Abstract—An 850-nm multi-mode vertical cavity surface emitting laser (VCSEL) bare chip with high-indium-density InGaAs/AlGaAs quantum-well pairs is demonstrated for directly encoded QAM-OFDM transmission in multi-mode fiber (MMF). By directly encoding the 850-nm VCSEL bare chip with a pre-leveled 14-GHz 16-QAM OFDM data, >50-Gbit/s transmission over 100-m-long OM4 MMF can be realized without using data recovery circuit. Increasing the bias current of the VCSEL beyond 7.5mA improves the signal-to-noise ratio (SNR) and bit error ratio (BER) of received QAM-OFDM data to 15.5 dB and 2.9 x 10^-3, respectively. The 100-m-long OM4 MMF transmission degrades the SNR with its covered bandwidth reducing to 13 GHz. The OFDM subcarrier pre-leveling technique with a slope of 0.2 dB/GHz ensures the 16-QAM-OFDM data transmission with an error vector magnitude of 17.1% and a BER of 3.4 x 10^-3.

Index Terms—Vertical cavity surface emitting lasers, fiber optics, infrared, optical interconnects.

I. INTRODUCTION

To improve access flexibility and increase the capacity of data streaming, storage, and exchange, numerous data centers that are equipped with short-reach optical interconnects by using intensity modulation and direct detection (IM/DD) architecture have been developed, providing a data rate of 100 Gbit/s [1], [2]. However, a rapid increase in data traffic creates difficulties for data centers in accessing data streams with higher capacities or more formats from numerous multimedia. Prospectively, the 400-Gbit/s standard (i.e. IEEE P802.11) will replace the currently available 100-Gbit/s optical interconnect in 2018-2019 [3]. With limited transmission distances and fixed modulation levels, an increase in channel numbers is necessary to realize an IM/DD interconnect data rate of up to 400 Gbit/s. To achieve high-speed transmission in data centers, a single-mode laser externally modulated by a Mach-Zehnder modulator (MZM) is typically employed [4]. However, the infrastructural cost of data centers might be increased when considering the compensation of inevitable insertion loss caused by the MZM with the use of optical amplification. Alternatively, directly modulated vertical cavity surface emitting lasers (VCSELs) with a sufficient modulation bandwidth can be introduced for realizing high-speed, error-free and cost-effective optical interconnects at 20 and 40 Gbit/s, respectively [5], [6]. VCSELs have numerous practical applications [7]-[10], offering advantages including high power-conversion efficiency with a low threshold current, efficient data transmission with a large modulation bandwidth, and low-loss fiber coupling with a circular mode field [11]. In the near future, the integrated VCSEL array (e.g., 16 x 25 Gbit/s or 8 x 50 Gbit/s) might become the standard transmitter for realizing 400-Gbit/s optical interconnects.

