IEICE TRANS. ELECTRON., VOL.E98–C, NO.8 AUGUST 2015

INVITED PAPER *Special Section on Microwave Photonics*

High-Power Photodiodes for Analog Applications

Andreas BELING[†a)], **Joe C. CAMPBELL**[†], **Kejia LI**[†], **Qinglong LI**[†], **Ye WANG**[†], **Madison E. WOODSON**[†],
Xiaojun XIE[†], ***and*** **Zhanyu YANG**[†], ***Nonmembers***

SUMMARY This paper summarizes recent progress on modified uni-traveling carrier photodiodes that have achieved RF output power levels of 1.8 Watt and 4.4 Watt in continuous wave and pulsed operation, respectively. Flip-chip bonded discrete photodiodes, narrowband photodiodes, and photodiodes integrated with antennas are described.

key words: *photodiode, photodetector, microwave photonics*

1. Introduction

High-power, high-speed photodiodes are being used in an increasing number of applications including fiber optic antenna links, radio frequency (RF) over fiber, and photonic generation of low phase noise microwave signals. The fact that the photodiode (PD) can be operated at high photocurrent levels provides several improvements in these systems including high dynamic range, high link gain, and low noise figure. In photonic wireless systems an antenna integrated photodiode can help to increase radiated RF power without the need for electronic amplification and hence simplify the RF circuitry at the antenna unit.

To achieve high RF output power, various photodiode structures have been developed [1]–[4] among which the uni-traveling carrier (UTC) photodiode [3] has demonstrated high saturation current and high bandwidth. We have developed charge-compensated modified uni-traveling carrier (MUTC) photodiodes flip-chip bonded on high-thermal conductivity substrates to address the two primary effects that limit the RF output power of photodiodes, space-charge and thermal.

2. Modified Uni-Traveling Carrier Photodiodes

The PD epitaxial layer structure corresponds to a charge-compensated MUTC PD with both non-absorbing (InP) and absorbing (InGaAs) depletion regions [4] and was presented in Ref. [5]. The transparent electron drift layer (InP) is lightly n-type doped to compensate the electric field reduction caused by the space charge in the

presence of high photocurrents [6]. A moderately doped cliff layer is integrated between the drift layer and the absorber to enhance the electric field in the depleted portion of the absorption layer (Fig. 1 (b)). Back-illuminated double-mesa PDs were fabricated using standard dry etching processes. Stacks of Ti/AuGe/Au and Ti/Pt/Au were used for n- and p-metal contacts, respectively. To facilitate flip-chip bonding Au bonding bumps with a diameter of 6 μm and height of 2 μm were plated on the p- and n-mesas to serve as electrical contacts and heat dissipation paths (Fig. 2).

A SiO_2 layer with a thickness of 250 nm was deposited on the back of the wafer as an anti-reflection coating. To improve thermal dissipation the 1 mm × 1.3 mm MUTC PD dies were flip-chip bonded onto high-thermal conductivity submounts using an Au-Au thermo-compression bonding process [5]. Using AlN submounts we found that the maximum dissipated power density of the photodiodes at the

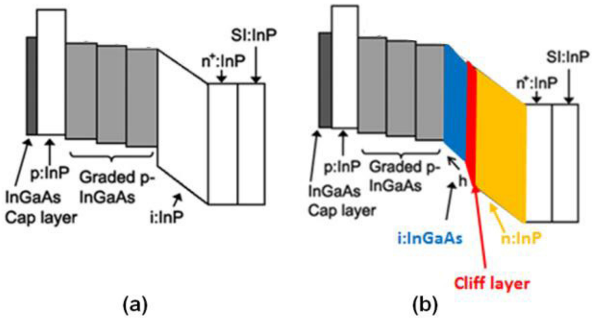


Fig. 1 Band diagrams of (a) UTC and (b) MUTC photodiode.

