# Four-Channel Coarse WDM 40 Gb/s Transmission of Short-Wavelength VCSEL Signals Over High-Bandwidth Silica Multi-Mode Fiber

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*The first experiment is reported to demonstrate the ability of upgrading future enterprise networks to building backbone speeds of 40 Gb/s carried by a single graded-index silica multi-mode fiber (MMF). We have used 20 nm total span coarse wavelength division multiplexing of four VCSEL channels centered at 825 nm and modulated at 10 Gb/s each for error-free data transmission over a recently developed high-performance MMF with 310 m link length.*

## 1. Introduction

The continuous increase of required data rates in local area networks (LANs) beyond the capacity of current protocol platforms like Gigabit Ethernet (GbE) has urged the establishment of a so-called Higher Speed Study Group within the IEEE in March 1999. These early efforts have resulted in focused work toward the successor of GbE, meanwhile known under [1] 10-Gigabit Ethernet (10-GbE) to be standardized as IEEE 802.3ae. Several options exist to reach the target data rate on the order of 10 Gb/s. Coarse wavelength division multiplexing (CWDM) is an attractive option for increasing the data throughput while utilizing the often low-bandwidth installed MMF base. CWDM modules based on 840 nm wavelength vertical-cavity surface-emitting lasers (VCSELs) [2] or 1310 nm distributed feedback lasers [3] have already been developed, enabling 4×2.5 Gb/s transmission over 100 m MMF or 300 m MMF, respectively, both with 62.5 $\mu$m core diameter. However, recent demonstrations of 10 Gb/s VCSEL transmitters and MMF receivers together with the progress of SiGe electronics clearly show the feasibility of a straight forward serial high-speed solution without the added complexity of optical multi- and demultiplexing. Indeed, recently 10 Gb/s data transmission over record distances of 1.6 km [4] or 2.8 km [5] of a new high-bandwidth 50 $\mu$m core diameter MMF have been reported. Subcarrier multiplexing and multilevel coding [6] as alternative upgrading methods have not yet been demonstrated in sufficient quality and are not considered competitive at present. Likewise, today's parallel optical modules with already up to 30 Gb/s aggregate data rate through 12 channels [7] seem unsuitable due to high cost of a few hundred meter long fiber ribbon cable. With a further increase of bandwidth demand beyond the direct current modulation capabilities of laser transmitters, CWDM approaches will certainly gain importance for building backbone links. In this paper we present a first realization of a four-channel, 40 Gb/s CWDM link over 310 m of high-performance MMF cable [8].

## 2. Experimental Setup

The present CWDM transmission system is implemented in a hybrid fashion. In the transmitter section, each two of the four VCSEL outputs are combined through a polarizing beam splitter (PBS) to reduce the regular 3 dB loss contribution. Maximum power transmission is achieved by proper rotation of the fixed polarization of the single transverse mode beams by means of half-wave plates. Both beams are then combined by a 3 dB MMF coupler that is connected to the 310 m length cabled and connectorized LazrSPEED™ MMF with 50 $\mu$m core diameter from Lucent Technologies. Fiber loss including one ST-type fiber connection is slightly below 1 dB. The fiber output is collimated, dispersed through a 850 nm, 400 lines/mm blazed grating, attenuated with a circular variable neutral density filter, and fed into a fiber pigtailed pin-receiver. For demultiplexing, the coupling unit is translated perpendicularly to the beam. Total fiber-to-fiber loss is below 3 dB for the demultiplexer. The electrical signal is amplified by 28 dB and analyzed by a bit error rate tester (BERT). The VCSELs are driven by the DATA and inverse DATA outputs of the BERT, where differing cable lengths ensure signal decorrelation.

## 3. Laser Source Characteristics

High-speed GaAs quantum well based oxide-confined transverse singlemode VCSELs [9] with emission wavelengths of 815, 822, 828, and 835 nm were selected from a molecular beam epitaxially grown wafer with intentional grading of layer thicknesses. 10 Gb/s signals drive the VCSELs through SMA-connectorized packages containing a coplanar stripline which is wire-bonded to the ground-signal-ground contacts of the laser. As shown in Fig. 1, threshold currents vary between 0.6 and 0.85 mA. At 3 mA bias, free-space optical powers between 1.15 and 1.45 mW are delivered.

