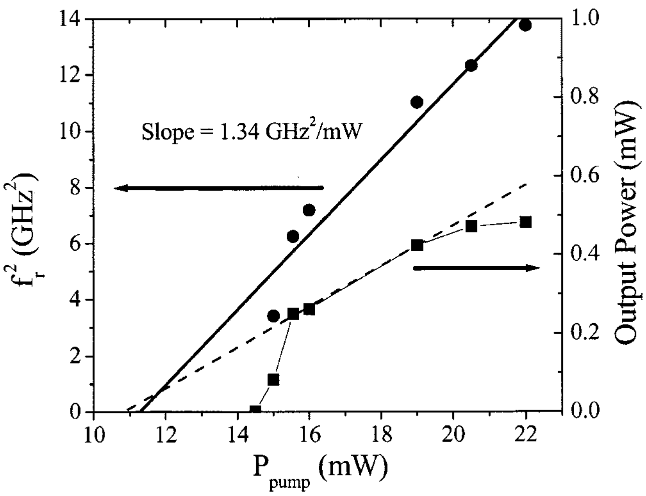

Fig. 2. The VCSEL output power corrected to the output mirror (squares, right axis) for increasing absorbed optical pump power. The dashed line is a linear extrapolation of the above threshold behavior. The square of the relaxation oscillation resonance is also shown (circles, left axis). The solid curve is a linear fit to the data.

relaxation oscillation resonance is dominated by pump noise, as expected. Thus, the intrinisic low frequency intensity noise should be much lower than observed here (in principle near the shot noise level). The solid curves are fit to the data using a single-mode quantum Langevin theory [6]. The corresponding parameters are the spontaneous emission lifetime $\tau_{sp} = 1.5$ ns, differential gain $dg/dN = 0.8 \times 10^{-16}$ cm^2 for $R = 0.49$ and 0.6 $\times$ 10^{-16} cm^2 for $R = 0.017$, equivalent threshold current density $J_{\rm th} = 21$ kA/cm^2 (for a threshold pump power on the surface of the chip of 11 mW), total differential quantum efficiency $\eta_e\eta_i = 7$%, internal differential efficiency $\eta_i = 75$%, and a pump noise level 1400 times shot noise. The differential gain and the pump noise level were the only free parameters used in the fit. The internal efficiency is an estimate based upon values reported in the literature for electrically pumped devices [7] and expecting that this efficiency is higher in optically pumped devices. The spontaneous emission lifetime was obtained from photoluminescence measurements on similar GaAsSb devices [8], [14].

The threshold current density used for the theoretical curves in Fig. 1 is significantly lower than the measured threshold of 14.8 mW (28 kA/cm^2). The measured output power versus pump power at the chip is shown in Fig. 2 (squares, right axis). This curve exhibits a sharp jump at threshold with an unusually high differential efficiency (40%) followed by a more gradual increase, $\eta = 5.6$% (7.2% correcting for pump absorption). Note that taking into account the estimated emission from the backside of this device (based on the mirror reflectivities), the efficiency may be higher by a factor of 1.5.

Also plotted on Fig. 2 is the square of the relaxation oscillation resonance frequency versus pump power (circles, left axis). The square of the resonance frequency is expected to increase linearly with the internal photon density. We find a linear relationship with the pump power indicating a constant internal efficiency. The squared relaxation resonance frequency intercepts the horizontal axis at the threshold pump power. While a linear dependence is observed, the intercept occurs at 11 mW, which is significantly below the observed threshold of 15 mW. The relaxation oscillation resonance exhibits an abrupt jump to 1.9 GHz at threshold, similar to the jump in output power. In fact, if we extend the linear region of the output power as shown by the dashed line, the intercept also occurs near 11 mW. These results indicate that once the laser is above threshold, it operates as though it has a lower threshold than observed. This behavior is repeatable for a given device and qualitatively similar behavior is observed for devices at other locations on the wafer. Furthermore, this jump was not found to be associated with any external feedback effects, nor with slow thermal heating of the chip, which was not temperature controlled.

