Long wavelength, vertical-cavity surface-emitting lasers (VCSELs) operating at 1.3 and 1.55 µm wavelengths have been the focus of much research recently as potentially low cost sources for optical communications. The best performance has been demonstrated using AlGaAs/GaAs mirrors fused to InGaAsP active regions,1 with submilliamp thresholds, high efficiencies, and a lifetime of over 3000 h.2

Transmission of digital signals over optical fiber for use in telecommunications applications has been demonstrated with these devices.3,4 1.5 µm VCSEL transmission at 2.5 Gb/s over 200 km of fiber was demonstrated.5 Much investigation has been done into short wavelength (840–980 nm) VCSELs,6–8 including the characterization of analog transmission.9 Transmission of analog signals from long wavelength devices, however, has not yet been analyzed. In this letter, we present the results of the first reported analog transmission experiments for such devices. The lasers exhibited reasonable values of dynamic range and low intermodulation distortion. This points to the potential use of VCSELs for CATV (cable television) employing optical fibers in commercial and other applications involving microwave signal transmission.

The lasers used in our measurements were double-fused, laterally oxidized VCSELs with 14 µm diameter active region apertures in 50 µm diameter pillars as reported in Ref. 1. These multimode devices were designed for high output power and generate up to 1 mW of continuous-wave (cw) light output power at 15 °C and operate cw up to a base temperature of 50 °C.1 The bottom-emitting devices were placed on a brass conducting plate which was maintained at a constant 15 °C via a thermocouple and LDT-5412 temperature controller. Electrical contact was made directly by a 20 µm probe tip on the top p side, while the bottom n substrate was grounded to the stage with conducting paste. The lasers in use were centered over a 5 mm hole in the stage through which the laser illumination was coupled into an angle-polished single-mode fiber via a GRIN (graded-index) lens.

A maximum coupled output of 180 µW was achieved at a bias of 14 mA. The fiber output was then connected to an erbium-doped optical fiber amplifier (EDFA) to strengthen the signal power. Since an amplifier was used, no special effort was taken to achieve the maximum coupling efficiency during the rf measurements. Consequently only 18 µW of output power was coupled through the fiber at a dc bias of 14 mA. A tunable filter (operating range 1.530–1.560 µm) was used to reduce RIN from the EDFA. Using the EDFA, the coupled laser output was amplified to the maximum reading of the lightwave multimeter (~1900 µW). The microwave signals were generated by an HP 8340B synthesized sweeper (range 10 MHz–26.5 GHz), connected to the dc current source input via a bias tee. A 6 dB attenuator was placed after the signal generator output to reduce signal reflections from the laser. The fiber output from the tunable filter was connected to an HP 70810A lightwave spectrum analyzer to characterize the analog signal received from the VCSEL.

To determine device parameters such as intermodulation distortion and dynamic range, a second signal generator was connected with the first signal generator via a combiner. The combined inputs were then connected to the 6 dB attenuator and bias tee. Two signals of equal power but different frequency were applied to the laser. Figure 1 shows the spectrum of two input signals at a power of ~16 dBm each. The particular laser used in this measurement had a threshold current of 8 mA. The dc bias point was set at 9.4 mA. Referring again to Fig. 1, the two input signals are at 200 and 208 GHz, connected with the first signal generator via a combiner. The combined inputs were then connected to the 6 dB attenuator. A 6 dB attenuator was placed after the signal generator output to reduce signal reflections from the laser. The fiber output from the tunable filter was connected to an HP 70810A lightwave spectrum analyzer to characterize the analog signal received from the VCSEL. This spectrum consists of a strong peak at the input signal frequency followed by higher order peaks of decreasing intensity at integer multiples of the input signal frequency.

FIG. 1. Spectrum of two carrier signals and third-order intermodulation peaks.
201 MHz. The side peaks at 199 and 202 MHz are third-order intermodulation peaks. At this particular input signal power and bias point the third-order IM peaks are 48 dB below the carrier signals. The modulation depth for this experiment was \( \sim 10\% \).

For the primary experiment, the input signal generators were set to 100 and 101 MHz, respectively. Using the same device and bias point as in Fig. 1, the amplitudes of the lower third-order IM peak (at 99 MHz) and first-order signal peak (at 100 MHz) were monitored as the input signal power levels of both generators were varied but kept equal. Figure 2 shows the data collected from this experiment (all values in electrical dBm), and measured with a resolution bandwidth of 50 Hz. The dynamic range is determined as a ratio between the first-order carrier signal and the third-order IM distortion power levels. As shown in Fig. 2, the dynamic range has a maximum value of 69 dB at an input power of \(-24\) dBm, when the third-order peak just begins to appear above the \(-86\) dBm noise floor.

In addition to the measurement described above, we also characterized the VCSEL’s harmonic response. This time only a single signal generator was used. At a constant input signal power of \(-26\) dBm, the amplitudes of the first three harmonic peaks were monitored as the signal frequency was varied. Figure 3 shows the data collected from this measurement. The first-order relaxation resonance frequency appears to be around 800 MHz.

This level of linearity is somewhat surprising, given the nonlinear LI curve (Fig. 4). The curve shown in Fig. 4 was measured through a single-mode fiber. The low value of output power measured is due to poor coupling, but is not important for purposes of this measurement. As a reference, the dc bias point (9.4 mA) and input signal amplitude (\(-16\) dBm) from Fig. 1 are indicated. This cw LI curve is clearly very nonlinear. Upon first inspection it is curious how such a nonlinear device could yield such a large dynamic range. It is apparent that the periodic fringes in the LI curve are due to interference between the laser output and reflections off the back of the wafer substrate. These fringes have always been observed under cw operation. We speculate that for an analog modulated signal, however, chirping of the laser frequency causes the reflected mode to be more incoherent, such that there is no longer interference with the output signal. The ac signal linearizes the LI curve and decreases the VCSEL nonlinearities.

Future plans involve device modeling to understand fundamentally what is happening to the device under analog signal transmission. We are also interested in obtaining data from single-mode devices, with lower RIN and less modal interference offering promising improvements. The initial results shown here are a first indication of the potential of VCSELs for analog applications.

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\[2\] N. M. Margalit, K. A. Black, Y. J. Chiu, E. R. Hegblom, K. Streubel, P.