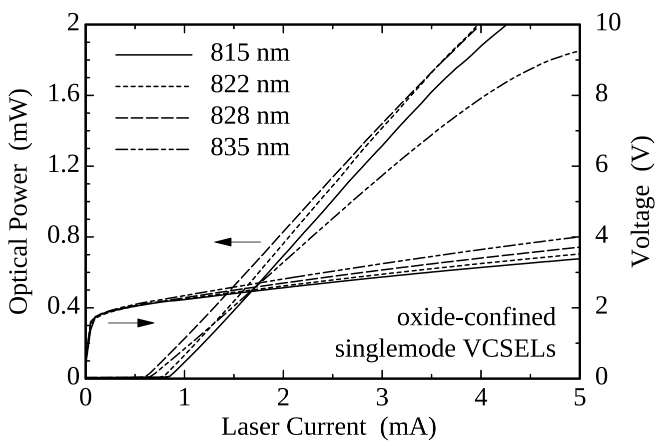


Fig. 1. VCSEL operation characteristics for all four WDM channels.

For the 815 nm device, the optical spectra in Fig. 2 reveal that the sidemode suppression ratio (SMSR) exceeds 40 dB at 3 mA and is reduced to still 30 dB at 4 mA current, corresponding to 1.85 mW output power. The active laser size is defined through the diameter of the oxide aperture which is in the range of 3 to 4 $\mu$m.

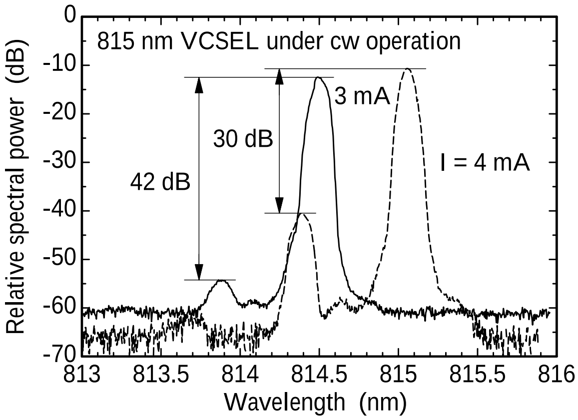


Fig. 2. Optical spectra of the 815 nm device for 3 and 4 mA driving currents.

Since the chosen method of homogeneous layer thickness variation on the wafer also affects the AlAs current aperture, the increase of oxidation rate has resulted in smaller activce diameters for longer wavelength devices. In the multiplexed spectrum depicted in Fig. 3, this effect translates into smaller transverse mode spacings and reduced SMSRs of shorter wavelength VCSELs.

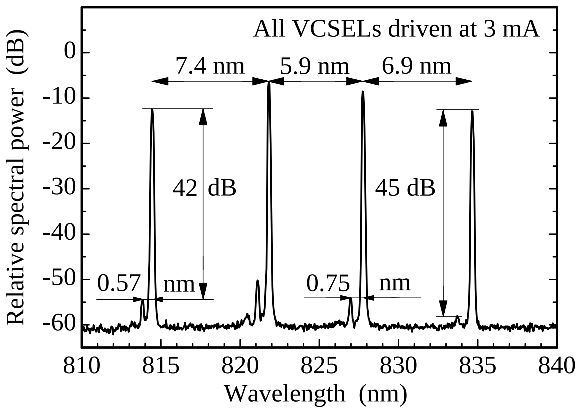


Fig. 3. Combined spectrum of the CWDM VCSEL source with all elements driven at 3 mA current.

## 4. Data Transmission Results

For the transmission experiment, all VCSELs were biased at 3 mA using bias tees. Owing to slightly varying differential resistances and quantum efficiencies, as seen in Fig. 1, optimum conditions were achieved with different modulation voltages. Signals with the following peak-to-peak voltages were incident onto the VCSEL packages: 1.12 V for the 815 nm wavelength channel, 1.35 V for 828 nm, and 1.56 V for 822 and 835 nm. With all four channels operating, an optical power of −0.25 dBm was launched into the fiber.

Fig. 4 illustrates measured bit error rates (BERs) for all channels at 10 Gb/s modulation as a function of average received optical power both with and without inserting the 310 m long MMF cable. In all cases, error rates down to $10^{-12}$ are achieved without indications

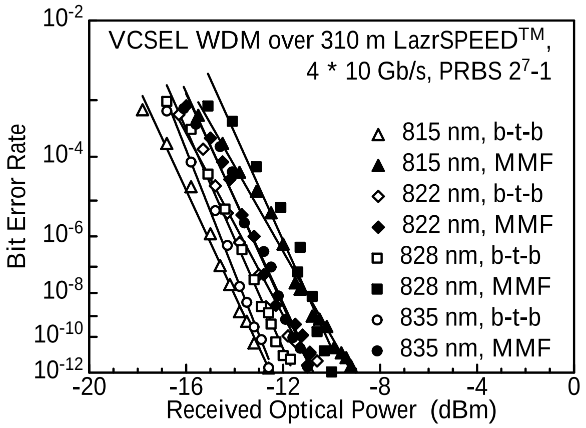


Fig. 4. Bit error rates for all four channels versus optical power at the receiver for 10 Gb/s back-to-back (b-t-b) operation and transmission over 310 m of 50 $\mu$m core diameter MMF cable.