Varied data formats are available for directly modulating VCSELs, such as on-off-keying (OOK), pulse amplitude modulation (PAM), and orthogonal frequency division multiplexed quadrature amplitude modulation (QAM-OFDM) [12], [13]. Among these formats, OOK is the simplest and most mature for fiber optics communication and high-speed optical interconnects [14]. Recently, Kuchta et al. demonstrated a 71-Gbit/s OOK transmission link by using an 850-nm multimode VCSEL in conjunction with driving IC and feed-forward equalization [15]. The multimode VCSEL
simultaneously induces chromatic and modal dispersions during transmission in a multimode fiber (MMF), which limits the transmission distance of carried OOK data. By employing an 850-nm single-mode VCSEL, Stepniak et al. demonstrated an OOK transmission link achieving a 54-Gbit/s data rate over a 2.2-km MMF [16]. However, it required an increased modulation bandwidth. To achieve the same data rate, the PAM-4 format required only half the modulation bandwidth [17]. In 2015, Karinou et al. successfully employed the PAM-4 format in directly modulating a 1530-nm VCSEL to implement data center interconnects at a data rate of up to 56 Gbit/s/λ [18]. However, the PAM-4 format with multilevel amplitude requires a VCSEL with markedly high differential quantum efficiency (modulation transfer function) to achieve high transmission performance. Note that the differential quantum efficiency (n0) which is defined as the ratio of output photon number to input electron number, as defined by the multiplying factor of q/hv with the first-order derivative of the power-to-current response of a laser diode, and the modulation transfer function of a laser is proportional to its differential quantum efficiency [19]. Compared with the OOK and PAM-4 data formats, the QAM-OFDM format provides the highest spectral usage efficiency [20]-[22] and can effectively reduce the required linearity of the modulation transfer function of the VCSEL. The use of QAM-OFDM data with high spectral usage efficiency is to enable the efficient use on the available bandwidth of transmitters for supporting high capacity. In addition, it provides a great immunity to the multi-path delay spreading induced inter-symbol interference during transmission in fiber. However, the QAM-OFDM data with high peak-to-average power ratio inevitably induces nonlinear distortion during amplification [23]. This practically limits its allowable capacity and reachable transmission distance. In 2007, Lee et al. used a discrete multi-tone (DMT) data format to adaptively modulate the VCSEL for implementing 24-Gbit/s transmission over 730-m MMF [24]. A recent study proposed using a bit-loading algorithm and a single-mode VCSEL to achieve a nearly 50-Gbit/s OFDM link over a 2.2-km OM4 fiber [25]. By employing a single transverse mode VCSEL, Bo et al. successfully demonstrated a 100-Gbit/s DMT transmission over 100-m MMF in 2016 [26]. Studies have demonstrated that the OFDM subcarrier pre-leveling technique effectively reduces chromatic dispersion induced signal-to-noise ratio (SNR) degradation during transmission in a single-mode fiber [27], which multiples weighting factors with different positive power-to-frequency slopes onto the OFDM subcarriers to pre-compensate the decline throughout after transmission. Nonetheless, pre-leveled QAM-OFDM modulation of an 850-nm multimode VCSEL for MMF transmission has yet to be performed.

In this study, an 850-nm multi-mode VCSEL bare chip with 4 pairs of high-indium-density InGaAs/AlGaAs quantum-wells is designed and fabricated for directly encoded QAM-OFDM transmission in MMF. The 850-nm multimode VCSEL chip directly modulated with pre-leveled 16-QAM OFDM data is demonstrated in 52-Gbit/s transmission over a 100-m MMF. The output characteristics of the proposed VCSEL chip include light-current response, slope efficiency, central wavelength, and frequency bandwidth. Additionally, the bias current of the VCSEL chip is optimized to improve the transmitted error vector magnitude (EVM), SNR, and bit error ratio (BER). By scaling the subcarriers with pre-leveled amplitudes, transmissions over a 100-m OM4 MMF is further optimized.

II. EXPERIMENTAL SETUP

Fig. 1 presents the 850-nm multimode VCSEL bare chip with a coplanar-waveguide type metal pad configuration. To enhance the high-speed encoding performance, the 850-nm VCSEL with four pairs of In0.15Ga0.85As/Al0.37Ga0.63As quantum wells was designed, and a 3λ/2 cavity was added to provide a higher differential gain at elevated temperatures. By doping the active region with indium at a high concentration of 15%, the highest energies of heavy-hole and light-hole bands of the VCSEL were separated each other, which provides a low-density state near the maximum of the valence band [28]. In addition, an oxide-confined aperture of 11 μm was implemented to control the transverse mode output of the VCSEL, which helps to improve the high-speed characteristics with a semiconductor VCSEL mesa of 18 μm. Fig. 1 also shows the metal pads of the VCSEL bare chip, which is designed as a low-parasitic-capacitance ground-signal-ground (GSG) contact configuration. The two gaps between GSG metal pads are set to 20 μm for reducing the parasitic capacitance to ~285 fF and resistance to ~4.35 Ω. The contact widths of the signal and ground pads are 120 and 130 μm, respectively, which can be contacted by coplanar GSG microprobes with a pitch of 100 μm.

