Indonesian Journal of Electrical Engineering and Computer Science
Vol. 29, No. 1, January 2023, pp. 174~180
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v29.i1.pp174-180

Modelling and simulation of optical transmitter for 5G passive optical networks

Sura Adil Abbas, Jaafar A. Aldhaibani
Department of Mobile Communications and Computing, Faculty of Engineering,
University of Information Technology and Communications, Baghdad, Iraq

Article Info

Article history:

Received Jun 1, 2022
Revised Sep 11, 2022
Accepted Oct 4, 2022

Keywords:

5G
Central office
OLT
Optical transmitter
PONs

ABSTRACT

5G is altering the communications future. The 5G literature focuses on wireless and radio technology, but fiber optics play a crucial supporting role in signal transmission to and from the next generation of base stations (BSs) that will serve customers. With the increasing bandwidth requirements of 5G ultra-high-speed applications, passive optical networks (PONs) are the optimal solution. Targeting long-reach 5G PONs, an integrated, high-speed, and cost-effective optical transmitter circuit was constructed and tested. This engine can be combined into a 5G-compliant optical transceiver module. For the purpose of validating the engine performance, a theoretical analysis and an OptiSim^{TM}-based design simulation model are carried out. Bit error rate (BER), phase-shifting, and eye diagram were all taken into account when analyzing the transmitter performance. The article findings validate the optical transmitter design. The design is cost-effective and requires no extra components, such as a filter.

Corresponding Author:

Sura Adil Abbas
Department of Mobile Communications and Computing, Faculty of Engineering
University of Information Technology and Communications
Baghdad, Iraq
Email: sura.adel@uoitc.edu.iq

1. INTRODUCTION

The first 5G cellphones will be commercially accessible in 2019, but it will take several years to properly implement the technology. By 2030, 5G services are expected to become widespread and enable communications for applications currently in their infancy, such as virtual reality and autonomous vehicles [1]. Due to 5G's high needs for coverage, bandwidth, and low latency, passive optical networks (PONs) of the subsequent generation will become even more prevalent [2]. Future wireless technology deployment will depend on PONs' smooth connectivity to cloud computing resources and wireless access networks. Combining radio access and PON features into an one convergent platform would help telecom service providers to minimize network complexity, reduce operating costs, improve service quality, better deploy resources across different access technologies, and serve as a catalyst for new markets. [3]. Figure 1 is a simplified representation of 5G PONs.

To address the issue of a lack of spectrum and support multi-gigabit wireless connectivity, 5G uses frequencies above 30 GHz [4]. Due to propagation losses, the generation of these higher frequencies is a difficult process, limiting the transmission distance. For this reason, these frequencies are generated at a center office (CO) and then transmitted to the base station (BS) through the modulation of microwave data signals over an optical carrier. The millmeterwave over fiber (MoF) is the name of this method. The optical domain is superior to its electrical counterpart for generating these higher frequencies due to its superior spectral purity, reduced equipment requirements, and vast transmission distance [5]. Numerous strategies using optical heterodyning [6]–[10], direct modulation [11]–[14] and external modulation [15]–[20] have been developed for the optical generation of high-frequency signals. External modulation is the most dependable technique; it generates optical harmonics with high-spectral-purity, higher tunability, and stability [21]. In order to keep up with ever-growing bandwidth demands, current optical fiber communications research focuses on boosting the link capacity [22]. Less-complex optical transmitters can boost link capacity [23].

