Optical Interconnects Using Injection-Locked VCSELs

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Abstract: Injection-Locked Vertical Cavity Lasers exhibit drastically enhanced performance. The 3-dB bandwidth can be increased up to 40 GHz, due to a resonance frequency enhancement. Such VCSELs may play a role in future optical interconnects.

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OCIS codes: (140.3520) Injection-locked lasers; (250.7260) Vertical cavity surface emitting lasers

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have the potential to play a major role in 10-40 Gbit/s data links, for applications such as 10 Gigabit Ethernet, and for 40 Gb/s very short reach interconnects. VCSELs are particularly appealing for these applications, as they are very small in size, can be low cost, consume very little power (both DC and RF), and are amenable to heterogeneous integration with CMOS. With increase in popularity, there are many manufacturers providing VCSELs with performance up to 10 Gb/s at 850nm, 1310 nm, and 1550 nm wavelengths.

The modulation bandwidth (in GHz) of a directly modulated laser is one of the most important figures-of-merit that determines the maximum data rate (in Gb/s) achievable in optical communication systems. The state of the art is a 20 GHz bandwidth and 25 Gb/s modulation in a 1.1 \( \mu m \) VCSEL [1], and 10 Gb/s modulation with a 1.55 \( \mu m \) VCSEL [2]. There has been little improvement in speed since the 1997 record (K. Lear) of 21 GHz for an 850 nm VCSEL. A plateau has been reached.

2. High-Speed VCSELs

There are several challenges associated with building a high-speed directly modulated optical source. The modulation response of semiconductor lasers is generally limited by: a) laser intrinsic response/relaxation oscillations, b) carrier dynamics, c) device parasitics, d) driver electronics, and e) packaging.

The most fundamental speed limitation in conventional directly modulated lasers is the rather low (<20 GHz) resonance frequency. The resonance frequency limitation in lasers is due to a relaxation oscillation (RO) between the carrier density and the photon density in the cavity, and is the primary limitation in today’s VCSELs. One method for increasing the laser resonance frequency and modulation bandwidth is the injection locking technique [3]. This topic has been thoroughly investigated by several groups with many types of lasers. Our group has demonstrated a >50 GHz resonance frequency in injection-locked 1.55 \( \mu m \) VCSELs, and a 3 dB bandwidth of >40 GHz [4].

The next limitation in high-speed lasers is the device parasitics, which can be effectively measured using an injection locking difference method [3]. A very effective geometry is the buried tunnel junction device [2], whose success stems from a small device volume, a reduced capacitance, and using a tunnel junction to nearly eliminate the p-doped material.

Typical device experiments probe the lasers with high-frequency (e.g., 50 GHz) microwave probes. This approach provides a good understanding of the device frequency limitations. However, for real commercial systems, the devices need to be packaged and interfaced to driver electronics. While the highest bit-rate VCSEL drivers to date operate at 20 Gb/s [5], CMOS has the potential for much higher frequency operation (e.g. 60 GHz CMOS amplifiers have been demonstrated). Most applications will require a heterogeneously integrated driver-VCSEL, either using a wire-bonding approach, or by flip-chip bonding.

The success of future VCSELs will require careful CAD simulations (using e.g., Crosslight Inc. software), including optical gain, carrier dynamics, device parasitic, laser thermal properties, microwave signal delivery, and packaging. Provided that the limitations in VCSEL bandwidths can be overcome, perhaps by using injection locking, VCSELs will play a major role in future 10-40 Gb/s optical interconnects.

6. References