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Modal Noise Penalties for Data Communication Links Employing Large Area VCSELs

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Abstract

For the first time, high mode selective loss (MSL) margins for large area VCSELs are theoretically justified. Calculated speckle visibility and power penalties agree with experiment. The predicted power penalty at 10^{-9} BER for a VCSEL link, employing 62.5/125 fibre, with six connectors, each with 1 dB MSL, is 0.75 dB.

Introduction

The data rate of cost effective shared medium access LANs has recently increased from 10 Mb/s to 100 Mb/s due to the new IEEE 802.12 and IEEE 802.3 standards. This combined with the introduction of switching hubs has created the need for higher data rate backbone links. To address this requirement, both IEEE 802.12 and IEEE 802.3 have started work on gigabit per second LANs.

The majority of installed building and campus backbone links use 62.5/125 multimode fibre as recommended by ISO/IEC 11801. Cost effective high data rate sources suitable for these multimode fibre links are critical to the development of the new high speed LANs. Fibre Channel and the ATM Forum have already specified high coherence, short wavelength, CD lasers for use with multimode fibre. The Fibre Channel and the ATM Forum specifications include modal noise power penalties of 1 dB and 0.5 dB for 50/125 and 62.5/125 multimode fibre links respectively. These specified power penalties have been calculated using a new theoretical model for modal noise due to Fabry Perot lasers[1]. Here maximum mode selective loss (MSL) of 3 dB distributed throughout the link is assumed for the calculations.

Large area VCSELs are new laser sources being developed for LANs. Experimentally, it has been shown that multi-transverse mode VCSELs have MSL margins of approximately 8 dB[2, 3]. However, no reported theoretical calculations have accounted for these high margin levels.

To apply speckle visibility[4] and modal noise theory[1] to VCSEL links, high resolution spectra of the modulated VCSEL must be calculated or measured. Some details of VCSEL spectra may be calculated[5]. However, no simple model predicts their spectra under modulation.

The small irregular mode spacings generated by a VCSEL have important implications for modal noise and speckle visibility. In this work, therefore, a high resolution optical spectrum analyser system has been constructed. The spectral measurements have been used to calculate speckle visibility[4] as a function of multimode fibre length. Modal noise power penalties are then predicted using the calculated VCSEL speckle visibility and modal noise theory[1]. The visibility and modal noise power penalties have been measured and found to agree with theory.

We believe this work is the first quantitative theoretical explanation for the excellent performance of large area VCSELs in multimode fibre links.

Theory

Dandliker[4] has shown that the speckle contrast and the speckle visibility produced by a Fabry Perot laser may be calculated from its optical spectrum and the impulse response of the fibre used for the link. In addition, Bates, Kuchta and Jackson[1] have shown that the speckle contrast can be used to predict worst case power penalties for a multimode system. Both theories assume equal frequency spacing of the laser modes, Gaussian longitudinal mode profiles and a Gaussian envelope for the longitudinal mode amplitudes. Other parameters needed to calculate the power penalties are k, the laser mode partitioning factor, the number of propagating fibre modes, the MSL and the effective number of laser modes. Worst case power penalties may then be calculated for a distribution of MSL[1].

Since no simple theory accurately predicts the detailed spectrum of a large area VCSEL, the amplitude, FWHM and frequency of VCSEL modes have been measured. The measured matrix of mode amplitudes, FWHM widths and frequencies have been used to calculate the auto-correlation spectrum and speckle visibility[4]. These have been used to calculate worst case power penalties due to modal noise[1]. The VCSEL spectra are measured under the identical laser drive conditions used for link BER testing.

Experimental Work

A 24 μm diameter, circular cavity, $In_{0.2}Ga_{0.8}As$/GaAs MQW VCSEL operating near a wavelength of 980 nm was used for this work. Current confinement was achieved by proton implantation. The bottom emitting device had a threshold current of 3.5 mA and was biased at 8 mA or 14 mA. A 1 V peak to peak modulation voltage was applied through a bias tee to the VCSEL from a PRBS generator operating at 622 Mb/s.

Detailed spectra of the VCSEL were measured using an optical preselector and a Fabry Perot etalon. The highest resolution of the optical spectral measurement system was 500 MHz.

