# A 4-λ, 40Gb/s/λ Bandwidth Extension of Multimode Fiber in the 850nm range

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**Abstract:** The bandwidth capacity of 50/125 μm multimode fiber is extended by using four VCSELs with wavelengths coarsely separated at 30nm and with each wavelength operating at 40Gb/s. All four wavelengths achieve BER <1E-12 at 100m.

***OCIS codes:*** *(060.2340) Fiber optics components (060.2360) Fiber optics links and subsystems; (060.2380) Fiber optics sources and detectors; (200.4650) Optical interconnects.*

## 1. Introduction

There is a desire to extend the bandwidth of VCSEL-based multimode fiber links from today's 40Gb/s and 100Gb/s to future 200Gb/s and 400Gb/s solutions while preserving a link distance of at least 100m. This is important for data centers, high performance computing, and cloud systems. One viable approach is to add more fibers to the link which widens the parallel interface. Another approach discussed in the IEEE 400Gb/s Ethernet Task Force, is Shortwave Wavelength Division Multiplexing (SWDM) in the spectral region between 860-1100nm. Between 840-860nm, standard OM3 and OM4 fibers specify minimum effective modal bandwidths (EMB) of 2000MHz*km and 4700MHz*km, respectively while requiring >500MHz*km EMB at 1310nm . Many of these fibers have their peak EMB somewhere between 860nm and 1310nm, and generally closer to 860nm. The chromatic dispersion of fiber decreases with increasing wavelength from -83ps/nm*km at 850nm to -45ps/nm*km at 980nm. In this spectral region, a decrease in EMB can be partially offset by the increase in chromatic bandwidth. To date, very few WDM experiments have been performed on standard multimode fiber in the range from 850-1100nm. A coarse WDM link was demonstrated with four 10Gb/s VCSELs on a 30nm spacing between 990-1080nm [1] and later shown to support a distance of 300m on OM3 fiber [2]. There is a commercial product with two 20Gb/s VCSELs in the range of 832-918nm that supports a minimum distance of 100m [3]. In this paper we present transmission results from four complete transmitters (drive IC + VCSEL) in the range of 850-940nm at 40Gb/s over a distance of 100m on OM4 fiber and up to 200m at 26Gb/s.

## 2. Experiment

The VCSELs used in this study were grown by Metal Organic Chemical Vapor Deposition (MOCVD) and fabricated in a production wafer processing facility using standard design rules. The 880, 910 and 940nm VCSEL designs are based on scaled N and P type mirror from production 850nm 28Gbps devices, with the primary differences in the quantum wells being the amount of indium needed to emit at the desired wavelength. All four VCSELs have emission diameters of approximately 7 microns. This diameter was chosen as a trade-off between reliability, optical power output, relative intensity noise, spectral bandwidth, and modulation bandwidth for the design. Reliability of the 850nm VCSEL was described previously [4], and initial tests on the longer wavelength VCSELs indicate reliability similar to the 850nm devices. Characterization of the VCSELs included static measurement of the light output and voltage as a function of current over temperature. Threshold currents are in the range of 700μA with slope efficiency in the 0.4 W/A range and series resistance around 70 Ω. Small signal AC measurements were made on each of the VCSEL wavelengths, the |S21| at 25 $^{o}$C and bias currents of 8-10mA are shown in Figure 1. The 3dB frequency was between 13 and 17GHz. Also shown in Figure 1 are the optical spectra. The center wavelengths are 855, 882, 914, and 947nm and the RMS spectral widths are 0.62, 0.49, 0.36, and 0.35nm, respectively.

The VCSELs are wirebonded separately to the differential output of two high-speed driver ICs similar to the one reported in [5] but with a 100 Ohm load resistance on the output stage. The 850nm device is biased at 8mA while the other 3 are biased at 10mA. Each VCSEL is characterized one at a time. The receiver IC has been described in [6] and this experiment uses a commercially available InGaAs surface illuminated PIN photodiode designed for high responsivity in the 1260-1620nm window. The responsivity at 850nm is 0.31A/W increasing linearly to 0.38 A/W at 940nm. The fibers used in these experiments are OM4 grade with an EMB that peaks >860nm and a DMD profile that is strongly left tilted. The high speed modulation format is NRZ and the pattern is PRBS7. All measurements included a 7m OM3 fiber link used for optical coupling to the VCSEL and photodiode.