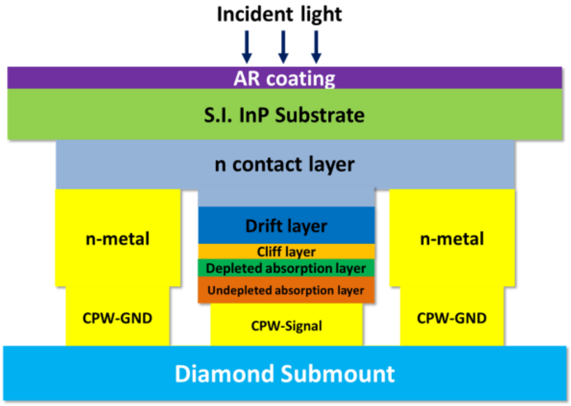


Fig. 2 Simplified schematic cross-sectional view of a photodiode flip-chip-bonded on diamond submount.

Manuscript received December 26, 2014.
Manuscript revised March 31, 2015.

[†] The authors are with the Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, USA.
a) E-mail: ab3pj@virginia.edu

DOI: 10.1587/transele.E98.C.764

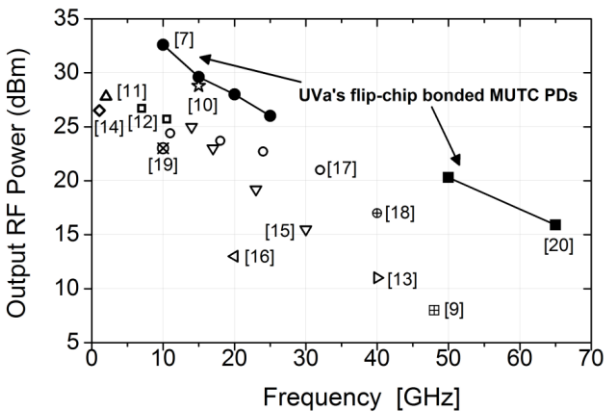


Fig. 3 Maximum output RF power vs. modulation frequency for single wideband photodiodes under continuous wave operation at 1.55 μm wavelength.

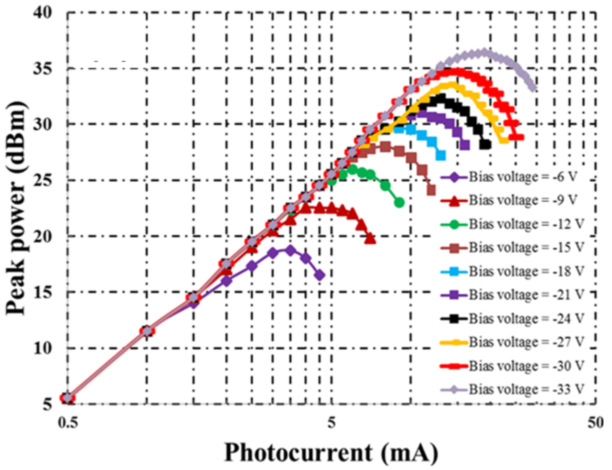


Fig. 4 Peak RF power at 10 GHz for bias voltages from −6 V to −33 V.

point of failure was increased by 65% to 90% when compared to standard back-illuminated PDs without flip-chip bonding. We obtained even higher values when using diamond submounts. Owing to the high thermal conductivity of the chemical-vapor-deposition diamond of > 500 W/m/K, photodiodes with diameters of 50 μm, 40 μm, 34 μm, and 28 μm reached RF output powers of 32.7 dBm at 10 GHz, 29.6 dBm at 15 GHz, 28 dBm at 20 GHz, respectively, and 26 dBm for a 28 μm device at 25 GHz, without active cooling [7].

Compared with the 50 μm-diameter MUTC PD on AlN submount reported in Ref. [8], the device bonded on diamond achieved 80% greater RF output power. The dissipated power in the device was as high as 2.5 W. The reponsivity was 0.75 A/W at 1.55 μ m and typical dark currents were 500 nA. Recently, miniaturization of the PD active area and optimization of the microwave coplanar waveguide (CPW) on chip enabled MUTC PDs with a 3-dB bandwidth of 65 GHz and an RF output power of 16 dBm [20]. In this design an air bridge connected the PD to a high-impedance (85 Ω) CPW transmission line, which served also as the bond pad in the flip-chip-bonding process. Since we designed the transmission line to provide slight inductive peaking, the bandwidth was significantly expanded beyond the conventional resistance-capacitance-limitation. Figure 3 summarizes our results together with data reported in the literature.