![Fig. 1. The 850-nm multimode VCSEL bare chip and its metal pads configuration.](image-url)

A commercial probe station was employed for driving the VCSEL chip, and a liquid cooling system stabilized the operating temperature at 25°C. Fig. 2(a) illustrates the VCSEL bare chip and its output light that are contacted and collected by a coplanar GSG microprobe and a commercial OM4 lens fiber, respectively. Fig. 2(b) presents 16-QAM OFDM transmission over the OM4 MMF based on the multimode VCSEL chip at 850 nm. To generate the transmitted data, a Matlab program firstly mapped pseudo-random bit sequence data with a length of 215–1 onto QAM symbols and then assigned them to OFDM subcarriers. Through inverse fast Fourier transform (IFFT) with an FFT matrix size of 512, a temporal waveform of the 16-QAM-OFDM data stream was produced. The maximal number of total subcarriers in this QAM-OFDM format is 256. Each subcarrier is with a bandwidth of 97.66 MHz. To cover the allowable bandwidth of the VCSEL, the number of encoded...
subcarriers for the QAM-OFDM data is 144 to support a bandwidth of 14 GHz. The ratios of the training sequence, the cyclic prefix and the forward error correction (FEC) overhead of the produced OFDM data were set as 3.1%, 3.1%, and 7%, respectively. Subsequently, an electrical waveform was generated by a Tektronix 70001A arbitrary waveform generator (AWG) with the 3-dB analog bandwidth of 15 GHz, which sampled the electrical QAM-OFDM signal with a sampling rate of 50 GS/s. The resampled QAM-OFDM stream was generated to directly encode the VCSEL through a high-speed bias-tee. For data center application, the output beam of the VCSEL chip was collected with a lens fiber and then launched into a 50/125-µm multi-mode fiber (MMF, OM4) with a length of 100 m. A GaAs PIN photodiode (PD, GCS, DO351) with an allowable bitrate of 25 Gbit/s was employed to receive the optical QAM-OFDM data. Additionally, a pair of electrical amplifiers with a power gain of 18 dB was employed to boost the received data. At receiving end, the received QAM-OFDM data is captured by using a digital real-time oscilloscope (Tektronix-71604C) with a 100-GS/s sampling rate and the 3-dB analog bandwidth of 16 GHz and off-line analyzed by using an homemade MATLAB decoding program to determine its EVM, SNR, and BER performances. There is no error correction chip used in the work, and the digital signal processing (DSP) is also implemented during the off-line demodulation.

The schematic diagram of the decoding program for the received QAM-OFDM data is shown in Fig. 3. At beginning, the received data waveform in time domain obtained from the digital real-time oscilloscope is sending into a fast Fourier transform sub-program after removing the CP. Subsequently, the obtained matrix elements are converted from serial sequence to parallel sequence for separating all of the data encoded on subcarriers. The parallel sequence data are equalized, and each data sequence is analyzed to obtain the respective EVM, SNR, and BER [29], [30].

III. RESULTS AND DISCUSSION

The power-to-current (P-I) response and corresponding slope efficiency (dP/dI) of the VCSEL chip at different bias currents are illustrated in Fig. 4(a), and a threshold current of 1.7 mA was observed. Although a saturated trend in the P-I response was revealed after increasing the bias current to greater than 14.8 mA (~8.7 Ith), an output maximum of 8.5 mW could still be obtained by continually enlarging the bias current up to 18 mA (~10.6 Ith). Additionally, we observe the distinct change of the dP/dI response after lasing the multi-mode VCSEL at a bias current of 17.1 mA. Such a kink occurred on the P-I curve is mainly attributed to the increase of lasing transverse modes from lower order to higher order. In principle, the kink effect is defined as either the nonlinearities (including the enriching modes and the mode hopping phenomenon) or the dynamic instabilities (including the coherence collapse and the self-/external-feedback) of the laser diode, which causes a corresponding change on the slope of the P-I throughput [31]. At even larger bias condition, the Auger effect which saturates the output power of the VCSEL practically limited both the allowable dc bias current and the modulation range of the VCSEL chip. Fig. 4(b) presents the bias current dependent compliance voltage and resistance responses of the VCSEL chip. The resistance approached 50 Ω for perfect impedance matching at a bias current of 9.9 mA, which enabled the greatest direct modulation depth of QAM-OFDM data. Moreover, the free-running VCSEL without modulation exhibited a central wavelength of 862.08 nm with a spectrum width of 7.11 nm (ranging between 856.07 and 863.18 nm), as shown in Fig. 4(c).

