Cascade Laser Power Converter for Simultaneous 10 Gbps Data Detection and Efficient Optical-to-Electrical DC Power Generation

F.-M. Kuo[1], S.-S. Lo[2], Ci-Ling Pan[3], and J.-W. Shi[1*]
[1]*Department of Electrical Engineering, National Central University*
Taoyuan 320, Taiwan
**Tel: +886-3-4227151 ext. 34466*
**FAX: +886-3-4255830*
**Email: jwshi@ee.ncu.edu.tw*
[2] *Department of Photonics and Institute of Electro-Optics, National Chiao Tung University, Hsinchu, 300, Taiwan*
[3]*Department of Physics, National Tsing-Hua University, Hsinchu, 300, Taiwan*

Abstract: We demonstrate a novel device; cascade high-speed laser power converter. Error-free 10 Gbit/sec data detection and 21.1% optical-to-electrical DC power generation efficiency can be achieved simultaneously at 850nm wavelength and +1V voltage.

OCIS codes: (230.5170) Photodiodes; (040.5350) Photovoltaic

I. Introduction

Recently, the idea of the “green internet”, which means reducing the energy consumption of the whole internet service or by use of the internet service to reduce the global energy consumption, has come into vogue [1]. The development of optical interconnect (OI) techniques [2,3], which could allow the replacement of the bulky and power-hungry active/passive microwave components with more energy-saving and high-speed optoelectronic devices, is one attractive way to realize such idea. However, for the case of traditional p-i-n photodiode in OI system, reverse bias operation is usually necessary to enhance the drift-velocity of hole and sustain its speed/responsivity performance. This approach should definitely result in the power consumption with excess heat generation during high-speed optical data detection. Recently, by use of the structure of uni-traveling carrier PD (UTC-PD), high-speed with reasonable responsivity performance under zero-bias operation [4,5] has been demonstrated. In this paper, we demonstrate a novel device; linear cascade GaAs/AlGaAs based high-speed laser power converter (LPC) [6], which can exhibit the performance of high-speed PD even when its operating voltage is further pushed to forward bias. We can thus generate (instead of consuming) DC electrical power by use of such device during high-speed data transmission in OI system. A more efficient and energy-saving green OI system can be expected. Error-free 10 Gbit/sec (5 Gbit/sec) optical data detection with a 21.1% (34%) optical-to-electrical power generation efficiency can be achieved simultaneously by using our device with linear cascade structure [7] at 850nm optical wavelength, which is an attractive wavelength for the modern OI system due to the mature technology of high-speed 850nm vertical-cavity surface emitting laser (VCSEL) [8].

II. Device Structure

Figures 1 (a), (b), and (c) shows the top-view of single LPC, conceptual diagram of linear cascade LPCs, and the cross-sectional view of the fabricated devices. We adopted the structure of a typical vertical-illuminated PD with an active circular mesa and a p-type ring contact on the top. The diameter of the whole mesa and the inner circle for light illumination, were 28μm and 20μm, respectively. As shown in Figure 1(c), the epi-layer structure of our device is similar with our reported GaAs/AlGaAs based UTC-PD [5] at 850nm wavelength and is mainly consisted of a p-type GaAs based photo-absorption layer with a 450nm thickness and graded p-doped profile ($1\times10^{19} cm^{-3}$ (top) to $1\times10^{17} cm^{-3}$ (bottom)) to accelerate the diffusion velocity of photo-generated electron and a un-doped $Al_{0.15}Ga_{0.85}As$ based collector layer with a 750nm thickness. Compared with the structure of a traditional p-i-n PD, a much higher speed performance of UTC-PD under forward bias operation can be expected due to that only electron is the active carrier, which can exhibit a much faster drift-velocity than that of hole in p-i-n PD under a small electric field (~10 kV/cm). In order to minimize the electron current blocking effect under forward bias operation in the interface between collector and absorption layers due to discontinuities of their conduction bands, a thick (20nm) graded bandgap layer with n-type doping is inserted between such two layers. As can be seen in Figure 1(c), the whole epi-layer structure of our LPC was grown on the n-type distributed-brag reflector (DBR) to enhance its responsivity performance. The main drawback of photovoltaic LPC is its low output voltage, which is usually too low to directly power other active components in OI system. In order to boost the operation voltage of our LPC, we may let several high-speed LPCs be series-wound (linear cascade). Furthermore, an improved high-speed performance of linear cascade LPCs compared with that of a single device can be expected due to the reduction of junction capacitance [7]. Figure 1 (c) shows the conceptual diagram of our linear cascade two-LPCs. As can be seen, we use two bias tees to let such two LPCs be series-wound in their DC part and extract the output RF signal in one of the LPCs.

