IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 22, NO. 5, MARCH 1, 2010

40-Gb/s Upstream Transmitters Using Directly Modulated 1.55-μm VCSEL Array for High-Split-Ratio PONs

C. W. Chow, *Member, IEEE*, L. Xu, *Student Member, IEEE*, C. H. Yeh, H. K. Tsang, *Senior Member, IEEE*,
W. Hofmann, *Member, IEEE*, and M. C. Amann, *Senior Member, IEEE*

***Abstract*—We propose and demonstrate a 40-Gb/s symmetric passive optical network with a high split-ratio of 64. The upstream 4×10 Gb/s signal is produced by using a directly modulated, uncooled 1.55-μm monolithic integrated vertical-cavity surface-emitting laser array. The downstream signal is a single-channel 40-Gb/s dark-return-to-zero (DRZ) data, broadcasting information to different optical networking units (ONUs). As the ONU is cost-sensitive, we also demonstrate, by means of simulations, using a 12-Gb/s receiver at the ONU to receive the 40-Gb/s DRZ downstream signal.**

***Index Terms*—Fiber-to-the-home (FTTH), passive optical network (PON), vertical-cavity surface-emitting laser (VCSEL).**

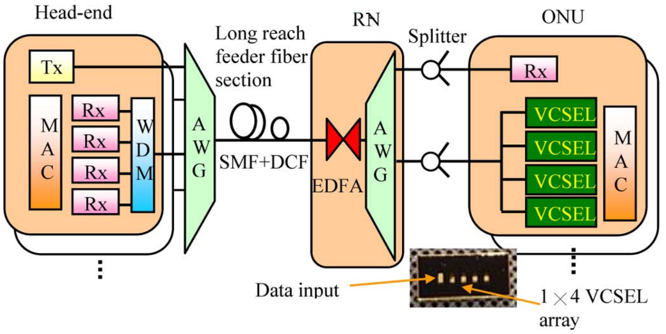

Fig. 1. Network architecture of a 40-Gb/s LR-PON using directly modulated VCSEL array as upstream transmitter. DCF: dispersion-compensating fiber. Inset: photograph of the 1 × 4 VCSEL array.

I. INTRODUCTION

To deliver future increased bandwidth services economically, carriers need to reduce the unit cost of bandwidth. One of the cost-effective access architectures is the passive optical network (PON). Gigabit PONs (GPONs) are standardized and typically offering 2.5-Gb/s downstream and ~1-Gb/s upstream data, shared among 32 optical networking units (ONUs) via passive optical splitters. They usually can provide a reach of up to 20 km. Although these PONs provide significant bandwidth increases compared to copper-based approaches, they may not provide the best ultimate solution for carriers seeking to reduce the cost significantly. Hence, the carriers will ask "What comes next after GPON?" Long-reach (LR)-PON [1]–[4] is considered by industries and research as a way of achieving this. Ten-gigabit/second symmetric LR-PON with high-split-ratio and a reach of ~100 km has been demonstrated to combine optical access and metro into a single system [5]. Because of this, cost can be reduced by decreasing the number of equipment interfaces and network elements. Although these LR-PONs offer significant bandwidth increases compared with standard PONs, the effective bandwidth per ONU does not increase by much since these LR-PONs usually have a high-split-ratio.

Recently, different 10-Gb/s PON solutions have been proposed [6]–[8] and researchers are going to further increase the data rate of PON towards 40 Gb/s and even more by using advanced modulation formats [9], [10]. Here, we propose a 40-Gb/s symmetric high-split-ratio PON and present the first demonstration of using a directly modulated, uncooled 1.55-μm monolithic-integrated vertical-cavity surface-emitting laser (VCSEL) array for an upstream transmitter (Tx) in the 40-Gb/s PON. The upstream signal is a 4×10 Gb/s wavelength-division-multiplexed (WDM) nonreturn-to-zero (NRZ) data. As the upstream signal in PON is bursty, and 40-Gb/s burst-mode receiver (Rx) is hard to implement, in this scheme, the upstream signal can be received by using four 10-Gb/s burst-mode Rx synchronized in the media access control (MAC) layer protocol. As the ONU is cost-sensitive, we also demonstrate, by means of simulations, using 12-Gb/s Rx at the ONU to receive 40-Gb/s dark-return-to-zero (DRZ) downstream signal.