For BER and speckle visibility measurements the output of the VCSEL was lens launched into 50/125 multimode fibre. The numerical aperture (NA) of the laser beam launch was matched to the NA of the 50/125 input fibre in an attempt to excite as many fibre modes as possible. A point of variable MSL was inserted approximately 14 m from the laser transmitter and was achieved by separating two FC/PC connectors using micro positioners. Three values of MSL were used (0 dB, 5 dB and 10 dB) during BER testing.

The speckle visibility of various lengths of fibre was also measured. To do this the output of the fibre was expanded and sampled with another 50/125 multimode fibre[2,4]. The speckle visibility $[(P_{max}-P_{min})/(P_{min}+P_{max})]$, was determined from the maximum and minimum power levels captured by the 50/125 fibre during two minutes of vigorous shaking of the fibre before the beam expander.

Since it is difficult to measure the worst case BER due to modal noise[2] two methods for determining the BER performance of the VCSEL link were used:

1. The BER penalty at 10^{-9} BER was measured without agitation of the fibre.

2. The maximum BER was recorded for several 20 second measurement periods during which the multimode fibre preceding the point of MSL was vigorously flexed. The received optical power was adjusted using an optical attenuator to approximately 5 dB above the 10^{-8} sensitivity point of the receiver.

The first test was expected to underestimate the worst case BER penalty. The second test was used to verify that the power penalty was less than 5 dB under near worst case conditions. Power budgets of LAN systems, including a 1 dB modal noise penalty, are typically in the range 5 to 7 dB. We therefore assumed that power penalties greater than 5 dB would indicate BER floors in practical systems.

Results

The optical spectra of the VCSEL were measured for both bias currents with the laser operating CW and modulated with a 2^7- 1, PRBS. The measured FWHM line widths were 500 MHz (resolution limited) and 5 GHz for CW and modulated operation respectively. The amplitudes and relative positions of the VCSEL laser modes are plotted in figure 1a and 1b. Unlike a Fabry Perot laser, the transverse modes of the VCSEL did not have equal frequency separations. In addition, the amplitude of each mode appeared random compared with that of the other transverse modes. From our experimental observations we estimated k to be equal to or less than 0.5 for the VCSEL investigated.

Figure 1a

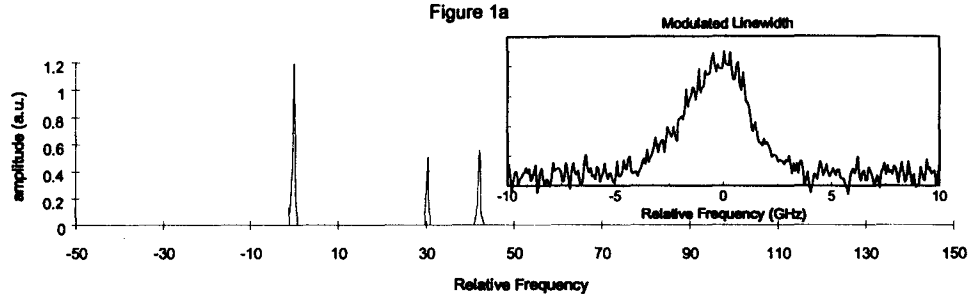

Figure 1b

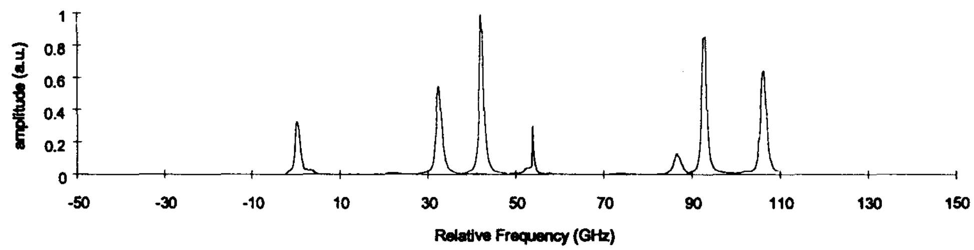

Figure 1 Optical Spectra of large area 980 nm VCSEL a) 8 mA bias current, Inset: modulated line width with 1V pk-pk modulation at 622 Mb/s, b) 14 mA bias current.

The measured mode amplitudes, FWHM widths, and relative frequencies were used to calculate[4] the VCSEL speckle visibility as a function of fibre length for both bias conditions. The fibre bandwidth was measured to be approximately 600 MHz.km for the laser launch conditions. Excellent agreement between theory and experiment was observed, see figure 2.