III.Measurement Result:

The measured DC responsivity of our device is around 0.41A/W, which corresponds to around 60% external quantum efficiency, under zero-bias operation. Such value slightly degrades to around 0.36A/W when the operating voltage reaches +0.9 V. A lightwave-component-analyzer (LCA) system was utilized to characterize the dynamic performance of the device under continuous-wave (CW) operation by measuring the frequency responses of the scattering (S) parameters. We employed a tunable semiconductor laser operated at 830nm as the light source for this system. The optical signal was injected into the device by using 2.5µm spot diameter lens-fiber. Figure 2 (a) and (b) shows the measured current-voltage (I-V) curves of our single LPC and linear cascade two-LPCs under different output photocurrents. As can be seen, the operation voltage of cascade device is around twice of the single cell with around one-half of the responsivity. Figure 2 (c) and (d) shows the measured optical-to-electrical (O-E) power conversion efficiency versus bias voltage of single device and cascaded two-LPCs under different optical pumping power, respectively. As can be seen, the maximum O-E power conversion efficiency of both devices under low pumping power and optimum bias voltage is around 34%, Figure 3 (a) and (b) shows the measured 3-dB optical-to-electrical (O-E) bandwidths versus forward operating voltage of single and linear cascade LPCs under different output photocurrents, respectively. The insets show the typical measured O-E frequency responses of single device and linear cascade two-LPC under the same effective forward (+0.5 and +1V, half of the turn-on) and reverse bias voltages (-3 and -6V). It can be seen that significant bandwidth degradation happens when both the forward bias (0 to +2V) and output photocurrent increase (50 µA to around 0.5mA), which can be attributed to serious photocurrent induced space-charge screening effect in our LPC with an extremely small electric field inside [4]. In addition, compared with the single device, the liner cascade LPC exhibits a faster speed performance under the same effective bias voltage, as shown in the insets of Figure 3. Under the +1V bias and 50 µA output photocurrent of linear cascade LPC, which corresponds to +0.5V bias on single device, the measured 3-dB bandwidth of cascade and single device is around 9 and 6GHz, respectively. Even when the output photocurrent of linear cascade device reaches 0.2mA, a 7.6 GHz 3-dB bandwidth can still be maintained, which clearly indicates the capability of our linear cascade LPC for 10 Gbit/sec data transmission under +1V bias voltage. The superior speed performance of cascade device may be attributed to the reduction of junction capacitance [7] and the detail mechanism will be reported somewhere else. Figure 4 (a) and (b) shows the measured bit error-rate (BER) versus forward bias voltage under different output photocurrents of single device at 5 Gbit/sec and linear cascade device at 10 Gbit/sec (pseudo random bit sequence, PRBS: 2^{15}-1), respectively. The insets show the corresponding eye-patterns at 5 and 10 Gbit/sec. As can be seen, regarding with the single-device, it can achieve the performance of 5 Gbit/sec error-free (BER$<10^{-9}$) data transmission even under the +1V bias voltage with around 0.2mA output photocurrent, which corresponds to around 34% O-E power conversion efficiency. On the other hand, by use of linear cascade structure, the error-free transmission data rate can be further boosted up to 10 Gibt/sec under the same operating voltage (+1V) and output photocurrent (0.2mA) with the degradation of conversion efficiency from 34 to 21.1%.

IV.Summary:

In conclusion, we have demonstrated a novel linear cascade high-speed LPC, which can sustain high-speed and high-responsivity performance even under forward operation and generate DC electrical power. This result overthrows the rule of high-speed PDs, which states that it must be a power-consumed device under reverse bias. Error-free 10 Gbit/sec data detection and 21.1% O-E power generation efficiency can be achieved simultaneously at +1 V forward bias and 850nm optical wavelength. This work was sponsored by the National Science Council of Taiwan under grant number NSC-96-2221-E-008-121-MY3.