The observations in Fig. 2 are consistent with a nonlinear reduction of the effective cavity losses. Similar behavior in other devices has been attributed to effects such as self-focusing and saturable absorption [9]–[11]. The spatial mode properties are likely to be dominated by the formation of a thermal lens, which for optically pumped devices is due to nonradiative recombination and absorption of stimulated emission, both in the active region. We calculate a temperature increase of 17 °C at the center of the pump spot relative to the surrounding material, based upon the absorbed pump power at threshold. The nonlinear jump at threshold is characteristic of a decrease in losses due to self-focusing effects and spatial hole burning. Both thermal lens formation and self-focusing are dependent on carrier spreading, and therefore, may also be related to the observed pump spot size sensitivity for CW lasing, as described above. Based upon photoluminescence versus temperature measurements on similarly grown structures, the defect densities are expected to be low for these devices, and therefore, saturable absorption is less likely to be important. Likewise, photoluminescence measurements indicate that the type II QW band alignment should not exhibit dramatic changes for the carrier densities present at threshold [8], [14]. Nevertheless, its not clear what role the band alignment plays in effects such as gain clamping and hole burning [12]. This material system continues to exhibit complex lasing properties [7]. A

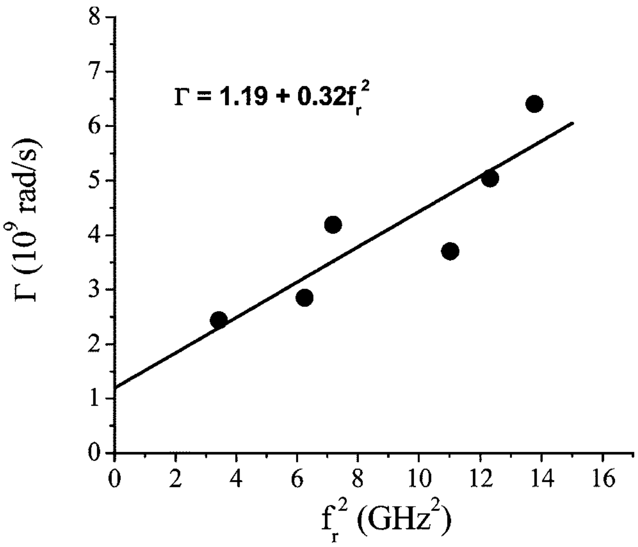

Fig. 3. Damping rate versus the square of the relaxation oscillation resonance. The linear fit is used to determine the K factor 0.32 ns.

complete understanding of these effects will be important in the development of GaAsSb VCSELs.

The parameters for the theoretical curves in Fig. 1 were adjusted to account for this nonlinear jump at threshold. The effective threshold current density of 21 kA/cm^2 and the 7% differential efficiency both reflect this change. The pump rates used for the theoretical fits were also adjusted for the lower effective threshold to be 0.36 and 0.95 corresponding to 0.017 and 0.49, respectively. Thus, the theoretical curves are generated using the lasing parameters for the laser behavior above threshold.

Using the linear fit to the square of the relaxation oscillation frequency in Fig. 2, a differential gain of 0.8×10^{-16} cm^2 is obtained. The maximum relaxation oscillation frequency is 3.7 GHz, observed at pump rate of 0.49 (0.95 corrected). Above this pump rate, the laser is multimode and the intensity noise spectrum broadens significantly, becoming multipeaked. The 3- dB modulation bandwidth can be related to the relaxation oscillation frequency and the damping rate. We obtain a modulation bandwidth of 5.7 GHz for the 0.49 pump rate. This bandwidth is intrinsic to the VCSEL and does not include the effect of parasitics that must be considered for electrical pumping.

The damping rate is related to the width of the relaxation oscillation resonance and was extracted by fitting the intensity noise spectra [13]. A reasonable value can only be obtained for single-mode operation with the assumption of low nonlinear transport effects. Thus, we only fit the data up to a pump rate of 0.49, and the values that we obtain are an upper limit on the damping. The spectra show evidence of additional broadening due to nonlinearities. The damping rate is related to the relaxation oscillation resonance through a simple formula: $\Gamma = 1/\tau_{sp} + K f_r^2$, where τ_{sp} is the spontaneous emission lifetime and f_r is the relaxation oscillation frequency, and K is the so called K factor [10]. Fig. 3 shows the damping rate plotted versus the square of the relaxation oscillation frequency. The spread in the data is likely to be due to the nonlinear effects mentioned above, as well as the uncertainty in fitting the intensity noise curves. The linear fit shown in Fig. 3 yields a spontaneous emission rate of 0.84 ns and $K = 0.32$ ns. The standard deviation from the fit is 0.76 Grad/s. From the K factor we calculate the maximum 3-dB modulation bandwidth to be $2\pi\sqrt{2}/K = 28$ GHz, which should be taken as a lower limit.

Measurements of the intensity noise spectra from GaAsSb VCSELs demonstrate the strong potential of this material system. The intrinsic frequency response of these devices was measured to 5.7 GHz with a maximum limit calculated to be greater than 28 GHz. A jump in the relaxation oscillation resonance frequency indicates that a strong nonlinear mechanism is playing a role in the threshold behavior and more progress is required to understand the lasing in this complex material system.