Fig. 4(d) shows the bias-dependent modulation throughputs

![Diagram](image-url)
of the VCSEL chip; it exhibited a relaxation oscillation frequency of 4.3 GHz and a 3-dB modulation bandwidth of 7 GHz when the dc bias was increased to 4 mA. By continually enlarging the bias current to 18 mA, the 3-dB bandwidth could be further enlarged to 15.2 GHz. For data encoding, electrical 16-QAM OFDM data with a peak-to-peak amplitude of 500 mV was employed to directly modulate the VCSEL chip, which covered a bandwidth of 14 GHz to provide a raw data rate of up to 56 Gbit/s (48.6 Gbit/s after removing the overhead). For OFDM data analysis, EVM is widely employed in optical communication systems for evaluating the signal quality, e.g., direct-detection optical OFDM systems [32], and bit- and power-loading systems [33]. The relationship among EVM, SNR and BER was simulated via Monte Carlo method by R. A. Shafik [34], and was experimentally verified [35], [36] with a good agreement of the theoretical analysis. That is, there will be almost identical BER obtained either by directly counting the bits or by calculating from the EVM under sufficient sampling rate [34]-[36]. EVM and BER are a one-to-one correspondence, in which a smaller EVM represents a better BER performance. As applying a FEC criterion with 7% overhead, the BER threshold of 3.8×10⁻³ is given by an EVM of 17.4% for 16-QAM OFDM. The SNR of the nth OFDM subcarrier was calculated using the following equation [34], [37]:

\[ SNR(n) = \frac{1}{1 + \frac{1}{2(BW)(M-1)}} \times \frac{3SNR}{2(M-1)} + \text{erfc} \left( \frac{3SNR}{2(M-1)} \right) \],

where \( S(n) \) denotes the received and normalized nth OFDM subcarrier, which is corrupted by channel response and noise; \( S(n) \), the ideal normalized constellation point of the nth OFDM subcarrier; and \( P(n) \), the average power of the nth OFDM subcarrier. Furthermore, the BER of the QAM-OFDM data is estimated by using the following equation [38]:

\[ BER \approx \frac{1}{\log_{2} M} + \frac{3}{2(M-1)} \times \text{erfc} \left( \frac{3SNR}{2(M-1)} \right), \]

where \( M \) denotes the QAM level.

\[ E_{b} = P_{total}/R, \] where \( P_{total} \) denotes the total required power of the active optical link and \( R \) denotes the bit rate [40]. In this work, the used active components include VCSEL and PD. Therin the bias current of the VCSEL is optimized to 13 mA with a corresponding compliance voltage of 2.44 V, which reveals a power \((P_{VCSEL})\) of 31.72 mW. After receiving the QAM-OFDM data at an optical power of 3.5 mW, the photodiode is biased at a reverse bias voltage of 3 V with a photocurrent of 0.32 mA to indicate a power \((P_{PD})\) of 0.96 mW. Therefore the required total power \((P_{total})\) for the proposed active optical link is \( P_{total} = P_{VCSEL} + P_{PD} = 4.46 \) mW. For the achieved bit rates of 56 and 52 Gbit/s at back-to-back and 100-m MMF transmission cases, the corresponding energy per bits of 79 and 86 fJ/bit can be obtained. Note that the energy per bit can also be expressed as \( E_{b} = P_{total}/R = W \times k \), where \( W \) denotes the required double-sideband (DSB) bandwidth and \( k \) the bit-number per symbol [40]. For achieving the same bit rate of 56 Gbit/s, the bit-number per symbols and required DSB bandwidths of OOK, PAM-4, and 16-QAM OFDM data are 1/24 and 112/56/28 GHz, respectively. By substituting these parameters into the above equation, three different data formats obtain the same energy per bit of 79 fJ/bit. Disregarding the very small detuning on the bias current for encoding different formats, the almost identical energy/bit consumption is obtained owing to the different spectral usage efficiencies among OOK, PAM-4, and QAM-OFDM data streams.