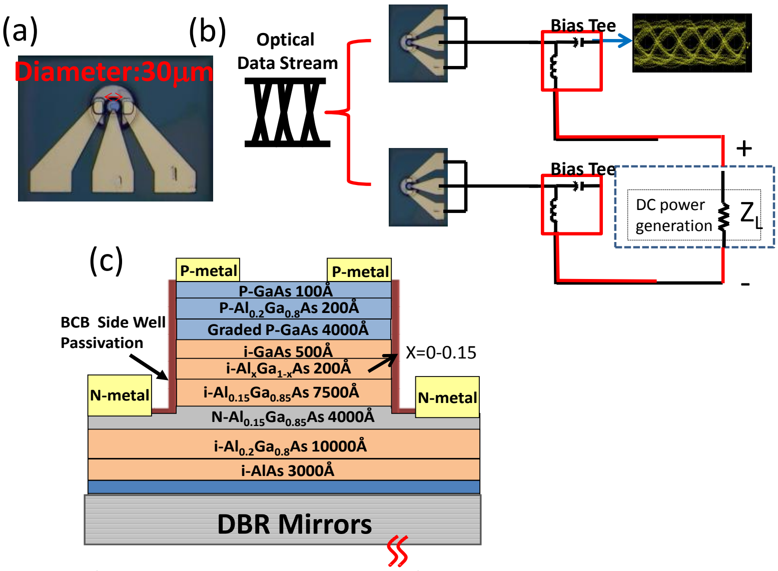

Figure 1. The (a) top-view of single device, (b) conceptual view of linear cascade device, and (c) the cross-sectional view of demonstrated high-speed LPC

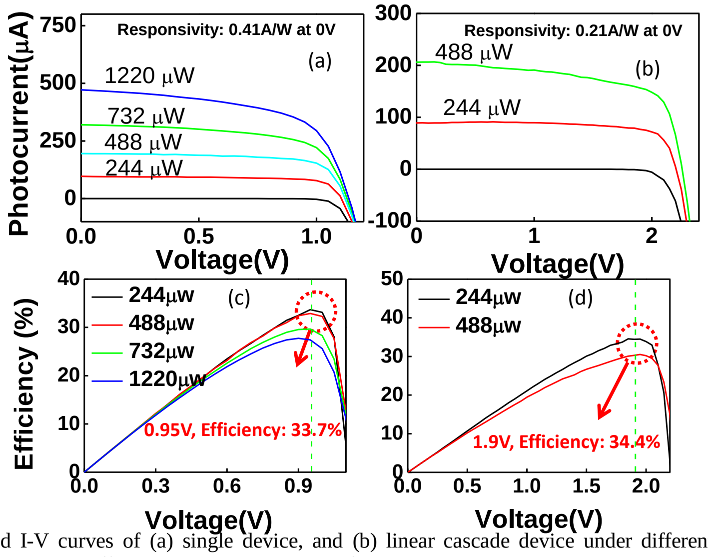

Figure 2. The measured I-V curves of (a) single device, and (b) linear cascade device under different optical pumping power. The measured O-E power conversion efficiencies vs. bias voltage of (c) single device, and (d) linear cascade device under different optical pumping power.

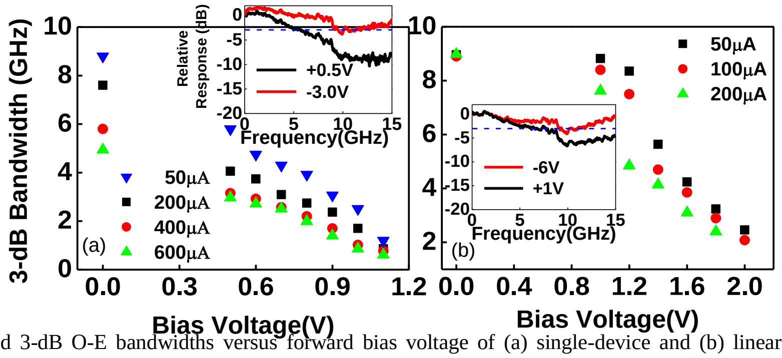

Figure 3. The measured 3-dB O-E bandwidths versus forward bias voltage of (a) single-device and (b) linear-cascade device under different output photocurrents. The inset in (a) and (b) shows the measured O-E frequency responses of single device and linear cascade device, respectively, under forward and reverse bias voltages.