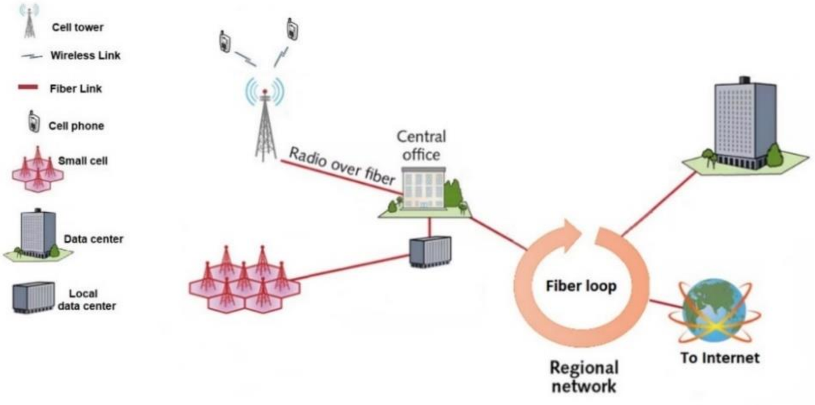

Figure 1. 5G PONs

The aim of this paper is to present a simple optical transmitter design for 5G PONs. There were several factors that were taken into consideration when analyzing the transmitter's performance, such as bit error rate (BER), phase-shifting, and eye diagram of the down-converted signal. The structure of this document is outlined below. Section 2 will go over the transmitter design principles. Section 3 contains the outcomes of computer simulations. Section 4 concludes the paper.

2. METHOD

Figure 2 depicts a schematic diagram of the MoF system configuration, including the proposed optical transmitter. It is obvious that it is divided into three PONs components: optical line terminal (OLT), optical distribution network (ODN), and optical network unit (ONU). The OLT is a central office device that serves as the starting point for the PONs, which are connected to a core switch via Ethernet cables. The OLT's primary responsibility is to convert frames and send data for the PON.

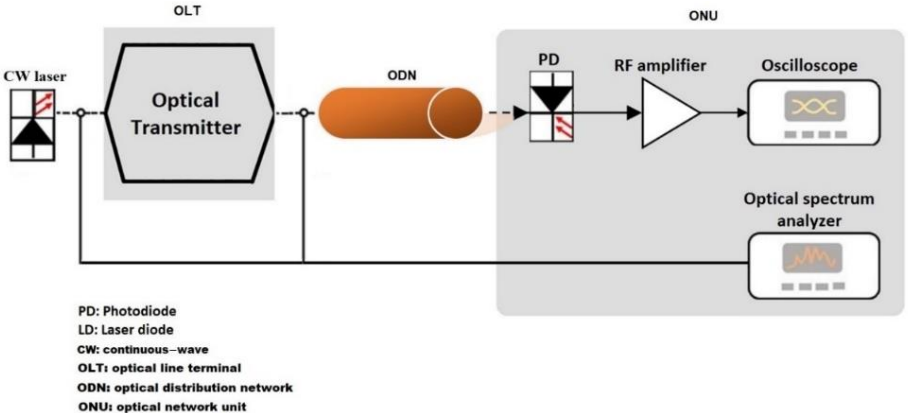

Figure 2. MoF system

PON data can't be sent without ODN, which directly affects a PON system's performance, reliability, and ability to grow. The ODN is a component of the PON system and serves as the physical path along which light travels from the OLT to the ONT. Its range is at least 20 km. Optical fibers, optical splitters, and fiber optic connectors work together in the ODN. An ONU is a device that transforms signals sent through fibers from optical to electrical. Then, these signals are sent to specific customers. In addition, the ONU is capable of transmitting, aggregating, and preparing various forms of client data for transmission to the OLT.

The proposed optical transmitter consists of two parallel single-electrode mach-zehnder modulators (SEMZMs) [24]. An optical splitter divides the injected lightwave into two parcels. Each parcel is assigned an SEMZM. Both SEMZMs must be biased at the maximum transmission bias point (MTBP) with ϕ=45° separating RF driving signals. Using an optical spectrum analyzer, the outputs of A and B are only even optical harmonics, as shown by the solid arrows in Figure 3. The index of modulation is 2.4. So, when the powers of two 2nd optical harmonics at the outputs of A and B are combined at the output of the optical transmitter, they make two 2nd optical harmonics with double the power, as shown in Figure 3. An oscilloscope is used to get a high-quality OCS signal with 4th times the frequency of radio frequency (RF) driving signals.

