Harmonic Distortion in 1.55-μm Vertical-Cavity Lasers

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***Abstract*—We investigate second and third order harmonics in the analog modulation response of InP–GaAs fused 1.55-μm vertical-cavity lasers (VCLs). These devices exhibit the lowest threshold current as well as the highest temperature of continuous-wave operation of any electrically pumped long wavelength VCL. Near the resonance frequency, harmonic distortion is dominated by electron–photon interaction, and it is close to the distortion measured with in-plane lasers. At low frequencies, distortions seem to be dominated by carrier transport effects. At 1 GHz modulation frequency, we measure a maximum spur-free dynamic range of 64 dB Hz$^{1/2}$ for second-order harmonic distortion and 81-dB Hz$^{2/3}$ for third-order harmonic distortion.**

***Index Terms*—Harmonic distortion, optical fiber communication, optical modulation, semiconductor lasers, surface-emitting lasers.**

I. Introduction

Long-wavelength vertical-cavity lasers (VCLs) operating at 1.3-m or 1.55-μm wavelength are potentially low cost light sources for optical communication and transmission systems. Direct analog laser modulation is of interest with applications like cable television, base station links for mobile communication, and antenna remoting. Laser performance requirements include high slope efficiency, low noise, and high linearity to achieve a large dynamic range. Currently, in-plane distributed-feedback (DFB) lasers are mainly used in single-mode analog applications. However, DFB lasers suffer from nonlinear distortions that severely restrict the dynamic range. Distortions in DFB lasers are often related to longitudinal hole-burning effects. VCLs are free from longitudinal hole burning and promise lower distortion. In this letter, we investigate second and third order harmonic distortion, i.e., additional output signals at double and triple the input modulation frequency, respectively.

Fig. 1 shows our top-emitting VCL. The strained InGaAsP/InP multiquantum well (MQW) active region is sandwiched between two AlGaAs–GaAs distributed Bragg reflectors (DBRs). The first AlGaAs layer of the p-doped top DBR is laterally oxidized for optical and electrical confinement. Here we investigate devices with 5-μm oxide aperture. Single-mode lasing is observed at 1507-nm wavelength. The near-field diameter is about 5 μm, i.e., the fundamental mode is well confined by the oxide layer. The continuous-wave (CW) lasing power versus current ($L - I$) characteristic is given in Fig. 2 as well as the voltage versus current ($V - I$) curve. The maximum output power is restricted by self-heating. The low slope efficiency of 6.4% could be improved by reducing the number of top-DBR layers, but this would lead to higher threshold current and stronger self-heating. Further details of VCL fabrication and performance are described elsewhere [1].

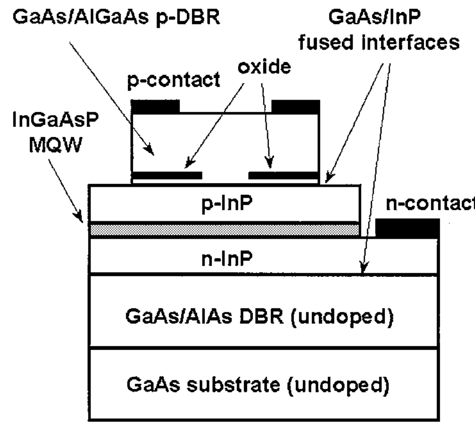

Fig. 1. Schematic view of our 1.55 μm vertical-cavity laser.

