Dynamic Range of Vertical Cavity Surface Emitting Lasers in Multimode Links

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Abstract— We report spurious free dynamic range measurements of 850nm vertical cavity surface emitting lasers in short multimode links for radio frequency communication. For a 27m fiber link, the dynamic range at optimal bias was greater than $95\text{dB-Hz}^{2/3}$ for modulation frequencies between 1 and 5.5 GHz, which exceeds the requirements for antenna remoting in microcellular networks. In a free space link, we have measured the highest dynamic range in an 850nm vertical cavity surface emitting laser of $113\text{dB-Hz}^{2/3}$ at 900MHz. We have also investigated the effects of modal noise and differential mode delay on the dynamic range for longer lengths of fiber.

Index Terms— Surface-emitting lasers, semiconductor lasers, optical fiber communication, optical modulation.

I. INTRODUCTION

Multimode fiber and vertical cavity surface emitting lasers (VCSELs) can be a solution for high speed optical communications such as intrabuilding antenna remoting for picocellular networks[1],[2] which can take advantage of the existing multimode fiber infrastructure for data communication. The spurious free dynamic range (SFDR) is a useful measure to characterize how third order intermodulation distortion (IMD3) caused by non-linearities in the modulated VCSEL limits system performance. While multimode links, in contrast to links using single mode fiber, enjoy the benefits of more relaxed mechanical tolerances and simpler packaging, they suffer from differential mode delay (DMD) and modal noise. DMD reduces the modal bandwidth and hence limits the distance bandwidth product of the optical link while modal noise can severely degrade the signal to noise ratio in the presence of mode selective losses. We report SFDR measurements of VCSELs spanning a frequency range of 600MHz to 10GHz to investigate their suitability for analog link applications and to investigate the performance of multimode links using these devices.

II. EXPERIMENT

Standard two-tone intermodulation distortion measurements were performed on short optical links employing a $10\mu\text{m}$ 850nm dual oxide aperture VCSEL[3]. The VCSEL was driven by two RF synthesizers (HP83712B) with a

Fig. 1. Output power vs. Input power for a typical dynamic range measurement.

frequency separation of 2MHz, and butt coupled to a length of multimode fiber. The output was coupled to a $10\mu\text{m}$ InGaAs PIN detector ($.27\text{A/W}$ responsivity)[4] or a commercial GaAs detector (ABB HAFO 1A354) in a TO-46 lensed can ($.42\text{A/W}$ responsivity) and measured with an RF spectrum analyzer (HP3566B). To measure the noise floor, the modulation was turned off and the noise amplified with a high gain, low noise amplifier (Miteq JS4-00401800-26-5P) which improved the system sensitivity to better than -164 dBm/Hz . The noise floor was calculated from the measured spectral density, assuming a 1 MHz measurement bandwidth. Fig. 1 shows typical output power vs. input power data from which we calculate the dynamic range. The dynamic range is defined as the input power range over which the fundamental is detectable above the noise floor while the third order intermodulation distortions are below the noise floor. The intrinsic SFDR of the intermodulation test system, measured without the optical link, was $118\text{dB-Hz}^{2/3}$, which is well above the dynamic ranges measured for the link. Link measurements were performed on a short, 27m fiber link, a directly coupled free space link, and a long 150m fiber link.

A contour plot of the SFDR for the 27m link composed of two fibers 14m and 13m long joined by a mating sleeve is shown in Fig. 2. For such short links, where modal dispersion is negligible, the shape of the SFDR is dominated by the intrinsic resonance of the device at high frequencies and modal noise at low frequencies.

At high frequencies, the modulation response is due to the carrier and photon dynamics in the semiconductor laser

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Fig. 2. Spur-free dynamic range for the 27m fiber link. The dashed line highlights the roll off in dynamic range due to resonant enhancement of the intermodulation distortion. The data has been smoothed by a weighted nine point moving average to clarify the features.

Fig. 3. Spur-free dynamic range for the freespace directly coupled link. The dashed line is a contour of constant dynamic range of $106\text{dB-Hz}^{2/3}$.

and can be described by rate equations that are coupled strongly through the semiconductor gain medium. This coupling gives rise to a relaxation oscillation resonance which enhances intermodulation distortions [5] and causes a roll off in SFDR highlighted by the dotted line in Fig. 2. The relaxation oscillation frequency initially increases with bias current as the photon density increases, and then becomes lower at high bias because device heating causes the material gain to detune from the cavity resonance. This causes the threshold carrier density to increase, which leads to a lower photon density and carrier lifetime, lower differential gain, and a subsequently lower relaxation oscillation resonance frequency. This emphasizes the importance of designing lasers with relaxation oscillation frequencies well above the application bandwidth to avoid resonant distortion, meaning the design constraint for intrinsic device speed is more stringent than avoiding parasitic bandwidth limitations since these can roll over at the application bandwidth.

At low frequencies, the link noise floor is raised due to modal noise from the mode-selective loss where the fiber is butt coupled to the VCSEL [6]. The noise power spectral density at low frequencies rises when the bias increases beyond 7mA because the VCSEL begins to lase in transverse modes that emit into a larger numerical aperture and do not couple completely into the fiber, introducing a mode selective loss. Modal noise degrades the signal to noise and dynamic range of multimode links at low frequencies and high bias currents, which is apparent in Fig. 2 where the dynamic range rolls off toward lower

Fig. 4. Spur-free dynamic range for the 150m link. The nulls in the dynamic range are due to differential mode delay where mode groups in the multimode fiber with different propagation delays interfere destructively at the detector. The data has been smoothed by a weighted nine point moving average to clarify the features.

frequencies. This result was observed clearly in television transmission experiments with these links. The picture quality was degraded when the laser bias was increased above 7mA and a mode selective loss was introduced. In a free space link where mode selective losses were reduced, clear transmission was observed over a much larger bias range. At frequencies above a few gigahertz, the modal noise spectral density falls off and the overall noise spectrum is determined by the intensity noise of the laser. A prime concern for link designers when considering multimode fiber is the effect of mode selective loss with the addition of connectors. Measurements were carried out in short links with 0-4 connectors, each spaced approximately 5 meters apart. The dynamic range was found to be insensitive to the addition of connectors. This is because the most severe mode selective loss occurred at the butt coupling of the fiber the VCSEL so the additional connectors did not have a significant effect.