## 3. Results

Figure 2 shows the received electrical eyes from 26 to 40Gb/s for all four wavelengths. The jitter is largest for the 880nm VCSEL which has the lowest bandwidth and increases for all four devices with data rate. At 40Gb/s, the eye

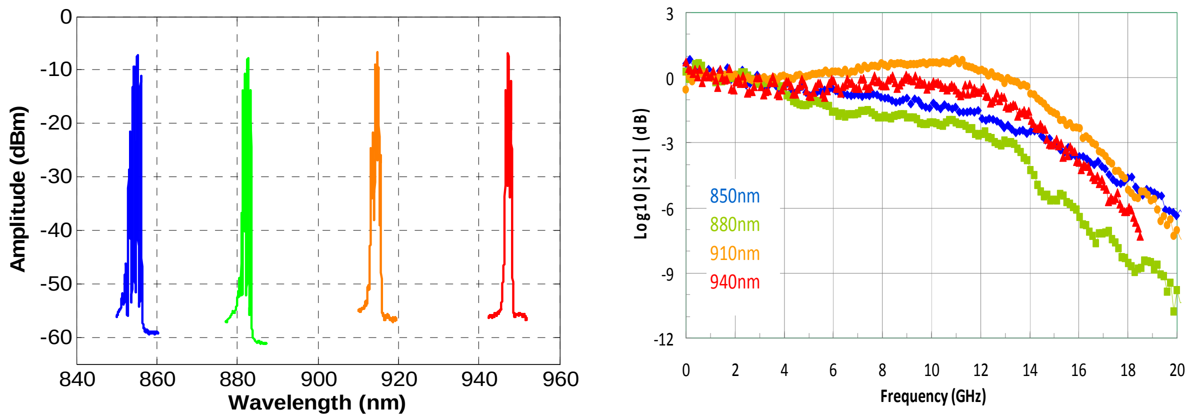


Figure 1. (left) Optical spectrum of four VCSELs with center wavelengths of 855, 882, 914 and 947nm, and (right) Small signal bandwidth of the same four VCSELs with bias currents of 8, 10, 10, and 10mA respectively.