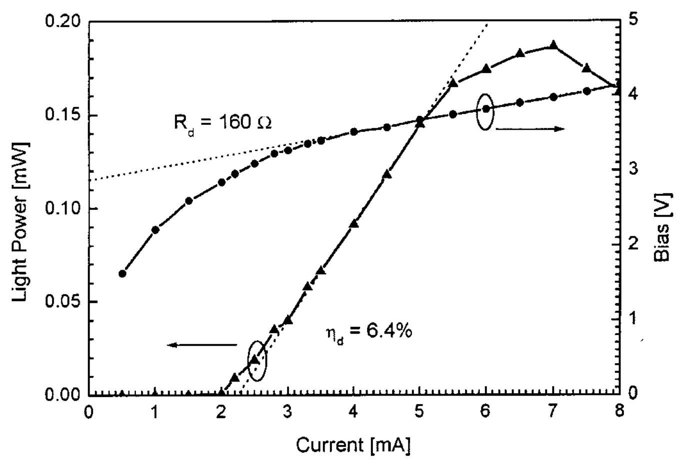

Fig. 2. Light–current ($L - I$) and voltage–current ($V - I$) characteristics measured (R_d is differential resistance and η_d is slope efficiency).

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For our analog modulation measurements, the devices are packaged using 25-mil-thick quartz with coplanar structure for microwave propagation. Short ribbon bonds connect the VCL to the package. The microwave signals are generated by a HP 8340B-synthesized sweeper with a frequency range from 0.1 to 26.5 GHz. The microwave signal and the dc current are connected to the laser via a bias tee. A 6 dB attenuator is placed after the signal generator output to reduce signal reflections from the laser. The laser light is coupled into a single-mode fiber through a Thor-Lab lens (numerical aperture 0.6). The fiber output is fed into a HP 70810A spectrum analyzer to characterize the analog signal received from the VCL.

Fig. 3 shows the ac output power versus modulation frequency f for the fundamental signal, the second-harmonic distortion (2HD), and the third harmonic distortion (3HD), respectively. The dc injection current is $I = 2.5$ mA and the current modulation depth is $m = 0.01$. The measured fundamental signal $P_1(f)$ is analyzed using the response function [2]

$$\left|\frac{P_1(f)}{P_1(0)}\right|^2 = \frac{|M(f)|^2}{1+(f/f_c)^2} = \frac{f_r^4}{(f_r^2-f^2)^2+(\gamma f/2\pi)^2} \times \frac{1}{1+(f/f_c)^2}. \tag{1}$$

The fit results in the electron–photon resonance frequency $f_r =$ 1.7 GHz, the damping constant $\gamma = 2.3$ GHz, and the cut-off frequency $f_c = 0.5$ GHz. Parasitic effects are responsible for the low cutoff frequency, which we mainly attribute to the capacitance of the contact pad. We calculate 2HD and 3HD using formulas from a perturbation analysis of the small-signal rate equations [3] and including parasitic effects

$$\left|\frac{P_2(f)}{P_1(0)}\right| = \frac{m|M(f)|^2}{\sqrt{1+(2f/f_c)^2}}\,|M(2f)|\left(\frac{f}{f_r}\right)^2 \tag{2}$$

$$\left|\frac{P_3(f)}{P_1(0)}\right| = \frac{1.5\,m^2|M(f)|^3}{\sqrt{1+(3f/f_c)^2}}\,|M(2f)|\;|M(3f)| \cdot\left[\left(\frac{f}{f_r}\right)^4+\frac{1}{2}\left(\frac{f}{f_r}\right)^2\right]. \tag{3}$$

The optical modulation depth is given by $m \times |M(f)|$. The calculated distortion curves in Fig. 3 are in good agreement with the measurement. This suggests that harmonic distortions in our VCLs are close to those in typical in-plane lasers [3]. In general, distortions near the resonance frequency are governed by stimulated recombination within the quantum wells (dynamic or intrinsic distortion). Static distortion caused by the nonlinearity of the $L-I$ characteristic is less important in this frequency range. Both the higher order harmonics in Fig. 3 exhibit multiple peaks. The common peak at f_r is caused by the general enhancement of the output spectrum at electron–photon resonance. Additional peaks occur at $f_r/2$ and $f_r/3$ input frequency, respectively, when 2HD and 3HD match the resonance frequency. In the case of the 3HD signal, the peak at $f_r/3$ is combined with another peak at $f_r/2$ from the 2HD resonance. With frequencies well below $f_r/3$, the intrinsic distortion drops by 40 dB/decade for both the distortion signals [4].

