# 2.5-Gb/s Hybrid Single-Mode and Multimode Fiber Transmission of 1.5-$\mu$m Wavelength VCSEL

Jin Joo Kim, Kyong Hon Kim, *Member, IEEE*, Min-Hee Lee, Hyun Sik Lee, El-Hang Lee, *Fellow, IEEE*, O-Kyun Kwon, Jay Roh, and Byueng-Su Yoo

***Abstract*—We report, for the first time, a successful 2.5-Gb/s transmission performance of a 1.5-$\mu$m emission monolithic vertical-cavity surface-emitting laser (VCSEL) over hybrid links composed of 25-km-long conventional single-mode fibers (SMFs) and a 2.2-km-long 50-$\mu$m core multimode fibers (MMFs). This result suggests that 1.5-$\mu$m wavelength VCSELs can be effectively used for multigigabit-per-second transmission over hybrid links interconnecting SMF-based long-distance and (or) subscriber network lines with MMF-based local-area network lines in the future ubiquitous network era.**

***Index Terms*—Fiber transmission, multimode fiber (MMF), subscriber networks, vertical-cavity surface-emitting laser (VCSEL).**

## I. Introduction

The 1.5-$\mu$m emission vertical-cavity surface-emitting lasers (VCSELs) have been recognized as potential low-cost high-quality signal light sources compared to the conventional distributed feedback laser diodes for optical communication systems[1], [2]. A low-cost 1.5-$\mu$m laser diode is important for fiber-to-the-home applications, especially with the wavelength-division-multiplexing access systems utilizing 1.5-$\mu$m wavelength regions [3], [4]. The 1.5-$\mu$m VCSELs can be an alternative choice as an eye-safe light source for subscriber networks and as an array source for long-distance optical interconnections. The optical interconnection between racks and equipments, for example, uses the 0.8-$\mu$m wavelength band for multimode fibers (MMFs) over relatively short distances. For ubiquitous network applications, the long-distance networks and the subscriber networks based on single-mode fibers (SMFs) and the intrabuilding networks based on MMFs need to be interconnected to form a combined complex network. Laser signal sources of 1.5-$\mu$m wavelength are more suitable for long length fiber transmission than the conventional 0.8- and 1.3-$\mu$m wavelengths. Thus, in this letter, we investigate on the potential use of a monolithic 1.5-$\mu$m emitting single-mode (SM) VCSEL for 2.5-Gb/s signal transmission over a long length of hybrid fiber links composed of conventional SMFs and MMFs without using any electrooptic conversion between the two different types of fibers.

Manuscript received August 29, 2006; revised October 30, 2006. This work was supported in part by the Ministry of Commerce, Industry and Energy under Project 10016905, and in part by Grants for Quantum Cryptography Technology and the OPERA Integrated Photonics Technology Research Center (R11-2003-022) of the Ministry of Science and Technology.

J. J. Kim, K. H. Kim, and M.-H. Lee are with the Department of Physics, Inha University, Incheon 402-751, Republic of Korea (e-mail: kyongh@inha.ac.kr).

H. S. Lee and E.-H. Lee are with Optics and Photonics Elite Research Academy (OPERA), School of Information and Communication Engineering, Inha University, Incheon 402-751, Republic of Korea.

O.-K. Kwon is with ETRI, Daejon 305-700, Republic of Korea.

J. Roh and B.-S. Yoo are with RayCan Co., Ltd., Daejeon 305-350, Republic of Korea.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2007.891243

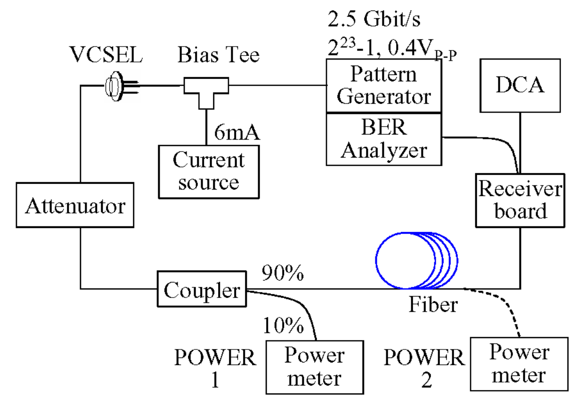


Fig. 1. Experimental scheme for the fiber transmission test of the 1.5-$\mu$m VCSEL.

It has been known that the joint connection between SMFs and MMFs causes significant optical losses and varying coupling efficiencies. Furthermore, the MMFs are known to cause the differential modal delay and the intersymbol interference at high-speed optical transmission rates[5]. Thus, this letter is intended to conduct experimental measurements to investigate the joint losses interconnecting the SMFs and MMFs, and is the first report, to our knowledge, of experimental evaluation on the transmission characteristics of the SM VCSEL along the hybrid SMFs and MMFs.