II. NETWORK ARCHITECTURE

Fig. 1 shows the schematic of a 40-Gb/s LR-PON implementing directly modulated VCSEL array as the upstream Tx. WDM is used to improve the bandwidth utilization of fiber. The downstream signal is a single 40-Gb/s channel generated by external modulation. It will be sent to the ONUs via the long-reach feeder fiber, which is dispersion compensated and a remote node (RN), which consists of optical amplifiers. In the ONU, each

Manuscript received September 24, 2009; revised November 16, 2009; accepted December 24, 2009. First published January 12, 2010; current version published February 17, 2010. This work was supported by the National Science Council, Taiwan, R.O.C., under Contract NSC-98-2622-E-009-185-CC2, Contract NSC-98-2221-E-009-017-MY3, and Contract NSC-97-2221-E-009-038-MY3.

C. W. Chow is with the Department of Photonics, Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: cwchow@faculty.nctu.edu.tw).

L. Xu and H. K. Tsang are with the Department of Electronic Engineering, the Chinese Universtiy of Hong Kong, Hong Kong.

C. H. Yeh is with the Information and Communications Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan.

W. Hofmann and M. C. Amann are with the Walter Schottky Institut, Technische Universitat Munchen, Munich, Germany.

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.2009.2039749

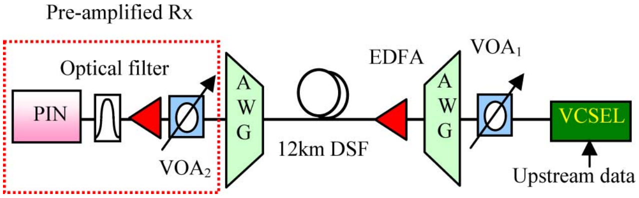

Fig. 2. Experimental setup of the upstream transmission.

laser in the VCSEL array is directly modulated at 10 Gb/s. The upstream signal is formed by wavelength multiplexing four of these channels using a WDM coupler having channel separation of ∼25 GHz. This is to ensure the 4 × 10 Gb/s upstream signal can pass through the passband of the arrayed waveguide grating (AWG) (200-GHz channel spacing). The upstream signal will then be detected by the head-end burst-mode Rxs, which are synchronized by the MAC.

III. EXPERIMENT AND RESULTS

The VCSELs are grown by molecular beam epitaxy on InP substrate, monolithically integrated in a 1 × 4 array, as shown in the photograph in the inset of Fig. 1. The high-speed VCSEL structure used here [11] has been improved from previous design [12], with optimized active area, mirror-reflectivities, and doping concentrations. The VCSEL consists of 32 pairs of InGaAs and InAlAs expitaxial output mirrors. In the active area, seven strained (tailored to be 2.5% of the compressive strain) quantum wells are fabricated in order to enhance the gain and differential gain, hence producing low threshold currents and high relaxation oscillation frequencies of the device. The back reflection mirror consists of CaF_2–ZnS and a gold layer. This produces a high reflectivity >99.9%, allowing to reduce the front mirror reflectivity. The lasing threshold was ∼1 mA. The output power was ∼0 dBm, having single longitudinal mode output. A differential series resistance of 40–50 Ω is achieved. By reducing the doping concentration in this version of the device, it suffers less parasitic capacitances owing to the space-charge region of the reverse-biased blocking diode around the buried tunnel junction used for current confinement. A flat modulation bandwidth above 7 GHz can be obtained for bias currents above 4 mA, sufficient for direct modulation at 10 Gb/s [11].