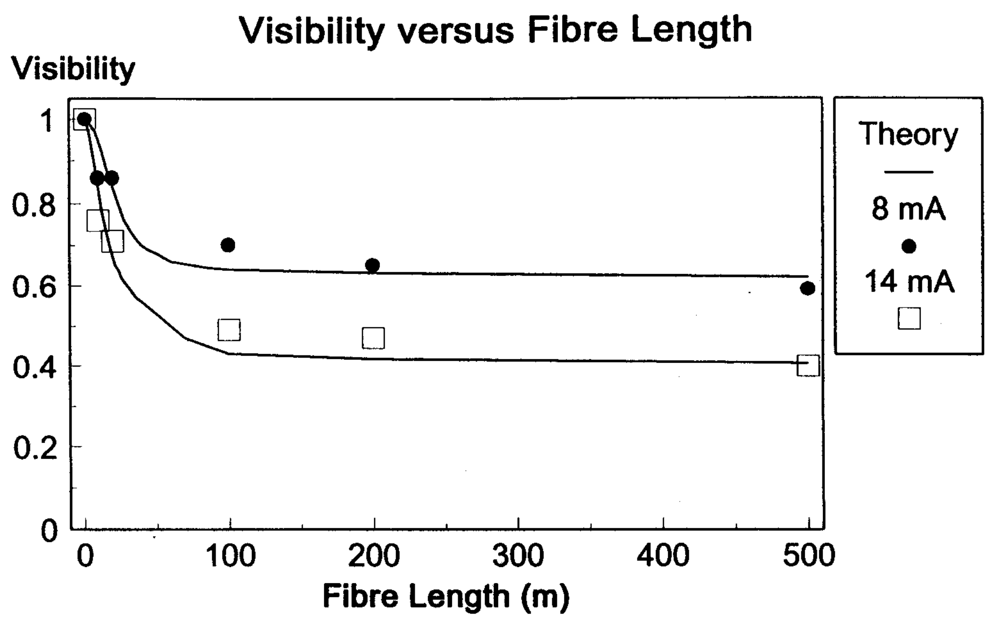

Figure 2 Speckle visibility of the large area 980 nm VCSEL, measured and calculated for 8 mA and 14 mA bias currents.

Using our measured VCSEL spectra and calculated speckle visibility[4], worst case power penalties were calculated[1]. For 8 mA and 14 mA bias currents the penalties were calculated to be 3.5 dB and 1.6 dB respectively for 5 dB MSL. For 10 dB MSL a BER floor above 10^{-9} was predicted for both cases.

By method 1, for 5 dB MSL the measured power penalties were less than 0.5 dB for both bias conditions and 2^7-1 or 2^{23}-1 PRBS modulation. With 10 dB MSL the measured penalty was 0.5 dB for 2^7-1 however a BER floor was observed with 2^{23}-1 PRBS for both bias currents. The penalties were always larger for 2^{23}-1 compared with 2^7-1 data patterns. These results are consistent with theory given that method 1 typically underestimates the penalties.

Using the second BER test method BER floors were not observed for 5 dB of MSL. However, for 10 dB MSL with 2^7-1 or 2^{23}-1 PRBS modulation, BER floors of 10^{-8} were observed for both bias currents.

Large single points of MSL are useful for laboratory experiments however they may not be representative of practical fibre installations. According to ISO/IEC 11801 connector losses are specified to be less than 1 dB per connection. Using our measured VCSEL spectrum, our calculated visibility as a function of fibre length and modal noise theory[1], we calculated maximum power penalties of 2 dB and 0.75 dB for 50/125 and 62.5/125 multimode fibre links. For these calculations a near worst case link having connectors at 2 m, 4 m, 6 m, 60 m, 62 m and 66 m was assumed. Each connector had an MSL of 1 dB.

Discussion

For the first time, the speckle visibility and power penalties of a VCSEL have been predicted. This was achieved by using high resolution spectral measurements and speckle visibility theory to calculate speckle visibility as a function of fibre length. The calculated speckle visibility was then used with modal noise theory to predict power penalties. BER floors were not predicted or observed for a 5 dB single point of MSL. However, for 10 dB MSL BER floors were predicted and observed. For a near worst case 62.5/125 multimode fibre link, having six points of MSL, each of 1 dB, a power penalty of 0.75 dB was calculated

This letter confirms theoretically and experimentally the excellent MSL margins of large area VCSELs in multimode fibre links.

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