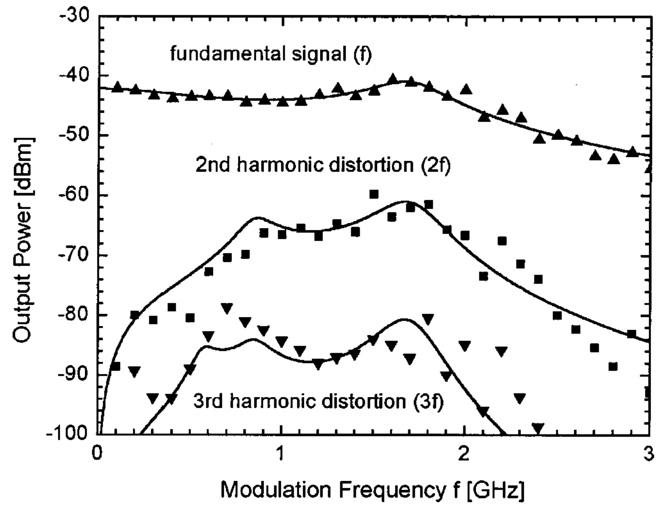

Fig. 3. Fundamental modulation response and harmonic distortions versus modulation frequency with 2.5-mA dc input current and 0.01 current modulation depth (dots: measurements; lines: calculation).

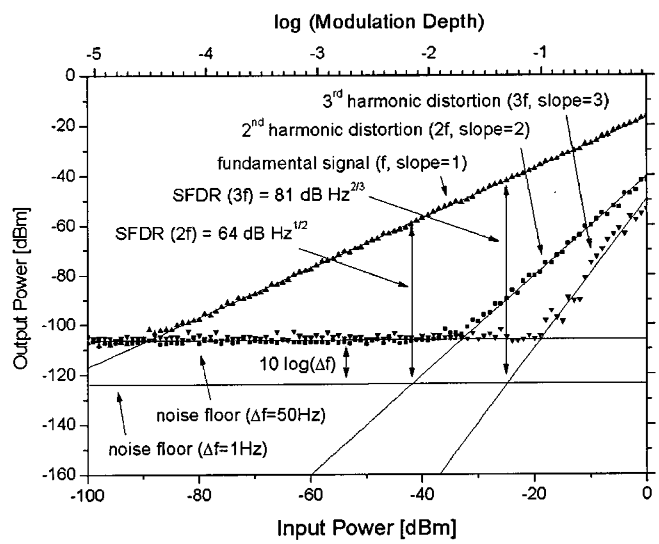

Fig. 4. Measured ac output power at different frequencies (f, $2f$, $3f$) versus ac input power and modulation depth (dc current 4 mA, modulation frequency 1 GHz). Lines illustrate the extraction of the spurious-free dynamic range SFDR for second- and third-order harmonic distortion.

Higher order harmonics are not desirable in most applications. The strong distortion range shown in Fig. 3 should be moved to frequencies well above the application frequency by increasing the injection current I. The resonance frequency increases as $f_r^2 = b(I - I_{\mathrm{th}})$ with I_{th} giving the threshold current. We measure $b = 13.5$ GHz^2/mA, which is substantially higher than with in-plane lasers due to the lower active volume of VCLs. Raising our dc current to 4 mA moves the resonance frequency to $f_r = 5$ GHz so that typical analog modulation frequencies up to 1 GHz are less affected by intrinsic distortion. For this case, Fig. 4 shows the ac output power at all three frequencies as function of modulation depth and ac input power. The 2HD and 3HD signals, respectively, vary as the square and the cube of the ac input power. The maximum dynamic range of the fundamental signal is obtained when the distortion signal is equal to the noise floor. It is 53 dB and 68 dB for 2HD and 3HD,