Using an optical heterodyne setup with a modulation depth close to 100% we measured a power conversion efficiency (PCE) of 42%, 38%, and 37% at 10 GHz, 20 GHz and 25 GHz, respectively, which compares favorably with previously reported results in Ref. [21]. An even higher PCE of 60% was obtained when using a Mach-Zehnder modulator biased away from its quadrature point [22].

Recently, similar MUTC PDs were used to generate pulsed RF signals at 10 GHz. In the experiment we used a continuous wave (cw) fiber laser followed by two Mach-Zehnder modulators which generated the 10 GHz carrier and a 100-ns gate signal, respectively. Figure 4 shows the detected RF peak power versus average photocurrent for 20% duty cycle and bias voltages in the range between −6 V and −33 V [23]. The peak power increases linearly as the photocurrent increases and then saturates due to the space-charge effect. The maximum RF peak power was 36.4 dBm (4.4 W) when the reverse bias voltage was 33 V and the average photocurrent was 18 mA. Under these operating conditions PD failure occurred at a dissipated DC power of about 1 W, which is significantly less than the dissipated power at failure for cw illumination. While thermal failure becomes less an issue we believe that photodiode operation under pulsed illumination was ultimately limited by junction breakdown. Junction breakdown under dark conditions was observed at 36 V.

A fully packaged flip-chip bonded MUTC PD was demonstrated in Ref. [24]. The fiber-pigtailed hermetic PD module was equipped with a V-connector and included a Peltier element for active temperature control. We measured high RF output power levels reaching 25 dBm at 10 GHz and 17 dBm at 30 GHz under large-signal modulation. When illuminated by short optical pulses an RF power of > 21 dBm was measured at 10 GHz using selective RF filtering. A very low amplitude modulation (AM)-to-phase modulation (PM) conversion factor was also measured, making the PD module suitable for the use in photonic systems for ultralow phase noise high-power RF signal generation as described in Ref. [25].

A similar packaging concept was recently applied to a high-speed MUTC PD with 10-μm active diameter. The PD module demonstrated a 3-dB bandwidth of 50 GHz and an output power of 13.5 dBm at 50 GHz. It should be noted that the packaged photodiodes were operated safely at power levels well below the failure limitation. The RF loss in the photodiode module was estimated to be less than 2 dB up to 50 GHz.

3. MUTC PDs Integrated with Microwave Matching Circuits and Antennas

To improve output power and RF responsivity in a narrow

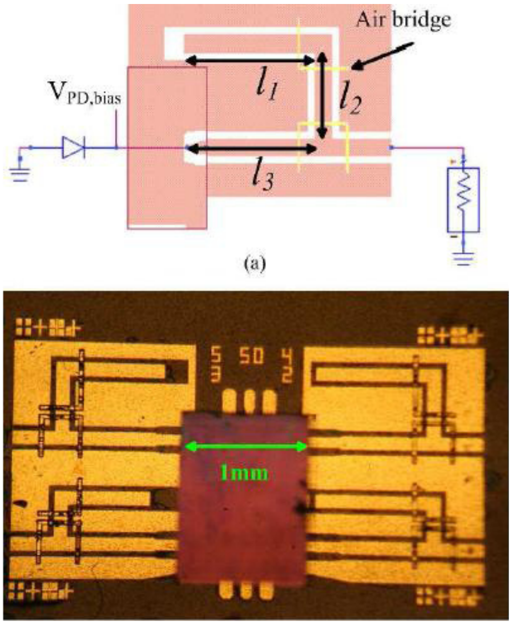


Fig. 5 Schematic (a) and micrograph (b) of PD on AlN substrate with open stub microwave matching circuits.

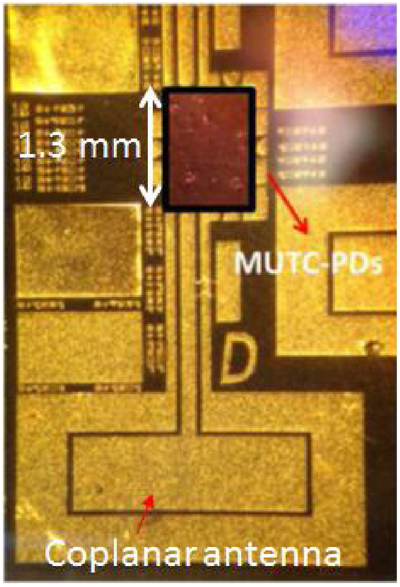


Fig. 6 Micrograph of flip-chip bonded PD with integrated coplanar antenna on AlN.

frequency band MUTC PDs were also integrated with microwave matching circuits [26]. Figures 5 (a) and (b) show a layout of a PD with an open stub circuit and the fabricated circuit on AlN substrate after flip-chip bonding the MUTC photodiode chip, respectively [27].