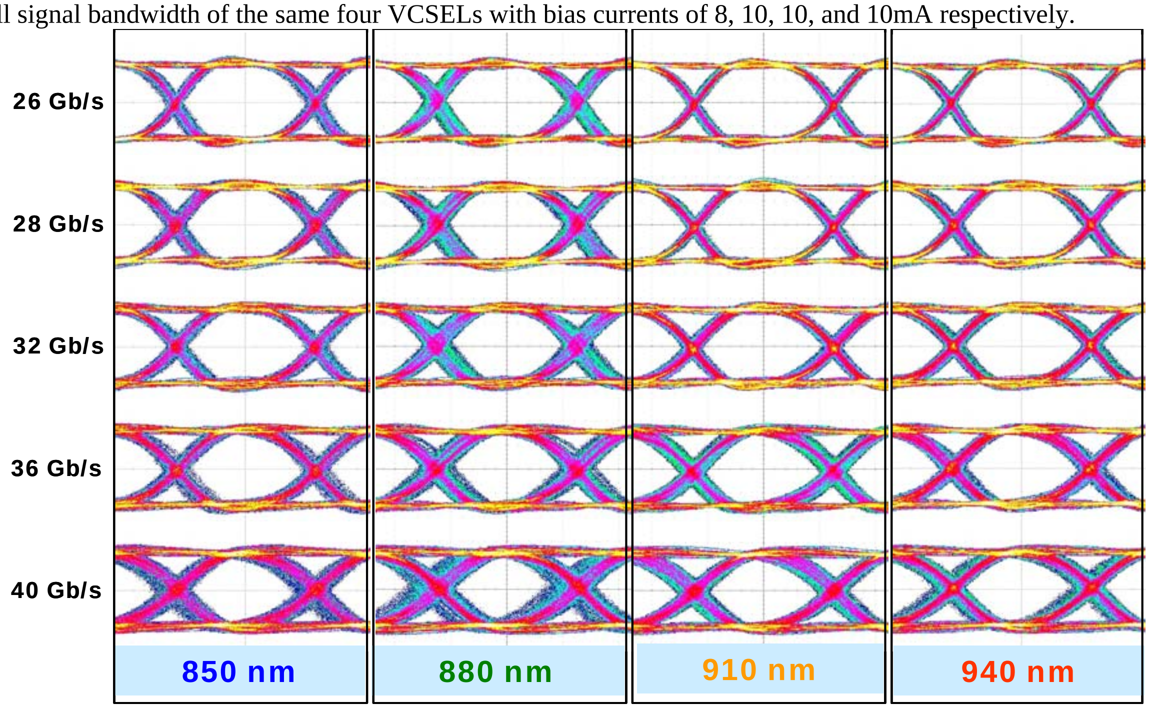


Figure 2 Received electrical eye diagrams after 7m OM3 fiber as a function of data rate from 26 to 40Gb/s (top to bottom) and wavelength from 850-940nm (left to right). The horizontal width for each eye diagram is 1.8 UI.

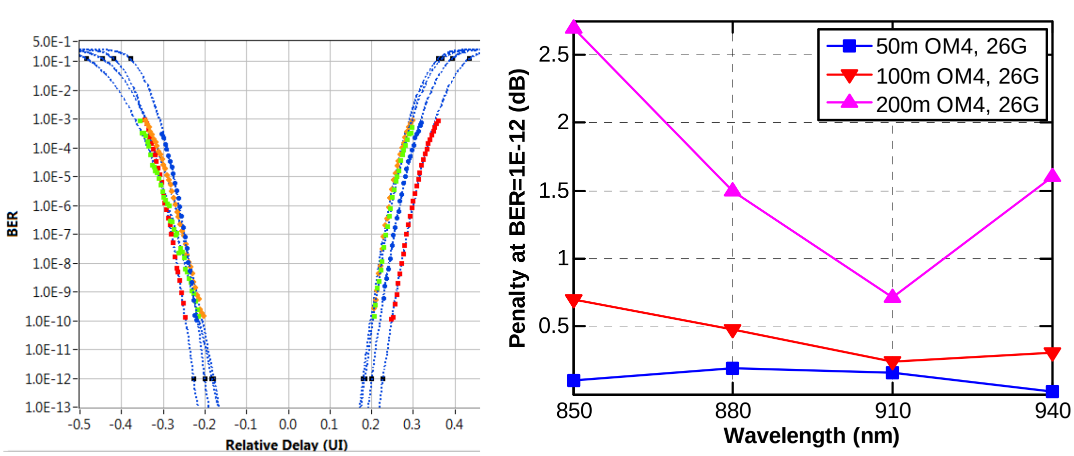


Figure 3. (left) Bathtub curves for each wavelength at 40Gb/s after 100m and (right) penalty vs. distance at 26G up to 200m.

opening at BER=1E-12 is >0.43UI for all four devices. The left side of Figure 3 shows the bathtub curve for each wavelength after 100m transmission over OM4 fiber. The smallest eye opening at BER=1E-12 is 0.36UI. Figure 4 shows the BER curves for each wavelength at 40Gb/s for 7m (left) and 100m (right). A BER <1E-12 is obtained with no evidence of an error floor. The largest penalty, at 850nm, was 2.2dB. At 26Gb/s, the transmisson distance can be increased to 200m and Figure 3 (right) shows the penalty versus wavelength for each distance. This plot shows that the penalty is lowest for 910nm, indicating that the fiber's bandwidth is likely peaked in this region.