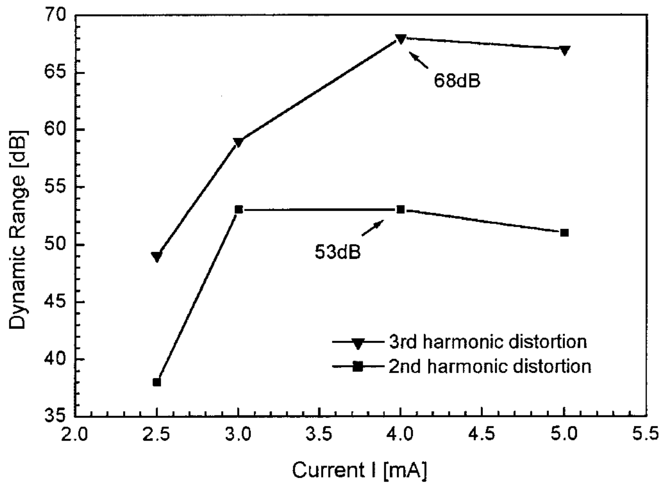

Fig. 5. Dynamic range (not SFDR) at 1-GHz modulation frequency for different input currents (as extracted from measurements like in Fig. 4).

respectively. Since the noise floor depends on the measurement bandwidth ($\Delta f = 50$ Hz), the spurfree dynamic range (SFDR) is given corresponding to $\Delta f = 1$ Hz. For 2HD and 3HD, respectively, we find SDFR = 64 dB Hz$^{1/2}$ and 81 dB HZ$^{2/3}$ (Fig. 4). The measured noise level is typical for VCLs. However, it is higher than for typical DFB lasers. The reasons are not yet fully understood in our case. In general, the relative intensity noise of VCLs is higher than in in-plane lasers due to lower output power and polarization instability, especially in polarization sensitive applications [5]. On the other hand, VCL noise was found to be less sensitive to external feedback than with in-plane lasers [6].

Fig. 5 shows that an input current of $I = 4$ mA is optimum to achieve a maximum dynamic range with our device. At the lowest current of 2.5 mA, the dynamic range is small since our target frequency of 1 GHz is within the region of high distortion (Fig. 3). With higher injection current, the strong distortion region moves away from 1 GHz and the dynamic range increases. However, our dynamic range does not continue to increase with higher current as expected for purely intrinsic distortion. Its saturation indicates the dominance of other nonlinear effects. The $L - I$ nonlinearity is known to dominate distortion's at low frequencies. Such nonlinearity may be caused by leakage currents or lateral spatial hole–burning. We observe a stable fundamental mode in these measurements, and lateral hole burning is assumed negligible with our low output power. In principle, VCLs are known to be sensitive to lateral hole burning which is expected to affect distortion at higher output power. In contrast to in-plane lasers, VCLs have no separate confinement layers and therefore exhibit less vertical leakage. At high temperatures, however, electron leakage from the quantum wells increases and contributes to the $L - I$ rollover (Fig. 2). Another source of nonlinearity at low frequencies is the fused p-GaAs–p-InP interface. Ionized donor-type interface defects with densities on the order of 10^{13} cm^{-2} are believed to create a potential spike within the valence band [7]. Holes need to cross this barrier by thermionic emission or tunneling. Thus, hole injection improves with higher temperature but lateral current spreading at this barrier causes a significant part of the injection current to be lost. All these transport effects change with the current injection level, and they seem to dominate the static harmonic distortion in our present devices.

Directly comparable measurements on in-plane lasers are hard to find in the literature. At 1-GHz modulation frequency, 2HD measurements on 1.3-μm DFB lasers gave static distortion of about -40 dB for $m = 0.1$ modulation depth [8]. From Fig. 4, we extract the same distortion for our VCLs. With DFB lasers, low distortion is often achieved only at discrete frequencies or bias points when different nonlinear mechanisms cancel each other [9]. With further improvements of our 1.55-μm VCLs, in particular of the fused GaAs-InP interface, we expect to accomplish low distortion over a wider frequency and bias range.

In summary, we have performed the first experimental analysis of second and third order harmonic distortion in long wavelength VCLs. Both intrinsic and static distortion levels measured are similar to results on in-plane lasers. Static distortion in our devices seems to be dominated by carrier transport effects.

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