By optimizing the lengths of the CPWs (l_1, l_2, and l_3) the impedance of the PD was matched to the 50-Ω external load at an operating frequency of 20 GHz. Our devices achieved RF power levels as high as 23 dBm at 6 V bias voltage and an average photocurrent of 140 mA. From a comparison with a similar PD but without matching circuit we found a power enhancement of 6 dB.

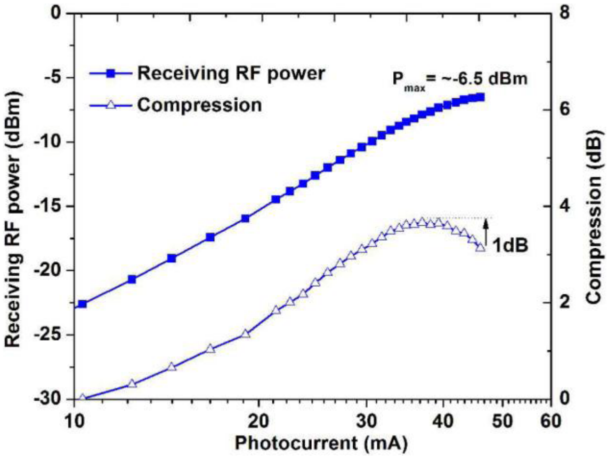


Fig. 7 Received RF power at 60 GHz and RF compression versus average photocurrent at 5 V after 6 cm free-space transmission [28].

In order to build a photonic mm-wave transmitter we also integrated the MUTC PD with a coplanar patch antenna. In our approach a 10-μm diameter PD was coupled to the antenna by flip-chip bonding (Fig. 6). Details about the antenna design can be found in Ref. [28]. Figure 7 shows the dependence of the received RF power on the average photocurrent of the antenna integrated PD at 60 GHz. The data was obtained for 6 cm free-space transmission using a receive-antenna with 15 dBi gain. The saturated receive power was −6.5 dBm at 5 V bias and the average photocurrent was 45 mA. Using the definition in [29] we estimated the effective radiated power to be 20 dBm which indicates that −50 dBm can be received with an antenna of 25-dBi gain at a distance of 25 m from our photonic transmitter.

4. Summary

We have demonstrated that flip-chip bonded charge-compensated MUTC photodiodes can provide record-high output RF power levels up to 65 GHz. Integration with passive microwave circuits can further enhance performance and functionality in analog applications including photonic generation of low phase noise microwave signals and fiber optic antenna links.

References

[1] X. Li, N. Li, X. Zheng, S. Demiguel, J.C. Campbell, D.A. Tulchinsky, and K.J. Williams, "High-saturation-current InP-InGaAs photodiode with partially depleted absorber," IEEE Photon. Technol. Lett., vol.15, no.9, pp.1276–1278, 2003.

[2] F.J. Effenberger and A.M. Joshi, "Ultrafast, dual-depletion region, InGaAs/InP pin detector," J. Lightw. Technol., vol.14, no.8, pp.1859–1864, 1996.

[3] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, and T. Furuta, "Uni-traveling-carrier photodiodes," Tech. Dig. Ultrafast Electronics and Optoelectronics, pp.83–87, 1997.

[4] D.-H. Jun, J.-H. Jang, I. Adesida, and J.-I. Song, "Improved efficiency-bandwidth product of modified uni-traveling carrier photodiode structures using an undoped photo-absorption layer," Japan. J. Appl. Phys., vol.45, no.4B, pp.3475–3478, 2006.

[5] Z. Li, Y. Fu, M. Piels, H. Pan, A. Beling, J.E. Bowers, and J.C. Campbell, “High-power high-linearity flip-chip bonded modified uni-traveling carrier photodiode,” Optics Express, vol.19, no.26, 2011.