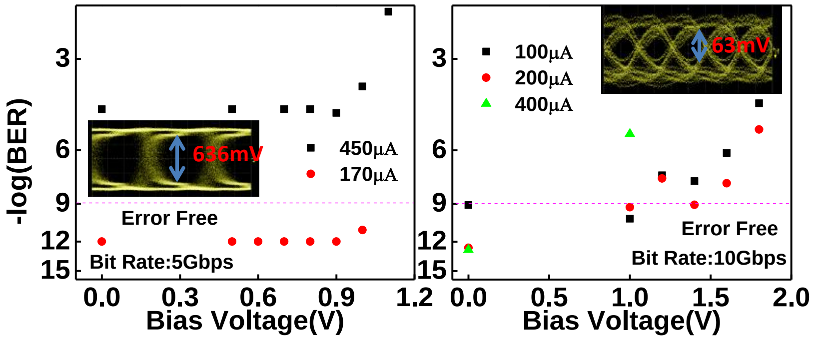

Figure 4. The measured BER versus forward bias voltages of (a) single device at 5 Gbit/sec and (b) linear cascade device at 10 Gbit/sec under different output photocurrents. The insets show the corresponding 5 Gbit/sec and 10 Gbit/sec eye-patterns.

V. References:

[1] R. S. Tucker, "A Green Internet," IEEE Lasers and Electro-Optics Society 2008(LEOS/2008) Annual Meeting, PLE3, 2008

[2] C. L. Schow, F. E. Doany, C. Tsang, N. Ruiz, D. Kuchta, C. Patel, R. Horton, J. Knickerbocker, and J. Kash, "300-Gb/s, 24-Channel Full-Duplex, 850-nm CMOS-Based Optical Transceivers," *Proc. OFC 2008, San Diego*, CA, USA, Feb., 2008, pp. OMK5.

[3] M. Oda, J. Sakai, H. Takahashi, and H. Kouta, "Chip-to-Chip Optical Interconnection for Next-generation High-performance Systems," IEEE Lasers and Electro-Optics Society 2007(LEOS/2007) Annual Meeting, WAA1, 2007

[4] H. Ito, S. Kodama, Y. Muramoto, T. Furuta, T. Nagatsuma, T. Ishibashi, "High-Speed and High-Output InP-InGaAs Unitraveling-Carrier Photodiodes," *IEEE J. of Sel. Topics in Quantum Electronics*, vol. 10, pp.709-727, Jul./Aug., 2004.

[5] J.-W. Shi, F.-M. Kuo, T.-C. Hsu, Ying-Jay Yang, Andrew Joel, Mark Mattingley, and J.-I. Chyi, "The Monolithic Integration of GaAs/AlGaAs Based Uni-Traveling-Carrier Photodiodes with Zn-Diffusion Vertical-Cavity Surface-Emitting Lasers with Extremely High Data-Rate/Power-Consumption Ratios" *IEEE Photon. Technol. Lett.*, vol. 21, pp. 1444-1446, Oct., 2009.

[6] J. Schubert E. Oliva, F. Dimroth, W. Guter, R. Loeckenhoff, and A. W. Bett, "High-Voltage GaAs Photovoltaic Laser Power Converters," *IEEE Trans. Electron Device*, vol. 56, pp. 170-175, Feb., 2009.

[7] J.-W. Shi, F.-M. Kuo, and M.-Z. Chou, "A Linear Cascade Near-Ballistic Uni-Traveling-Carrier Photodiodes with Extremely High Saturation-Current Bandwidth Product (6825mA-GHz, 75mA/91GHz) under a 50Ω Load," *Postdeadline Papers OFC 2010, San Diego*, CA, USA, March, 2010, PDP 6.

[8] P. Westbergh, J. S. Gustavsson, A. Haglund, A. Larsson, F. Hopfer, G. Fiol, D. Bimberg, and A. Joel, "32Gbit/sec multimode fiber transmission using high-speed, low current density 850nm VCSEL," *Electron. Lett.*, vol. 45, no. 7, March, 2009.