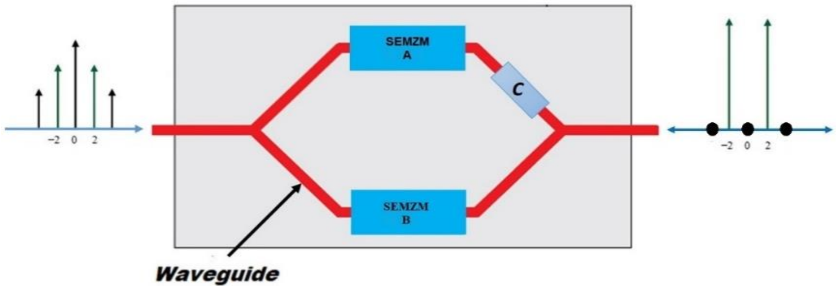

Figure 3. Proposed optical transmitter

The output field of the SEMZM A or SEMZM B is given by:

$$\xi_A = \xi_B = \left(\gamma e^{j\phi_1} + (1-\gamma)e^{j\phi_2}\right) = \left(\gamma e^{j\phi_1} + (1-\gamma)e^{j\phi_2}\right) = \left(\frac{1}{2}e^{j\frac{\pi}{V_\pi}V_1} + \frac{1}{2}e^{j\frac{\pi}{V_\pi}V_2}\right) \quad (1)$$

where $\phi 1$, ϕ_2, V_1, and V_2 are phases and driving signals to electrode1 and electrode2 of SEMZM A, γ is the splitting ratio = ½ and V_π is the π-phase difference:

$$= \frac{e^{j\frac{\pi}{2V_\pi}(V_1+V_2)}}{2} . \left(e^{j\frac{\pi}{2V_\pi}(V_1-V_2)} + e^{-j\frac{\pi}{2V_\pi}(V_1-V_2)}\right) = e^{j\frac{\pi}{2V_\pi}(V_1+V_2)} . cos[(\pi/2V_\pi).(V_1 - V_2)] \quad (2)$$

with $V_2 = - V_1$, the (2) become:

$$\xi_A = \xi_B = cos\left(\frac{\pi}{V_\pi}V(t)\right) = cos\left[\frac{\pi}{V_\pi}.(V_{bias} + V_m\, cos(\omega_D t))\right] \quad (3)$$

as SEMZM A is operated at the MTBP (i.e., V_{bias}=0), only even optical harmonics are observed. Expanding the (3) using Bessel functions, ξ_A can be rewritten as [25]:

$$\xi_{A(MTBP)} = g_0\, cos(\omega_c t) + g_2\, cos(\omega_c t + 2\omega_m t) + g_2\, cos(\omega_c t - 2\omega_m t) \quad (4)$$

as SEMZM A is operated at the MITBP (i.e., $V_{bias} = V_\pi$), only odd optical harmonics are observed. ξ_A can be rewritten as [25]:

$$\xi_{A(MITBP)} = g_1\, cos(\omega_c t + \omega_m t) + g_1\, cos(\omega_c t - \omega_m t) \quad (5)$$

where ω_c , ω_D are the continuous wave (CW) and driving signal frequencies, respectively, and, g is the nth order Bessel function of the first kind. The output field of the optical modulator is given by:

$$\xi_{out} = \xi_{A(MTBP)} + \xi_{B(MTBP)} .\xi_c = \xi_{A(MTBP)} + \xi_{B(MTBP)} .1 = \xi_{A(MTBP)} + \xi_{B(MTBP)} \quad (6)$$

the driving signals sent to A and B modulators are:

$$V_A = V_D \, sin(\omega_D t) \tag{7}$$

$$V_B = V_D \, sin(\omega_D t + 45^0) \tag{8}$$

where V_D is the amplitude of the driving signal. The modulated output lightwave can be expressed as:

$$\xi_A = g_0 \, sin(\omega_C t) + g_2 \, sin(\omega_C t + 2\omega_D t) \tag{9}$$

$$\xi_B = g_0 \, sin(\omega_C t) + g_2 \, sin(\omega_C t - 2\omega_D t) \tag{10}$$

with index of modulation=2.4, the (6) can be written as:

$$\xi_{out} = g_2 \, sin(\omega_C t + 2\omega_D t) + g_2 \, sin(\omega_C t - 2\omega_D t) \tag{11}$$

3. RESULTS AND DISCUSSION

To verify the transmitter performance, Optisystem is used to simulate the MoF system (Figure 2). Optisystem is a simulation software that is utilized for the purposes of planning, testing, and optimizing the performance of optical networks. Table 1 displays the values of the simulated MoF system parameters.

Table 1. Parameter values of the simulated MoF system.