## II. Experiment

Fig. 1 shows the schematic view of an experimental setup used for the measurement. The 1.5-$\mu$m light source was an InP-based long wavelength VCSEL. The device was formed in an all monolithic structure with a one-step growth by low-pressure metal–organic chemical vapor deposition technique. The 0.5-$\lambda$-thick active region consists of seven pairs of strain compensated InAlGaAs quantum wells. The carbon-doped InAlAs tunnel junction was positioned at the standing-wave node of the cavity mode between the top n-InP layer and active region. The 2.0-$\lambda$-thick n-InP cladding layers were used for efficient heat dissipation and low series resistance. The undoped-InAlGaAs–InA1As distributed Bragg reflectors (DBRs) with about 3.2 and 3.49 for low and high indexes resulted in the reduced free-carrier absorption loss. A

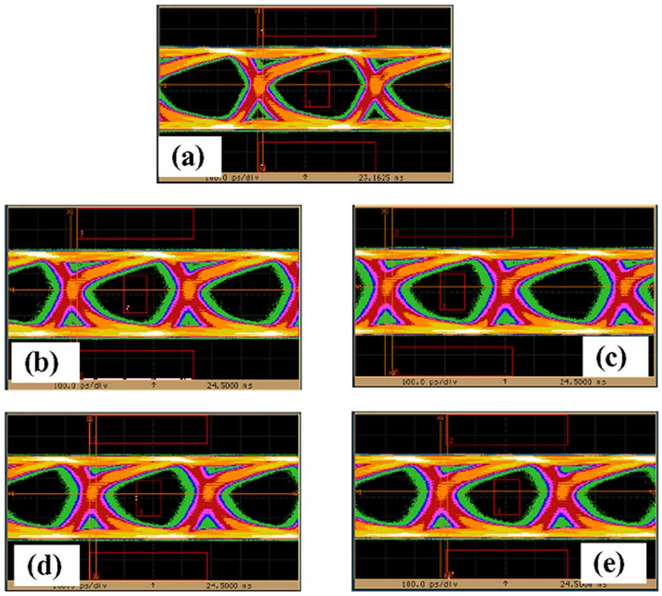


Fig. 2. Measured eye diagrams (a) BTB, (b) 2.7-km MMF, (c) 30-km SMF, (d) 25-km SMF + 2.2-km MMF, (e) 2.2-km MMF + 25-km SMF.

double intracavity contact was used for reducing the voltage drop in InAlGaAs DBR. An air-gap aperture using selectively wet etched InAlGaAs active layer provided the current confinement. The devices used in this experiment had a diameter of $\sim 10\mu$m and showed a single-mode operation with the side-mode suppression of more than 35 dB. The detailed description of the VCSEL device is reported in [6].

The VCSEL was biased with a driving current of 6 mA and modulated directly with a pulse pattern generator. The modulated optical signal was divided by a 9 : 1 splitter, and the 90% signal beam was sent through the fibers while the 10% beam was used for the power monitor. The main beam passing through the fiber line was measured with an optical receiver whose board was connected either to the error detector of a bit-error rate (BER) or to the digital communication analyzing oscilloscope. The output power of the VCSEL was about $-7.2$ dBm at the 6-mA bias current. The pulse pattern generator was set to 0.4 V for the driving voltage and to a bit sequence of $2^{23}-1$ pseudorandom binary sequence. The maximum fiber lengths of each of SMF and MMF were tested first for the 1.5-$\mu$m wavelength VCSEL signal transmission. The measured maximum fiber lengths were 30 km long for the SMF and 2.7 km long for the MMF, respectively. Then, when a hybrid fiber transmission over SMF and MMF was tested, their maximum fiber lengths were 25 and 2.2 km, respectively. The bandwidth of the MMF for the 1.5-$\mu$m wavelength VCSEL signals turned out to be about 6.75 GHz $\cdot$ km, which was much larger than its conventional values for 850 nm. A comparative measurement on three different vendors' MMFs shows that the maximum bandwidth for the 1.5-$\mu$m SM VCSEL wavelength varied depending on the vendors from 5.5 to 6.75 GHz $\cdot$ km. For the MMF and hybrid fiber transmission, experiments with and without a Mandrel wrap of five turns of the MMF over a 25.3-mm diameter cylinder was performed to compare its effectiveness over the MMF data transmission.