[6] N. Li, H. Chen, S. Demiguel, X. Li, J.C. Campbell, T.D. Isshiki, G.S. Kinsey, and R. Sudharsansan, “High-Power Charge-Compensated Unitraveling-Carrier Balanced Photodetector,” IEEE Photon. Technol. Lett., vol.16, no.10, pp.2329–2331, 2004.

[7] X. Xie, Q. Zhou, K. Li, A. Beling, and J.C. Campbell, “1.8 Watt RF Power and 60% Power Conversion Efficiency Based on Photodiode Flip-chip-bonded on Diamond,” in CLEO: 2014 Postdeadline Paper Digest, OSA Technical Digest (online) (Optical Society of America, 2014), paper JTh5B.9.

[8] Q. Zhou, A.S. Cross, F. Yang, A. Beling, and J.C. Campbell, “Development of narrowband modified uni-travelling-carrier photodiodes with high power efficiency,” in Avionics, Fiber-Optics and Photonics Conference (AVFOP) 2013 (IEEE, 2013), pp.65–66.

[9] X. Li, S. Demiguel, N. Li, J.C. Campbell, D.L. Tulchinsky, and K.J. Williams, “Backside illuminated high saturation current partially depleted absorber photodetectors,” Electron. Lett., vol.39, no.20, Oct. 2003.

[10] Z. Li, Y. Fu, H. Pan, A. Beling, and J.C. Campbell, “Photodiode with 0.75 W RF Output Power at 15 GHz,” in Proc. 37th Europ. Conf. Optical Commun. (ECOC 2011), Geneva, Switzerland, Sept. 2011.

[11] N. Duan, N. Li, S. Demiguel, and J.C. Campbell, “An InGaAs/InP Photodiode with 600 mW RF Output Power,” in 19th Annu. Meeting IEEE Lasers Electro-Optics Soc.(LEOS 2006), Oct. 2002, pp.52–53, paper WD2.3.

[12] K. Sakai, E. Ishimura, M. Nakaji, S. Itakura, Y. Hirano, and T. Aoyagi, “High-Current Back-Illuminated Partially Depleted-Absorber p-i-n Photodiode With Depleted Nonabsorbing Region,” IEEE Trans. Microwave Theory Tech., vol.58, no.11, pp.3154–3160, 2010.

[13] N. Shimizu, Y. Miyamoto, A. Hirano, K. Sato, and I. Ishibashi, “RF Saturation mechanism of In/InGaAs uni-travelling-carrier photodiode,” Electron. Lett., vol.36, no.8, pp.750–751, April 2000.

[14] D.A. Tulchinsky, J.B. Boos, D. Park, P.G. Goetz, W.S. Rabinovich, and K.J. Williams, “High-Current Photodetectors as Efficient, Linear, and High-Power RF Output Stages,” J. Lightw. Technol., vol.26, no.4, pp.408–416, 2008.

[15] X. Wang, N. Duan, H. Chen, and J.C. Campbell, “InGaAs–InP photodiodes with high responsivity and high saturation power,” IEEE Photon. Technol. Lett., vol.19, no.16, pp.1272–1274, 2007.

[16] M. Chtioui, A. Enard, D. Carpentier, S. Bernard, B. Rousseau, F. Lelarge, F. Pommereau, and M. Achouche, “High-Power high-linearity uni-traveling-carrier photodiodes for analog photonic links,” IEEE Photon. Technol. Lett., vol.20, no.3, pp.202–204, 2008.

[17] Z. Li, H. Pan, H. Chen, A. Beling, and J.C. Campbell, “High Saturation Current Modified Uni-Traveling-Carrier Photodiode with cliff layer,” IEEE J. Quantum Electronics, vol.46, no.5, pp.626–632, 2010.

[18] N. Li, X. Li, S. Demiguel, X. Zheng, J.C. Campbell, D.A. Tulchinsky, K.J. Williams, T.D. Isshiki, G.S. Kinsey, and R. Sudharsansan, “High-Saturation-Current Charge-Compensated InGaAs InP Uni- Traveling-Carrier Photodiode,” IEEE Photon. Technol. Lett., vol.16, no.3, pp.864–866, 2004.

[19] M. Chtioui, F. Lelarge, A. Enard, F. Pommereau, D, Carpentier, A. Marceaux, F. Van-Dijk, and M. Achouche, “High Responsivity and High Power UTC and MUTC GaInAs-InP Photodiodes,” IEEE Photon. Technol. Lett., vol.24, no.4, pp.318–320, 2012.