In principle, the energy per bit \((E_{b})\) can be expressed as \( E_{b} = P_{total}/R \), where \( P_{total} \) denotes the total required power of the active optical link and \( R \) denotes the bit rate [40]. In this work, the used active components include VCSEL and PD. Therin the bias current of the VCSEL is optimized to 13 mA with a corresponding compliance voltage of 2.44 V, which reveals a power \((P_{VCSEL})\) of 31.72 mW. After receiving the QAM-OFDM data at an optical power of 3.5 mW, the photodiode is biased at a reverse bias voltage of 3 V with a photocurrent of 0.32 mA to indicate a power \((P_{PD})\) of 0.96 mW. Therefore the required total power \((P_{total})\) for the proposed active optical link is \( P_{total} = P_{VCSEL} + P_{PD} = 4.46 \) mW. For the achieved bit rates of 56 and 52 Gbit/s at back-to-back and 100-m MMF transmission cases, the corresponding energy per bits of 79 and 86 fJ/bit can be obtained. Note that the energy per bit can also be expressed as \( E_{b} = P_{total}/R = W \times k \), where \( W \) denotes the required double-sideband (DSB) bandwidth and \( k \) the bit-number per symbol [40]. For achieving the same bit rate of 56 Gbit/s, the bit-number per symbols and required DSB bandwidths of OOK, PAM-4, and 16-QAM OFDM data are 1/24 and 112/56/28 GHz, respectively. By substituting these parameters into the above equation, three different data formats obtain the same energy per bit of 79 fJ/bit. Disregarding the very small detuning on the bias current for encoding different formats, the almost identical energy/bit consumption is obtained owing to the different spectral usage efficiencies among OOK, PAM-4, and QAM-OFDM data streams.

The average SNR slightly decreased from 15.5 to 14.7 dB, and its compensation with the OFDM subcarrier amplitude pre-leveling technology was required. With a properly selected slope (defined as \( R = dP/df \) in unit of dB/GHz) of 0.2 dB/GHz on the envelope of OFDM subcarrier amplitudes, SNR degradation can be mitigated. Therefore, the EVM and the BER
of 100-m OM4 MMF transmitted 56-Gbit/s data were slightly reduced from 18.3% to 18.1% and from 5.6 \times 10^{-3} to 5.2 \times 10^{-3}, respectively, which failed to meet the FEC-required EVM of 17.4% and BER of 3.8 \times 10^{-3}, as presented in Fig. 5(d). The BER could not be further optimized by continually scaling up the pre-leveling slope because the subcarrier SNRs at low frequencies would be sacrificed accordingly. To suppress the SNR degradation to achieve 100-m OM4 MMF transmission by shrinking the data bandwidth, the modulation bandwidth of the 16-QAM OFDM data was slightly reduced to 13 GHz at a cost of reducing the transmission capacity by 4 Gbit/s. By introducing pre-leveling with a slope of 0.2 dB/GHz, the received EVM and BER of the QAM-OFDM data could be improved from 17.5% to 17.1% and from 4.1 \times 10^{-3} to 3.4 \times 10^{-3}, respectively. Constellation plots of the VCSEL chip carried 14-GHz 16-QAM OFDM data at 56 Gbit/s before and after 100-m OM4 MMF transmissions are illustrated in Fig. 6. The BtB transmitted data had the clearest constellation plot with an average EVM of 16.7%. The average EVM was increased to 18.3% after transmission through the 100-m OM4 MMF, and the constellation plot became blurred as both chromatic dispersion and power fading affected the data waveform distortion. The amplitude pre-levelled OFDM subcarriers could reduce the EVM only to 18.1%, which is higher than the FEC-required EVM of 17.4%. Reducing the OFDM bandwidth to 13 GHz reduced the EVM to 17.5%, and pre-leveling the OFDM amplitude with a slope of 0.2 dB/GHz further optimized the EVM to 17.1% after 100-m OM4 MMF transmission at 52 Gbit/s (45.1 Gbit/s after removing the overhead).