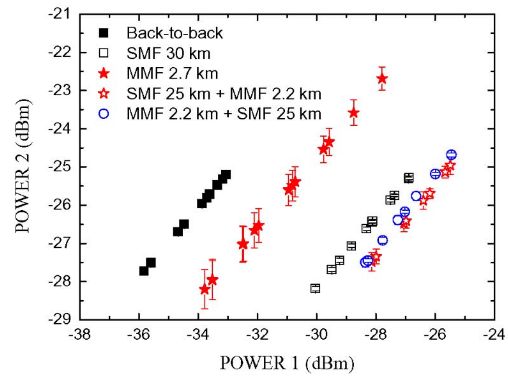


Fig. 3. Optical powers (POWER 2) measured after fiber transmission versus the input optical powers (POWER 1).

Various fiber combinations were tested for the transmission experiment of up to 2.5-Gb/s data rates. There was no problem in the fiber transmission over the fiber lengths specified by the InfiniBand standards, which were 20-km SMF and 600-m-long 50-$\mu$m core MMF, when the fiber line was composed of either the SMF or MMF alone or of a hybrid combination of the SMF and MMF. Fig. 2 shows the measured eye diagrams for the maximum fiber transmission compared to the back-to-back (BTB) eye diagram. The maximum transmission length with available fiber spools in our laboratory was about 2.7 km for the 50-$\mu$m core MMF, and about 2.2-km MMF in a hybrid combination with a 25-km SMF. The hybrid transmission over these distances can be sufficient to cover the existing subscriber networks interconnected with the intrabuilding networks. The eye diagrams were measured and tested for an accumulation longer than 30 min with a sufficient optical signal power from the VCSEL, and the masks shown in the diagrams correspond to the 2.5 Gb/s of STM-16/OC-48 specification. Even though some root-mean-square (rms) jitters increasing from 17 ps for BTB to 23 ps for the hybrid MMF + SMF were observed, the eyes were well open compared to the mask pattern which indicated good transmission characteristics for the hybrid fiber combination in both directions. The measured extinction ratio was 8.96 dB for the 1550-nm SM VCSEL.

In order to achieve relatively accurate BER test results, we needed to know how much the optical power after the MMF varies with time as well as for each interconnection between the SMF and the MMF. Fig. 3 shows the measured optical powers after the fiber transmission as a function of the input monitor powers measured for many trials of fiber connections and for computer interfaced time average over a time period long enough for BER data by changing the attenuator value in Fig. 1. The data points with error bars indicate the average value and the variation range with sequential SC connector unplugging and plugging trials measured at the POWER 2 point versus the POWER 1 for all four different fiber combinations with respect to the BTB case. As expected, the measured power variation for the MMF and the hybrid combination of SMF and MMF was relatively large compared to those for the BTB and SMF cases.

Fig. 4 shows the measured BERs for the SMF and MMF fiber transmissions compared to the BTB cases. In order to see the power fluctuation effect over the MMF transmission and the

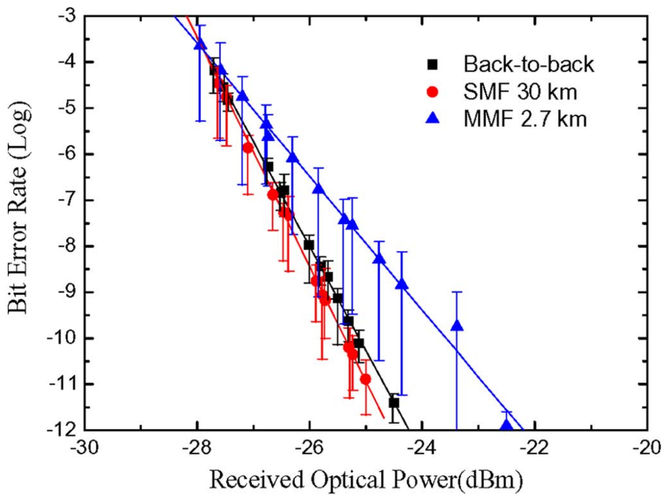


Fig. 4. Measured BERs for SMF and MMF transmission.

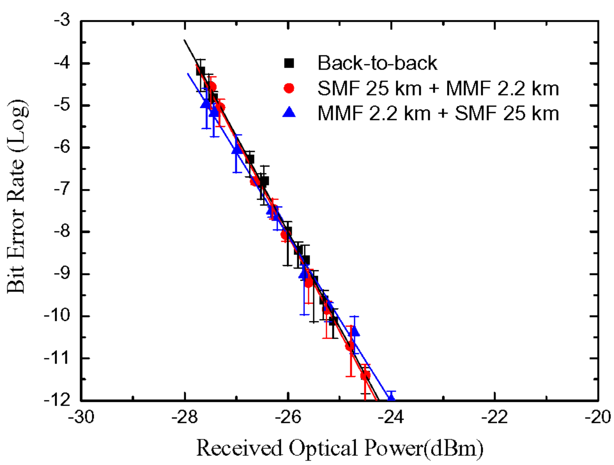


Fig. 5. Measured BERs for the hybrid SMF and MMF transmission.

connection interface between the SMF and MMF, the BER data were measured for several times by unplugging and plugging the connectors. The BER curve for the 30-km SMF shows no significant power penalty and slope difference compared to those of the BTB case within the error bars, while the BER curve for the 2.7-km MMF shows a significant power penalty and a large data fluctuation as indicated by the error bars and caused by consecutive connector plugging trials.