The combination the high frequency roll-off due to resonant distortion and modal noise at low frequencies results in a modest local maximum in the SFDR that peaks at $96\text{dB-Hz}^{2/3}$ at 3.9GHz with a 20mA bias current for the 27m fiber link.

Because SFDR is a complete link measurement, it depends on many parameters including laser linearity, RF source linearity, photodetector linearity, and in the case of links that are not RIN limited, photodetector responsivity and coupling efficiency. It was of interest to gauge the intrinsic linearity of the VCSEL independent of coupling losses and photodetector response, so free space measurements were performed with the commercial GaAs PIN detector with higher responsivity. This allowed a higher coupling efficiency that reduced mode selective losses and modal noise. The bandwidth of the detector was approximately 5GHz, which was sufficient to examine the high dynamic range region of operation in Fig. 2.

A contour plot of the dynamic range is shown in Fig. 3. In this case, the dashed line encircles a region where the dynamic range was greater than $106\text{dB-Hz}^{2/3}$, which meets the requirements of applications in this frequency range such as local CATV distribution ($\text{CTB} = -53\text{dB} \sim 106\text{dB-Hz}^{2/3}$ [7],[8]) and antenna remoting in PCS networks ($82\text{dB-Hz}^{2/3}$ [2]). The reason for the relatively large differences in overall dynamic range for the fiber and

freespace link is that the link noise floors were not RIN limited and improving the coupling efficiency and detector responsivity raised the signal levels more than the noise floor. For the 12dB improvement in link gain between the free space and fiber measurements, we saw a gain in dynamic range of approximately 8dB. At low frequencies, the improvement was higher because of the reduction of modal noise in the free space case. The peak dynamic range was 113dB-Hz^{2/3} at 900MHz and 15mA bias. These dynamic ranges are the highest measured for a VCSEL and are comparable to those measured in Fabry-Perot and DFB edge emitters[9]. This implies link performance is not limited by the dynamics intrinsic to the device, but rather a consequence of its multi-transverse mode operation. For a 150m link, the effects of modal dispersion are apparent in the SFDR contour plot shown in Fig. 3. The valleys in the SFDR around 4 and 8 GHz were caused by interference between mode groups with different propagation delay that were excited by the VCSEL. Because the transverse mode profile changes with bias, the depth and position of the nulls changed as the bias current increased. This problem with differential mode delay (DMD) has been studied previously [10],[11] and it was found that controlling the launch condition into the fiber could extend the modal bandwidth. These results were obtained by launching light from a single mode fiber into the multimode fiber with well controlled offsets to selectively excite mode groups with similar propagation delay. In our case, butt coupling a multi-transverse mode VCSEL into a multimode fiber did not allow sufficient control over the launch condition to overcome the modal bandwidth of the fiber and while the frequency response did change with the launch condition, for this 150m link, the bandwidth was limited to approximately 2.5GHz for applications requiring greater than 85dB-Hz^{2/3} dynamic range. The overall dynamic range was lower for this 150m link because the roll over in the fundamental response due to the modal bandwidth of the fiber counteracted the decrease in modal noise with increasing frequency.

III. CONCLUSIONS

We have measured the SFDR in 850nm VCSELs over a wide frequency range to determine their suitability for analog link applications. Link performance was limited by the multi-transverse mode operation of the VCSEL and its intrinsic resonance. The multimode operation of these VCSELs for bias currents above a few times threshold degraded the signal to noise and dynamic range at frequencies below a few gigahertz.

While modal noise was not significant for bias currents below a few times threshold, the dynamic range suffered because the relaxation oscillation resonance was closer to the signal band and resonant enhancement of the intermodulation products degraded signal fidelity. The tradeoff between modal noise and resonant distortion lead to an optimal operating region for these VCSELs which ranged from approximately 1 to 5 GHz for links where the bandwidth was not limited by the modal bandwidth of the fiber. The measured dynamic range was found to exceed

95dB-Hz^{2/3} at optimal bias for frequencies between 1GHz and 5.5GHz for the short 27m link, and for the 150m link, where the bandwidth was limited by the modal bandwidth of the multimode fiber, the dynamic range was greater than 85dB-Hz^{2/3} for frequencies between 600MHz and 2.6GHz. This performance exceeds the requirements for antenna remoting for PCS networks in fiber lengths useful for in-building applications. For a free space link where coupling losses were reduced and a higher responsivity detector was used, the dynamic range exceeded 106dB-Hz^{2/3} from 100MHz to 3GHz with a peak dynamic range of 113dB-Hz^{2/3} at 900MHz. This is the highest dynamic range measured for a VCSEL and suggests that link performance is not fundamentally limited by the dynamics of the device. VCSELs which emit into a smaller numerical aperture for more efficient coupling can improve the performance of low frequency applications. Overall, devices with high single mode output powers will improve modal noise performance and allow sufficient mode control to overcome the modal bandwidth of the fiber.

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