![Fig. 6. Constellation plots of VCSEL chip carried 16-QAM OFDM data before and after 100-m OM4 MMF transmissions.](image)

### IV. CONCLUSION

An 850-nm multi-mode VCSEL bare chip with high-indium-density InGaAs/AlGaAs quantum-well pairs is demonstrated to operate the direct encoding of high-spectral-usage-efficiency data beyond 50 Gbit/s. For directly encoded transmission without using data recovery circuit, the MMF transmission of directly 16-QAM OFDM encoded multi-mode VCSEL bare chip beyond 50 Gbit/s is achieved. To enhance the spectral-usage efficiency of directly modulated transmitters for data centers, the pre-leveled 16-QAM OFDM of a multi-mode VCSEL chip at 850 nm was demonstrated for 52-Gbit/s transmission over a 100-m OM4 MMF. At a bias current of 18 mA (equivalent to 10.6I_{th}), the proposed VCSEL chip provides an output maximum of 8.5 mW and exhibits a 3-dB modulation bandwidth of 15.2 GHz. The optical spectrum indicates that the central wavelength of the VCSEL chip is located at 862.08 nm with a FWHM of 7.11 nm. Setting the bias current at 9.9 mA optimizes impedance matching between the VCSEL chip and the driving circuit under direct QAM-OFDM modulation. In BtB transmission with a modulation bandwidth of 14 GHz, optimizing the bias current to 13 mA improves the EVM, SNR and BER of BtB transmitted 56-Gbit/s 16-QAM-OFDM data to 16.7%, 15.5 dB and 2.9 \times 10^{-3}, respectively. After 100-m OM4 MMF transmission, the SNR degradation can be mitigated by slightly reducing the OFDM data bandwidth to 13 GHz and increasing the OFDM amplitude pre-leveling slope to 0.2 dB/GHz. This successfully provides QAM-OFDM data transmission at up to 52 Gbit/s with an FEC-certified EVM of 17.1% and a BER of 3.4 \times 10^{-3}.

### REFERENCES


1310 nm Vertical Cavity Surface Emitting Lasers (VCSELs) for optical interconnect applications and Optical-Electronics device package and modulation.

Yun-Chen Wu was born in Kaohsiung, Taiwan April 14, 1991. He is received his B.S. degree in Photonics from National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 2013 and M.S. degrees in Integrated Optoelectronic Device Laboratory, Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, Taiwan, R.O.C. His researching interests include high-speed integrated optoelectronic Resonance Cavity Light-emitting Transistors (RLCETs) and Vertical Cavity Transistor Lasers (VCTLs) and high speed Vertical Cavity Surface Emitting Lasers (VCSELs) for optical interconnect applications.

Shan-Fong Leong received the B.S. degree in Electrophysics from National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 2014. He is currently working toward the M.S. in the Integrated Optoelectronic Device Laboratory, Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, Taiwan, R.O.C. His researching interests include high-speed integrated optoelectronic 980 nm Light-emitting Transistors (LETs) and 980 nm Vertical Cavity Transistor Lasers (VCTLs) and high speed 850 nm and 1310 nm Vertical Cavity Surface Emitting Lasers (VCSELs) for optical interconnect applications.

Hsuan-Yun Kao received his B.S. degree in Department of Photonics from National Cheng Kung University, Tainan, Taiwan, R.O.C., 2015. He is the M.S. student in the Laboratory of Fiber Laser Communication and Si Nano-Photonics, Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, Taiwan, R.O.C. His researching interests include fiber-optic communication systems, digital signal processing, optical data formats and laser devices.

Yu-Chi Chiu received his B.S. degree in Department of Electrical Engineering (EE) from National Taiwan University, Taipei, Taiwan, R.O.C. in 2005, the M.S. degree in Department of Electro–Optical Engineering from NTUT, Taiwan, in 2007, and the Ph. D. degree in Graduate Institute of Photonics and Optoelectronics (GIPO) from National Taiwan University (NTU), Taipei, Taiwan, in 2012. He is now a postdoctoral research scholar at the GIPO, NTU, Taiwan. Dr. Chiu has co-authored more than 75 papers in international periodicals and over 50 papers in international conferences. His research interests include semiconductor laser diodes and optical amplifiers, fiber-optic communication, optoelectronic oscillator, all-optical signal processing, visible light communication and millimeter-wave radio fiber systems.