Fig. 5 shows the measured BER for data transmission over the hybrid combination of SMF and MMF which shows relatively large error bars caused by the MMF. No significant difference between the SMF-to-MMF and MMF-to-SMF fiber transmissions was observed. The connection losses for the SMF-to-MMF and MMF-to-SMF were measured to be 1.18 and 1.38 dB, respectively, with a difference of only 0.2 dB when they were placed between the VCSEL and a power meter both with SMF pigtails.

The BER data were observed up to error rates of $10^{-13}$ without any fails, and the received optical powers for the error rate of $10^{-12}$ were about $-24.3$ dBm for BTB, the 30-km SMF and the hybrid combinations of 25-km SMF and 2.2-km MMF, and about $-22.3$ dBm for 2.7-km MMF. The same measurements were performed with a Mandrel wrap at the beginning part of the MMF both in the single MMF transmission measurement and in the hybrid fiber transmission measurement. No significant improvement on the BER data could be visible because they were within the error bar. In addition, two types of MMFs, each with core diameter of 50 and 62.5 $\mu$m, respectively, were compared for the MMF—only transmission and the hybrid transmission of SMF and MMF. The transmission characteristics of both types of MMFs were also comparable within the error bar range.

## III. Conclusion

We have successfully demonstrated transmission up to 2.5-Gb/s bit rates of 1.5-$\mu$m wavelength SM VCSEL over fiber paths: 1) a 30-km SMF, 2) a 2.7-km MMF, and 3) a hybrid combination of 25-km SMF and 2.2-km MMF. These fiber lengths are much longer than the fiber lengths standardized for optical interconnections with the conventional 1.3- and 0.8-$\mu$m VCSELs. This experimental study strongly suggests that the 1.5-$\mu$m emission VCSEL can be a useful light source for future ubiquitous networks composed of SMF-based primary networks and MMF-based intrabuilding and home networks.

## Acknowledgment

The authors gratefully acknowledge that the SMFs were provided by Optomagic Co. Ltd., and the MMFs were spooled by LS Cable Company. The authors would also like to thank Prof. S. G. Lee and Prof. B.-H. O of Inha University and Prof. H.-H. Park of ICU for allowing them to access their measuring equipment.

## References

[1] M. Ortsiefer, S. Baydar, K. Windhorn, G. Böhm, J. Rosskopf, R. Shau, E. Rönnerberg, W. Hofmann, and M.-C. Amann, “2.5-W single-mode operation of 1.55-$\mu$m buried tunnel junction VCSELs,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1596–1598, Aug. 2005.

[2] R. J. Stone, R. F. Nabiev, J. Boucart, W. Yuen, P. Kner, G. S. Li, R. Carico, L. Scheffel, M. Jansen, D. P. Worland, and C. J. Chang-Hasnain, “50 km error-free 10 Gbit/s WDM transmission using directly modulated long-wavelength VCSELs,” *Electron. Lett.*, vol. 36, no. 21, pp. 1793–1794, Oct. 2000.

[3] S.-J. Park, C.-H. Lee, K.-T. Jeong, H.-J. Park, J.-G. Ahn, and K.-H. Song, “Fiber-to-the-home services based on wavelength-division-multiplexing passive optical network,” *J. Lightw. Technol.*, vol. 22, no. 11, pp. 582–2591, Nov. 2004.

[4] T. Shimada, N. Sakurai, and K. Kumozaki, “WDM access system based on shared demultiplexer and MMF links,” *J. Lightw. Technol.*, vol. 23, no. 9, pp. 2621–2628, Sep. 2005.

[5] A. Risteski and P. Pepeljugoski, “Optimization of launch conditions in 10-Gb/s links using next-generation multimode fibers,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1394–1396, May 2004.

[6] J.-H. Shin, B.-S. Yoo, W.-S. Han, O.-K. Kwon, Y.-G. Ju, and J.-H. Lee, “CW operation and threshold characteristics of all-monolithic nAlGaAs 1.55-$\mu$m VCSELs grown by MOCVD,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1031–1033, Jul. 2002.