of a BER floor. Power penalties for fiber transmission vary between 1 and 3 dB. Compared to previous publications [4, 5], where receiver sensitivities between −17.5 to −17 dBm at BER = $10^{-9}$ have been observed, values in the range of −13.5 to −12 dBm can be extracted from Fig. 4 for back-to-back operation, although measurements were performed with the same pin-receiver. Some of this penalty can certainly be attributed to electrical parasitics introduced by the laser package (previous experiments employed direct microwave probing of the VCSEL chip), whereas we assign the largest contribution to polarization noise. Although the VCSEL's fundamental modes were linearly polarized, at least within the about 30 dB extinction ratio limit of the employed polarizer, the higher transverse order modes from Fig. 3 in any case are polarized perpendicularly to the zero order modes. These modes are dropped in the PBS which induces excess laser noise. The contribution of this effect could be quantified by repeating the experiment with regular 3 dB beam splitters. Variations of the fiber response with wavelength might also give rise to part of the observed channel-to-channel fluctuations.

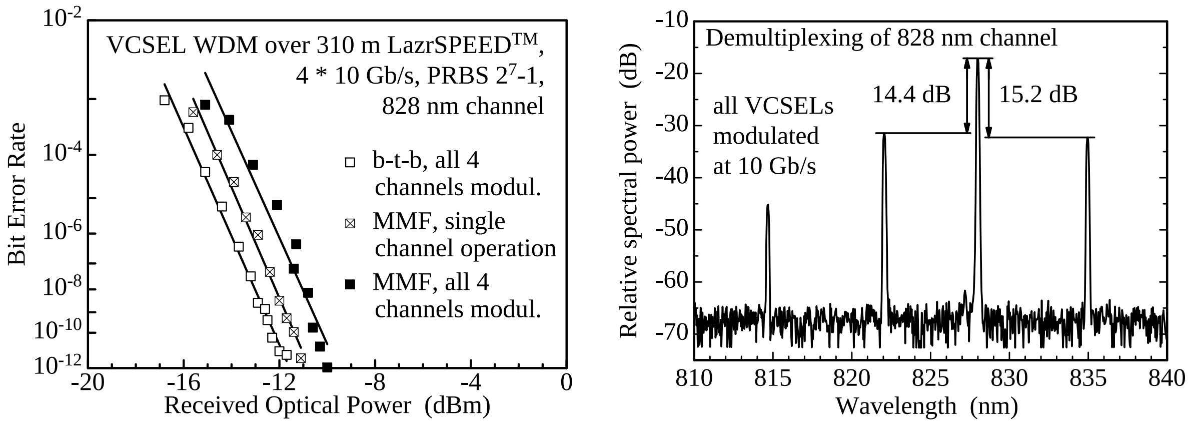


Fig. 5. Bit error rates **(left)** and received optical spectrum **(right)** during measurement of the 828 nm channel, illustrating the influence of optical crosstalk.

Fig. 5 repeats the error rate behavior of the 828 nm channel and shows an additional curve for the case of the other three channels being switched off. The power penalty of 1 dB for full system operation can be attributed to optical crosstalk induced by the relatively low neighboring channel suppression of about 15 dB, as seen in the right-hand part of Fig. 5. In the present set-up, crosstalk can be easily reduced by increasing the path length between grating and pick-up fiber.

## 5. Conclusions

Relying on single transverse mode, single polarization VCSELs emitting in the 815 to 835 nm wavelength range we have successfully demonstrated the first 40 Gb/s MMF system by multiplexing 4 CWDM optical channels operating at 10 Gb/s each. Instrumental for this experiment was the availability of a high-bandwidth MMF with an improved representation of a parabolic graded-index profile, thus minimizing the group delay differences between the multiple guided modes for a certain target wavelength. The mismatch between the optimization wavelength of 850 nm and the actually used wavelength interval clearly indicates a wide spectral range of fiber bandwidth sufficient for 10 Gb/s data rates, so that either a higher channel count could be realized or the channel spacing could be increased to, e.g. 15 nm, as would be required to ensure a stable operation of uncooled components over an extended temperature range. The present demonstration thus opens up new perspectives for the realization of higher throughput building backbone links even beyond the aims of the upcoming 10-GbE standard. A more compact system configuration can be achieved with integrated multiplexing units like in [2] and [10] as well as a dielectric filter based demultiplexer [11, 3].

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