ACKNOWLEDGMENT

The authors would like to thank J. Shah for his valuable contributions to this research.

REFERENCES

[1] C. W. Coldren, M. C. Larson, S. G. Spruytte, and J. S. Harris, “1200 nm GaAs-based vertical cavity lasers employing GaInNA’s multiquantum well active regions,” *Electron. Lett.*, vol. 36, pp. 951–952, 2000.
[2] M. Yamada, T. Anan, K. Kurihara, K. Nishi, K. Tokutome, A. Kamei, and S. Sugou, “Room temperature low-threshold CW operation of 1.23 μm GaAsSb VCSEL’s on GaAs substrates,” *Electron. Lett.*, vol. 36, pp. 637–638, 2000.
[3] K. D. Choquette, J. F. Klem, A. J. Fischer, O. Blum, A. A. Allerman, I. J. Fritz, S. R. Kurtz, W. G. Breiland, R. Sieg, K. M. Geib, J. W. Scott, and R. L. Naone, “Room temperature continuous wave InGaAsN quantum well vertical-cavity lasers emitting at 1.3 μm,” *Electron. Lett.*, vol. 36, pp. 1388–1390, 2000.
[4] M. Dinu, J. E. Cunningham, F. Quochi, and J. Shah, “Characterization of GaAsSb/GaAs quantum wells for 1.3 μm VCSELs,” in *OSA Trends in Optics and Photonics (TOPS) Conf. Lasers and Electro-Optics (CLEO 2001)Technical Dig. Postconf. Edition*. Washington, DC: Optical Society of America, vol. 56, pp. 35–36.
[5] F. Quochi, D. C. Kilper, J. E. Cunningham, M. Dinu, and J. Shah, “Continuous-wave operation of a 1.3 μm GaAsSb/GaAs quantum-well vertical-cavity surface-emitting laser at room temperature,” *IEEE Photon. Technol. Lett.*, vol. 13, pp. 921–923, Sept. 2001.
[6] Y. Yamamoto, S. Machida, and O. Nilsson, “Amplitude squeezing in a pump-noise-suppressed laser oscillator,” *Phys. Rev. A*, vol. 34, pp. 4025–4042, 1986.
[7] S.-W. Ryu and P. D. Dapkus, “Low threshold current density GaAsSb quantum well (QW) lasers grown by metal organic chemical vapor deposition on GaAs substrates,” *Electron. Lett.*, vol. 36, pp. 1387–1388, 2000.
[8] J. E. Cunningham, M. Dinu, J. Shah, F. Quochi, D. C. Kilper, W. Y. Jan, and J. Perna, “Growth and optical properties of GaAsSb quantum wells for 1.3 μm VCSEL,” J. Vac. Sci. and Technol. B, to be published.
[9] J. H. Shin, J. K. Hwang, K. H. Ha, and Y. H. Lee, “Anomalous above-threshold spontaneous emission in gain-guided vertical-cavity surface-emitting lasers,” *Appl. Phys. Lett.*, vol. 68, pp. 2180–2182, 1996.
[10] J.-P. Zhang and K. Petermann, “Beam propagation model for vertical-cavity surface-emitting lasers: Threshold properties,” *IEEE J. Quantum Electron.*, vol. QE-30, p. 1529, 1994.
[11] G. C. Wilson, D. M. Kuchta, J. D. Walker, and J. S. Smith, “Spatial hole-burning and self-focusing in vertical-cavity surface-emitting laser diodes,” *Appl. Phys. Lett.*, vol. 67, p. 314, 1995.
[12] W. W. Chow and H. C. Schneider, “Charge-separation effects in 1.3 mm GaAsSb type-II quantum-well laser gain,” *Appl. Phys. Lett.*, vol. 78, pp. 4100–4102, 2001.
[13] J. D. Ralston, S. Weisser, I. Esquivias, E. C. Larkins, J. Rosenzweig, P. J. Tasker, and J. Fleissner, “Control of differential gain, nonlinear gain, and damping factor for high-speed application of GaAs-based MQW lasers,” *IEEE J. Quantum Electron.*, vol. 29, pp. 1648–1658, June 1993.
[14] T. Anan, M. Yamada, K. Nishi, K. Kurihara, K. Tokutome, A. Kamei, and S. Sugou, “Continuous-wave operation of 1.30 μm GaAsSb/GaAs VCSELs,” *Electron. Lett.*, vol. 37, pp. 566–567, 2001.