Hao-Chung Kuo (S’98–M’99–SM’06–F’14) received the B.S. degree in physics from National Taiwan University, Taipei, Taiwan, the M.S. degree in electrical and computer engineering from Rutgers University, New Brunswick, NJ, USA, in 1995, and the Ph.D. degree from the University of Illinois at Urbana Champaign, Urbana, IL, USA, in 1999. He has an extensive professional career both in research and industrial research institutions that includes: Research Assistant at Lucent Technologies, Bell Laboratories, from 1993 to 1995; and a Senior R&D Engineer in Fiber-Optics Division at Agilent Technologies from 1999 to 2001 and at LuxNet Corporation from 2001 to 2002. Since October 2002, he has been with the National Chiao Tung University (NCTU) as a Faculty Member of the Institute of Electro-Optical Engineering. He is currently the Associate Dean, Office of International Affairs, NCTU. He has authored and coauthored 300 international journal papers, two invited book chapters, six granted and 12 pending patents. His current research interests include semiconductor lasers, VCSELs, blue and UV LED lasers, quantum-confined optoelectronic structures, optoelectronic materials, and solar cell. He is an Associate Editor of the IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY and a Guest Editor of the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS issue on Solid-State Lighting in 2009. He received the Ta-Yau Wu Young Scholar Award from the National Science Council Taiwan in 2007 and the Young Photonics Researcher Award from OSA/SPIE Taipei chapter in 2007. He was elected as an OSA Fellow and the SPIE Fellow in 2012.

Jian Jang Huang (M’98–SM’08) received the B.S. degree in electrical engineering and the M.S. degree from the Graduate Institute of Photonics and Optoelectronics (GIPO), National Taiwan University (NTU), Taipei, Taiwan, in 1994 and 1996, respectively, and the Ph.D. degree in electrical engineering from the University of Illinois, Urbana-Champaign, Illinois, USA, in 2002. He is currently a Professor with GIPO, NTU.

Prof. Huang has been involved in applying nanostructures to optoelectronic devices. He developed a spin-coating method for nanosphere lithography, which can be applied to nanomaterials or nanostructures for significant performance improvement of light-emitting diodes, solar cells, and nanorod devices. His recent focus is on GaN-based power electronics, and applying nanostructures and field-effect transistors to wavelength division multiplexing (WDM) and long-reach passive optical networking (LR-PON) and optical data format such as orthogonal frequency-division multiplexing (OFDM) and multicarrier code division multiple access (MC-CDMA).

Zu-Kai Weng received his B.S. degree in the department of Engineering Science and Ocean Engineering from National Taiwan University, Taipei, Taiwan, R.O.C., in 2015. He is the M.S. student in the Laboratory of Fiber Laser Communication and Si Nano-Photonics, Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, Taiwan, R.O.C. His researching focuses on fiber-optic communication systems, all-optical millimeter-wave generation, millimeter-wave-over-fiber systems and laser devices.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JQE.2017.2703645, IEEE Journal of Quantum Electronics
Tai-Cheng Lee was born in Taiwan in 1970. He received the B.S. degree from National Taiwan University, Taipei, Taiwan, in 1992, the M.S. degree from Stanford University, Stanford, CA, USA, in 1994, and the Ph.D. degree from the University of California, Los Angeles, CA, USA, in 2001, all in electrical engineering.

He was with LSI Logic from 1994 to 1997 as a Circuit Design engineer. He served as an Adjunct Assistant Professor at the Graduate Institute of Electronics Engineering (GIEE), National Taiwan University, Taipei, Taiwan, from 2001 to 2002. Since 2002, he has been with the Electrical Engineering Department and GIEE, National Taiwan University, where he is a Professor. His main research interests are in high-speed mixed-signal and analog circuit design, data converters, PLL systems, and RF circuits.