Then we evaluated the transmission performance of the upstream Tx (Fig. 2). The upstream signal was generated by directly modulating the VCSEL at 10 Gb/s, pseudorandom binary sequence (PRBS) $2^{31} - 1$ via a coplanar radio-frequency (RF) probe. The signal was then launched to the head-end direction via a variable optical attenuator (VOA_1), an AWG, an erbium-doped fiber amplifier (EDFA) (gain = 28 dB and noise figure of 5 dB), and then 12 km of dispersion-shifted fiber (DSF) before it was received by the head-end Rx, which was optically preamplified with an EDFA, an optical filter (3-dB bandwidth of 50 GHz), and a 10-GHz PIN. Using EDFA or semiconductor optical amplifier (SOA) is considered [3], [5] for future LR-PON to increase the reach and split-ratio. The VOA_1 was used to emulate the achievable split-ratio of the 40-Gb/s PON. Fig. 3 shows the bit-error-rate (BER) measurements of the 4 × 10 Gb/s upstream NRZ signals at back-to-back (B2B) and after 12 km of DSF. Two-decibel power penalties at a BER of 10^{-9} were achieved in the upstream transmission when the VOA_1 was set at −21 dB, corresponding to a split-ratio of 128 theoretically or 64 in practice. The DSF has the dispersion parameter of 3.5 ps/nm/km, which is corresponds to ∼2.5 km of standard single-mode fiber (SMF). It implies that the directly modulated 10-Gb/s VCSEL can have a dispersion tolerance of ∼2.5-km SMF at the 2 dB penalty window. Typical eye diagrams at B2B and after the 12 km from the VCSEL (Ch1: 1547.6 nm) were shown in the insets. The inset of Fig. 3 shows the measured optical spectra (resolution bandwidth of 0.07 nm) of the four lasing outputs from the VCSEL array, with wavelength separation of ∼25 GHz.

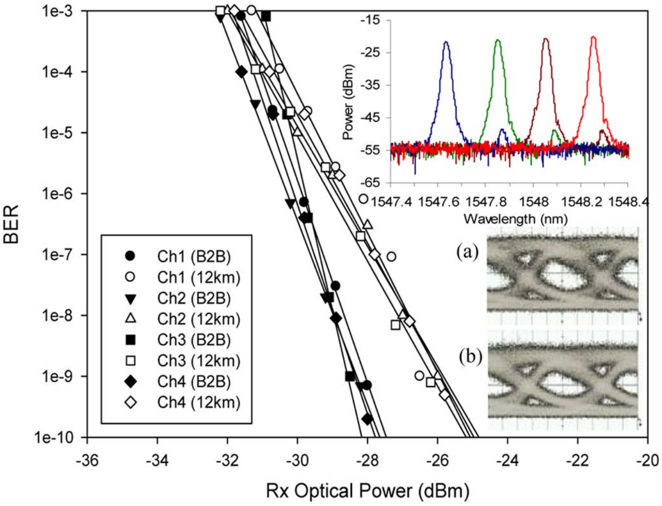

Fig. 3. Measured BER of the 10-Gb/s upstream signals. Insets: optical spectra of the VCSEL array (wavelength separation of 25 GHz), corresponding eye diagrams at (a) B2B and (b) 12-km transmission.

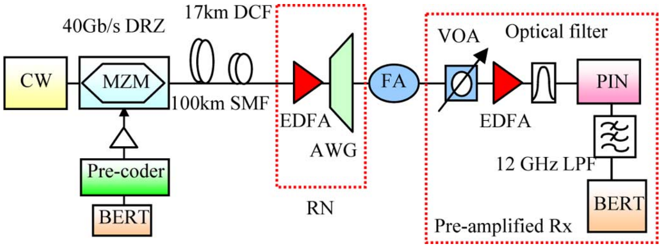

Fig. 4. Schematic of 40-Gb/s downstream DRZ transmission for simulations. BERT: BER tester; LPF: low-pass filter.

IV. SIMULATION AND DISCUSSION

Since the ONU is cost-sensitive, we also propose using low bandwidth Rx at ONUs to receive 40-Gb/s downstream signal. Due to the unavailability of a 40-Gb/s electrical NRZ pattern generator at the laboratory, simulations using commercially available software (VPI TransmissionMakerV7.5) were performed. Fig. 4 shows the schematic of the downstream signal transmission of the high split-ratio LR-PON using DRZ modulation. The DRZ was generated by a single-drive balanced Mach–Zehnder modulator (MZM), which was driven by a differentially precoded 40-Gb/s NRZ data with an amplitude of 2 V_π. The MZM was biased at a minimum of the transmission curve and the NRZ drive voltage switched the MZM towards the two adjacent maxima. When there is a transition from low-to-high or high-to-low in the NRZ drive voltage, the output state of the MZM is swept from a maximum, through a minimum, to an adjacent maximum, so generating a dark