[20] Q. Zhou, A.S. Cross, A. Beling, Y. Fu, Z. Lu, and J.C. Campbell, “High-power V-band InGaAs/InP Photodiodes,” IEEE Photon. Technol. Lett., vol.25, no.10, pp.907–909, 2013.

[21] U. Gliese, K. Colladay, A.S. Hastings, D.A. Tulchinsky, V.J. Urick, and K.J. Williams, “53.5% Photodiode RF Power Conversion Efficiency,” in Optical Fiber Communication Conference (OFC2010) paper PDPA7, 2010.

[22] X. Xie, Q. Zhou, K. Li, A. Beling, J.C. Campbell, “1.8 Watt RF Power and 60% Power Conversion Efficiency Based on Photodiode Flip-chip-bonded on Diamond,” CLEO 2014, San Jose, CA, 8-13 June, 2014, Postdeadline paper 2 (JTh5B).

[23] X. Xie, Q. Zhou, K. Li, A. Beling, and J.C. Campbell, “Photonic Generation of High-Power Pulsed Microwave Signals with Peak Powers up to 7.2 Watt,” Optical Fiber Communication Conference (OFC 2015), OSA Technical Digest (online) (Optical Society of America, 2015), paper Tu3F.2, 2015.

[24] E. Rouvalis, F.N. Baynes, X. Xie, K. Li, Q. Zhou, F. Quinlan, T.M. Fortier, S.A. Diddams, A.G. Steffan, A. Beling, and J.C. Campbell, “High-Power and High-Linearity Photodetector Modules for Microwave Photonic Applications,” Journal of Lightwave Technology, vol.32, no.20, pp.3810–3816, 2014.

[25] T.M. Fortier, F. Quinlan, A. Hati, C. Nelson, J.A. Taylor, Y. Fu, J.C. Campbell, and S.A. Diddams, “Photonic microwave generation with high-power photodiodes,” Opt. Lett. vol.38, no.10, pp.1712–1714, 2013.

[26] H. Ito, Y. Hirota, A. Hirata, T. Nagatsuma, and T. Ishibashi, “11 dBm photonic millimetre-wave generation at 100 GHz using uni-travelling-carrier photodiodes,” Electron. Lett., vol.37, no.20, pp.1225–1226, Sept. 2001.

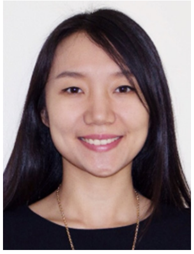
[27] K. Li., X. Xie, Q. Zhou, A. Beling, and J.C. Campbell, “High Power 20-GHz Photodiodes With Resonant Microwave Circuits,” IEEE Photon. Technol. Lett., vol.26, no.13, pp.1303–1306, 2014.

[28] K. Li, X. Xie, Q. Li, Y. Shen, M.E. Woodsen, Z. Yang, A. Beling, J.C. Campbell, “High-Power Photodiode Integrated with Coplanar Patch Antenna for 60 GHz Applications,” accepted for publication in Photon. Technol. Lett., vol.27, no.6, pp.650–653, 2015.

[29] K. Takahata, Y. Muramoto, S. Fukushima, T. Furuta, and H. Ito, “Monolithically integrated millimeter-wave photonic emitter for 60-GHz fiber-radio application,” presented at the Microwave Photonics Conference (MWP 2000), Oxford, UK, paper WE3.4, pp.229–232, 2000.

Andreas Beling received the Dipl.-Phys. degree (M.S.) in physics from the University of Bonn, Germany, in 2000 and the Dr.-Ing. degree (Ph.D.) in electrical engineering from Technical University Berlin, Germany, in 2006. He was a staff scientist in the photonics division at the Heinrich-Hertz-Institute in Berlin in 2001–2006, a Research Associate in the Department of Electrical and Computer Engineering at the University of Virginia in 2006–2008, and has two years of industry experience as a project manager working on optical communication devices. He returned to University of Virginia and became Assistant Professor in the Department of Electrical and Computer Engineering in 2013. His research interests include high-speed optoelectronic devices, photonic integrated circuits, microwave photonics, and optical communications. Andreas Beling has authored or co-authored more than 110 technical papers, two book chapters, and four patents. Dr. Beling is a Senior Member IEEE and became an Associate Editor of the IEEE/OSA Journal of Lightwave Technology in 2014.