Prof. Lee has served as an associate editor of IEEE Transactions on Circuits and Systems-II: Express Briefs since 2012.

Tien-Tsong Shih was born in Taiwan, R.O.C., in 1965. He received the B.S. and Ph.D. degrees from the National Chiao Tung University, Taiwan, R.O.C., in 1986 and 1991, respectively.

In 1991, he joined Telecommunication Laboratories, Taiwan, R.O.C. as a Research Associate. From 1996 to 2000, he was with Chunghwa Telecommunication Laboratories, Taiwan, R.O.C., as a Project Manager. In 2000, he founded the Inomax Optical Technology Corporation and was its CEO during 2000-2003. He is currently an Assistant Professor in the Department of Electronics Engineering, National Kaohsiung University of Applied Science, Kaohsiung, Taiwan, R.O.C. His research interests include the theoretical study of optical waveguides and III–V optoelectronic devices; fabrication of laser diodes, photodiodes, and planar lightwave circuits; packaging technology for optoelectronic devices; transceiver modules; and transmission technologies for fiber-optics communication applications.

Jau-Ji Jou received the B.S. and M.S. degrees in electronic engineering from the National Taiwan University of Science and Technology, Taipei, in 1993 and 1995, respectively. He is currently pursuing the Ph.D. degree in the Department of Electronic Engineering, National Taiwan University of Science and Technology. His research interests include fiber amplifiers, optical fiber communications, and optoelectronic devices.

Wood-Hi Cheng (M’95–SM’00–F’09) received the Ph.D. degree in physics from Oklahoma State University, Stillwater, OK, USA, in 1978. From 1994 to 2014, he was a Professor, the Director of the Institute of Electro-Optical Engineering, the Dean of College Engineering, the Director of the Southern Taiwan Opto-Electronics Center of Excellence, and a Chair Professor, all from National Sun Yat-sen University, Kaohsiung, Taiwan.

He is currently a Professor at the Graduate Institute of Optoelectronic Engineering, National Chung Hsing University, Taichung, Taiwan. His research and development has contributed to photonic package technologies, including high-speed laser module packaging, high-coupling devices and modules packaging, mode-locked fiber lasers employing carbon nanotubes and graphene, high-reliability glass-doped white-light-emitting diodes, wideband Ce-doped fibers, and 300-nm ultra broadband Cr-doped fiber amplifiers.

He served as the Chair for the IEEE Photonics Society, Taipei Chapter, from 1999–2000, served as the Chair for the OSA, Taipei Chapter from 2005–2006, and also served as the Program Director of Optoelectronics in the Ministry of Science and Technology (MOST) of Taiwan providing research grants and direction during 2009–2011. He received three-times Outstanding Research Award by the MOST, the IEEE Photonics Engineering Achievement Award in 2010 for his contributions to design, development, and commercialization of compact solid-state laser modules, and the 2011–2013 IEEE Photonics Society Distinguished Lecturer Award for the title of lecturers: The art and science of packaging photonic devices and modules and Broadband chromium-doped fiber amplifiers for next-generation optical communication systems. He is a Fellow of OSA and SPIE.

Gong-Ru Lin Gong-Ru Lin (S’93, M’96 and SM’04) received the B.S. degree from the Department of Physics, Soochow University, Taiwan, in 1988, the M.S. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 1990, and the Ph.D. degree from the Institute of Chiao Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 1996. He has been engaged with several universities in Taiwan from 1997-2006, and has promoted as associated professor in 2001 and full professor in 2004. Since 2006, He directs the Laboratory of Fiber Laser Communications and Si Nano-Photonics with the Graduate Institute of Photonics and Optoelectronics in National Taiwan University. He is the Senior Member of IEEE, the Fellow of SPIE, the Fellow of IET, the Fellow of OIP, and the Fellow of OSA. He serves as the Chair of IEEE Photonics Society Taipei Chapter from 2008-2011, and is currently the chair of GIPO in NTU. He has a broadband research spectrum covering the fiber-optical communications, the femtosecond mode-locked fiber lasers, the all-optical data processing, the nanocrystallite Si photonic, and the millimeter-wave photonic phase-locked loops.