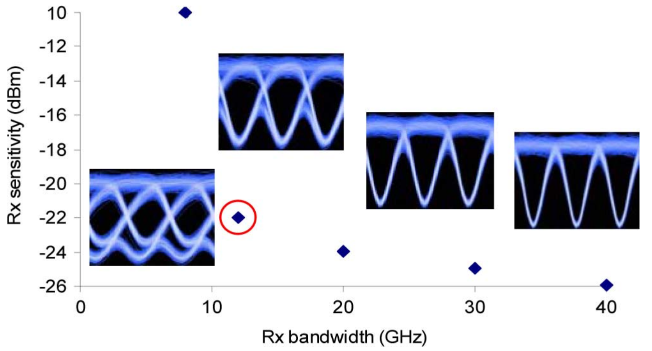

Fig. 5. Simulated Rx sensitivities of the DRZ signal detected by different Rx bandwidth. Inset: eye diagrams at bandwidths 12, 20, 30, and 40 GHz.

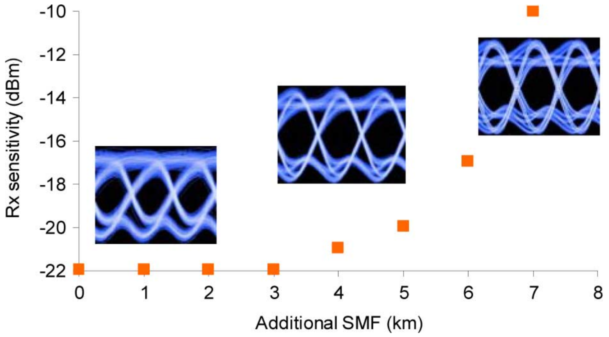

Fig. 6. Simulated Rx sensitivities of the received DRZ signal at different residual dispersions set by additional lengths of fibers. Inset: eye diagrams at B2B, additional SMF of 5 and 6 km.

optical pulse. This is similar to differential phase-shift keying (DPSK) generation, but the data is encoded onto the intensity instead of the phase of the optical carrier. The DRZ propagated through 100-km SMF (dispersion parameter: 17 ps/nm/km) and 17-km dispersion-compensating fiber (DCF) (dispersion parameter: -100 ps/nm/km) and the RN. A fixed attenuator (FA) of -21 dB was used to emulate the fiber splitter. The signal was then detected by the optically preamplified Rx, which consisted of a VOA, an EDFA (noise figure 5 dB), an optical fiber (Gaussian-shaped, 3-dB bandwidth of 100 GHz) to filter the out-of-band amplified spontaneous emission (ASE), and a PIN photodiode (PD). An electrical third-order Bessel low-pass filter (LPF) was used to model different bandwidth of the PD.

Fig. 5 shows the Rx sensitivities of the received DRZ signals detected by using different Rx bandwidths, with the corresponding eye diagrams at bandwidths 12, 20, 30, and 40 GHz. By reducing the Rx bandwidth from 40 to 12 GHz, we only sacrifice $\sim$4 dB in the Rx sensitivity, and the costly 40-GHz Rx can be removed from the ONU. For PON applications, although the long-reach feeder fiber can be dispersion-compensated, the distribution/drop fibers (between ONUs and the splitter) cannot. Then we evaluated the dispersion tolerance of the 40-Gb/s DRZ signal. The residual dispersion was set with additional lengths of fibers, and the Rx bandwidth was 12 GHz. Fig. 6 shows that the 2-dB penalty window is at $\sim$5-km SMF; and this is good enough for PONs. Corresponding eye diagrams at B2B and additional SMF of 5 and 6 km are shown in the insets.

We numerically analyzed the dispersion tolerance of the proposed network. For the 10-Gb/s upstream signal, the power penalty is 2 dB at dispersion $=$ 42 ps/nm (12 km of DSF), $\sim$0 dB at dispersion $=$ 24.5 ps/nm (7 km of DSF), and $\sim$7 dB at dispersion $=$ 59.5 ps/nm (17 km of DSF). For the 40-Gb/s downstream signal, the power penalty is negligible at dispersion $=$ 42 ps/nm (12 km of DSF) and 24.5 ps/nm (7 km of DSF); and power penalty $<$1 dB at dispersion $=$ 59.5 ps/nm (17 km of DSF).