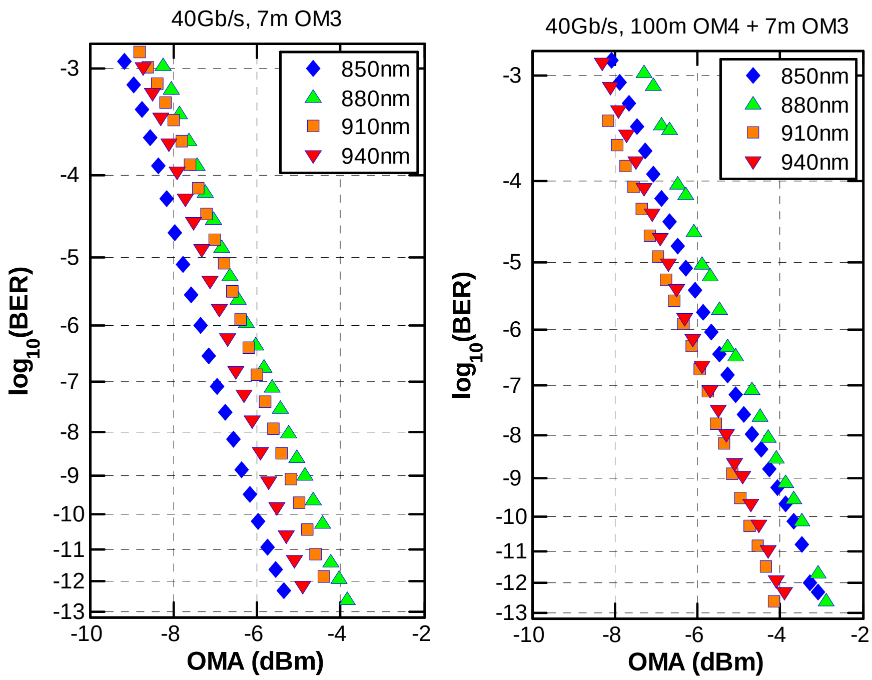


Figure 4. BER vs. OMA at 40Gb/s for 7m (left) and 107m (right) transmission for each wavelength

## 4. Conclusion

A four wavelength, 40Gb/s/wavelength, SWDM transmission experiment has been demonstrated error free to 100m over OM4 fiber. This is the first known experimental data above 25Gb/s in this wavelength regime. In the future it can be extended to 50Gb/s/wavelength [7]. The experiment demonstrates the bandwidth capacity of standard multimode fiber and shows that it is possible to support future 200Gb/s and 400Gb/s solutions using the same parallel interface width as today's 40Gb/s and 100Gb/s multiimode fiber solutions.

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**References**


[1] Brian E. Lemoff, Mohammed E. Ali, George Panotopoulos, Edwin de Groot, Graham M. Flower, Glenn H. Rankin, Andrew J. Schmit, Kostadin D. Djordjev, Michael R. T. Tan, Ashish Tandon, William Gong, Richard P. Tella, Benjamin Law, and David W. Dolfi, "500-Gbps Parallel-WDM Optical Interconnect", Proceedings of the 55th Electronic Components and Technology Conference, 1027-1031 (2005)

[2] Sun, Y.; Ali, M.E.; Balemarthy, K.; Lingle, R.L., Jr.; Ralph, S.E.; Lemoff, B.E., "10 Gb/s transmission over 300 m OM3 fiber from 990-1080 nm with electronic dispersion compensation," Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006 , vol., no., pp.3 pp.,, 5-10 March 2006 doi: 10.1109/OFC.2006.215360

[3] See Cisco Inc. datasheet for p/n QSFP-40G-SR-BD

[4] J. Guenter, B. Hawkins, b. Hawthorne, G. Landry, "Reliability of VCSELs for >25Gb/s," OFC, M3G-2, (2014).

[5] A. Rylyakov, C. Schow, J. Proesel, D. M. Kuchta, C. Baks, N. Y. Li, C. Xie, and K. Jackson, "A 40-Gb/s, 850-nm, VCSEL-Based Full Optical Link", Optical Fiber Communication Conference (OFC), Los Angeles, California, March 4, 2012, Transceivers and Devices for Photonic Links (OTh1E)

[6] Dupuis, N.; Kuchta, D.M.; Doany, F.E.; Rylyakov, A.; Proesel, J.; Baks, C.W.; Schow, C.L.; Luong, S.; Xie, C.; Wang, L.; Huang, S.; Jackson, K.; Li, N.Y., "Exploring the limits of high-speed receivers for multimode VCSEL-based optical links," Optical Fiber Communications Conference and Exhibition (OFC), 2014 , vol., no., pp.1,3, 9-13 March 2014

[7] Kuchta, D.M.; Rylyakov, A.V.; Schow, C.L.; Proesel, J.E.; Baks, C.; Westbergh, P.; Gustavsson, J.S.; Larsson, A., "64Gb/s transmission over 57m MMF using an NRZ modulated 850nm VCSEL," *Optical Fiber Communications Conference and Exhibition (OFC), 2014* , vol., no., pp.1,3, 9-13 March 2014