Joe C. Campbell received the B.S. Degree in Physics for the University of Texas at Austin in 1969, and the M.S. and Ph.D. degrees in Physics from the University of Illinois at Urbana-Champaign in 1971 and 1973, respectively. From 1974 to 1976 he was employed by Texas Instruments where he worked on integrated optics. In 1976 he joined the staff of AT&T Bell Laboratories in Holmdel, New Jersey. In the Crawford Hill Laboratory he worked on a variety of optoelectronic devices including semiconductor lasers, optical modulators, waveguide switches, photonic integrated circuits, and photodetectors with emphasis on high-speed avalanche photodiodes for high-bit-rate lightwave systems. In January of 1989 he joined the faculty of the University of Texas at Austin as Professor of Electrical and Computer Engineering and Cockrell Family Regents Chair in Engineering. In January of 2006, Professor Campbell became a member of the faculty at the University of Virginia in Charlottesville as the Lucian Carr, III Chair of Electrical Engineering and Applied Science. Professor Campbell's research has focused on the optoelectronic components that are used to generate, modulate, and detect the optical signals. At present he is actively involved in single-photon-counting avalanche photodiodes, Si-based optoelectronics, high-speed, low-noise avalanche photodiodes, ultraviolet photodetectors, and quantum-dot IR imaging. To date he has coauthored ten book chapters, 400 articles for refereed technical journals, and more than 400 conference presentations. He is a member of the National Academy of Engineering.

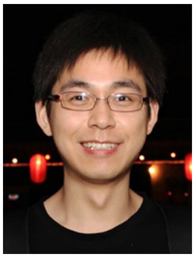


Kejia Li was born in Tianjin, China. She received the M.S. degree in Electrical Engineering from Peking University in 2008, and the Ph.D. degree in Electrical Engineering from University of Virginia in 2012. She is currently a research scientist in Joe C. Campbell Group, University of Virginia, Charlottesville. Her current research interests include high-power photodetectors and microwave photonics.

Qinglong Li was born in Tianjin, China in 1985. He received his bachelor degree at Nankai University in Tianjin in 2008. Later, he worked in Semiconductor manufacturing industry in China for 1.5 years. After which, he continued his graduate study and received his Master of Science degree at Rochester Institute of Technology, NY, US in 2013. He is currently pursuing his Ph.D. degree in JCC group at ECE department at University of Virginia in Charlottesville, VA, US with his research interests focusing on high power and high speed photo-detector for optical communication application.

Ye Wang has been a Ph.D. student in the ECE department at U.Va. since 2014. He received his B.E. in Optoelelctronic Information Engineering from Huazhong University of Science and Technology (HUST), 2014. Ye's research interests focus on design, fabrication and characterization of high power photodiodes and MWIR Multi-Quantum Well (MQW) detectors.

Madison Woodson received her B.S. degree in biomedical engineering with a minor in electrical engineering from the University of Virginia, Charlottesville, in 2013, and is currently pursuing an electrical engineering Ph.D. within the Electrical Engineeirng Department of the University of Virginia. Her current research interest focus on using Monte Carlo simulations to model semiconductor device physics for photodetector applications.



Xiaojun Xie received his B.S. in optical information science and technology from University of Electronic Science and Technology of China (UESTC), China, in 2010, and M.S. in electromagnetic field and microwave technology from Beijing University of Posts and Telecommunications (BUPT), China, in 2013. He is currently pursing Ph.D. in electrical engineering at University of Virginia, USA. His research interests lie in the design, fabrication and characterization of high power and high linearity photodiodes as well as the high-performance photodiodes application on analog photonics link and pulsed RF signal generation. He also focuses on InP photodiode integration on silicon photonic-electronic platform.

Zhanyu Yang was born in Anhui Province, China, in 1989, and received the B.S. degree in physics from Beijing Capital Normal University (CNU) in 2010. In 2013, he received the M.S. degree from State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), China. He is currently working toward his Ph.D degree in Electrical and Computer Engineering at University of Virginia. His research interest focus on high power photodiodes and their applications in analog links.