V. CONCLUSION

We demonstrated a 40-Gb/s high-split-ratio PON and presented the first demonstration of using a directly modulated, 1.55-μm VCSEL for upstream Tx in the 40-Gb/s PON. Simulation results show that 12-GHz Rx can be used in the ONU to receive the 40-Gb/s DRZ downstream signal. Hence, expensive 40-GHz optical components can be removed in the cost-sensitive ONU for the future 40-Gb/s high-split-ratio PON. In this scheme, there is a trade-off of using lower speed optical component in the ONU or better receiver sensitivity.

ACKNOWLEDGMENT

The authors thank Phytrex Technology Corp. for useful discussions.

REFERENCES

[1] R. P. Davey, P. Healey, I. Hope, P. Watkinson, D. B. Payne, O. Marmur, J. Ruhmann, and Y. Zuiderveld, "DWDM reach extension of a GPON to 135 km," in *Proc. OFC'05*, Anaheim, CA, Mar. 2005, Paper PDP35.

[2] D. Shea, A. Ellis, D. Payne, R. Davey, and J. Mitchell, "10 Gbit/s PON with 100 km reach and x1024 split," in *Proc. ECOC'03*, Italy, 2003, Paper We4P.147.

[3] D. Nessett, M. Scopes, R. Davey, D. Shea, P. Healey, A. Borghesani, D. Moodie, A. Poustie, and R. Wyatt, "Demonstration of 100 km reach amplified PONs with upstream bit-rates of 2.5 Gb/s and 10 Gb/s," in *Proc. ECOC'04*, Stockholm, Sweden, 2004, Paper We2.6.3.

[4] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM long reach PON for next generation optical access," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2827–2834, Jul. 2006.

[5] G. Talli, C. W. Chow, E. K. MacHale, and P. D. Townsend, "Rayleigh noise mitigation in long-reach hybrid DWDM-TDM PONs," *J. Opt. Networking*, vol. 6, no. 6, pp. 765–776, Jun. 2007.

[6] C. W. Chow, C. H. Yeh, C. H. Wang, F. Y. Shih, and S. Chi, "Signal remodulation of OFDM-QAM for long reach carrier distributed passive optical networks," *IEEE Photon. Technol. Lett.*, vol. 21, no. 11, pp. 715–717, Jun. 1, 2009.

[7] M.-F. Huang, J. Yu, D. Qian, N. Cvijetic, and G.-K. Chang, "Lightwave centralized WDM-OFDM-PON network employing cost-effective directly modulated laser," in *Proc. OFC'09*, Anaheim, CA, Paper OMV5.

[8] P.-L. Tien, Y.-M. Lin, and M. C. Yuang, "A novel OFDMA-PON architecture toward seamless broadband and wireless integration," in *Proc. OFC'09*, Anaheim, CA, Paper OMV2.

[9] D. Qian, J. Hu, P. N. Ji, and T. Wang, "10.8-Gb/s OFDMA-PON transmission performance study," in *Proc. OFC'09*, Anaheim, CA, Paper NME6.

[10] D. Qian, N. Cvijetic, J. Hu, and T. Wang, "40-Gb/s MIMO-OFDM-PON using polarization multiplexing and direct-detection," in *Proc. OFC'09*, San Diego, CA, Paper OMV3.

[11] W. Hofmann, M. Müller, G. Böuhm, M. Ortsiefer, and M.-C. Amann, "1.55 μm InP-based VCSEL with enhanced modulation bandwidths $>$10 GHz up to 85°C," in *Proc. OFC'09*, Anaheim, CA, Paper OTuK5.

[12] W. Hofmann, N. H. Zhu, M. Ortsiefer, G. Böuhm, Y. Liu, and M.-C. Amann, "High speed $>$11 GHz modulation of BCB-passivated 1.55 um InGaAlAs–InP VCSELs," *Electron. Lett.*, vol. 42, pp. 976–977, 2006.