Component	Parameter	Values
Extinction Ratio	ER	25 dB
Half-wave voltage	V_π	4 volt
Responsivity	µ	0.7 A/W
Noise Figure	NF	5 dB
Thermal noise	F	10^{-11} A/Hz$^{0.5}$
insertion loss	α	5 dB
Fiber length	L	60 km

Figures 4-6 depict the eye diagrams of the down-converted signal from the SMF for different fiber lengths (10, 30, and 60 km). The eye diagram was displayed on the eye diagram analyzer, which functioned like an oscilloscope. It can be seen that the shape of the eye patterns changes slightly, but the eye patterns are still clear and stay open even when optical signals are sent over 60 km.

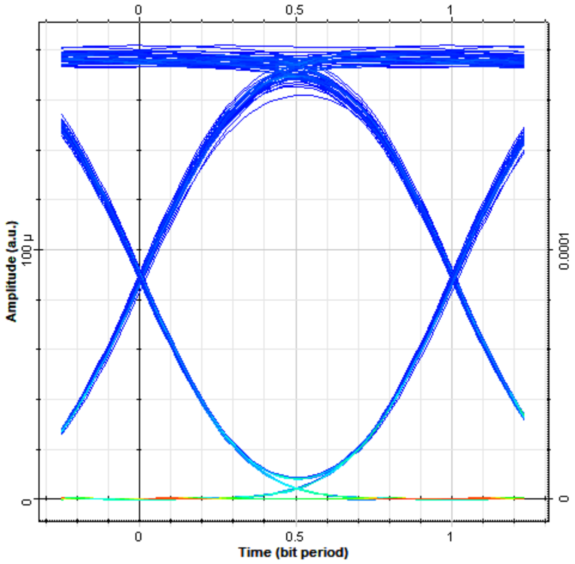

Figure 4. The eye diagram at 10 km

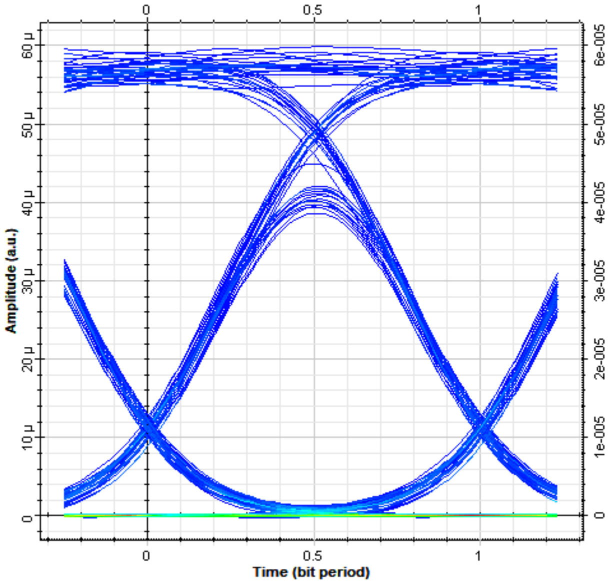

Figure 5. The eye diagram at 30 km

The effect of phase-shifting on the amplitude of the sideband suppression ratio is depicted in Figure 7. The phase shift between RF driving signals is varied between 0° and 15°. Figure 7 shows that for a phase shift near the ideal value, i.e., 0°, the highest amplitude of sideband suppression can be obtained. The value then decreases slightly as the phase shift value increases. If the deviation is less than 10 dB, an amplitude of 15 dB can be obtained. That should suffice for the majority of MoF applications [26].

Figure 8 shows the relationship between simulated BER and fiber length. At a data rate of 5 Gbit/s, two effective input light power values ($P_r = 0$ and $P_r = 5$ dBm) were taken. The BER is approximately 10^{-25} when the light power is $P_r = 0$ dBm and the transmission distance is 60 km. The MoF system has a high BER value (BER $\geq 10^{-12}$) when the effective light power is dropped to 5 dBm. Increased fiber length, attenuation, and dispersion all contribute to increased BER. Figure 9 illustrates the B-T-B (0 km) and 30 km BER simulations as a function of the received power at a data rate of 5 Gbit/s. The penalty is around 0.65 dB when the BER is 10^{-10}. Fiber propagation loss is responsible for the diminished signal strength.

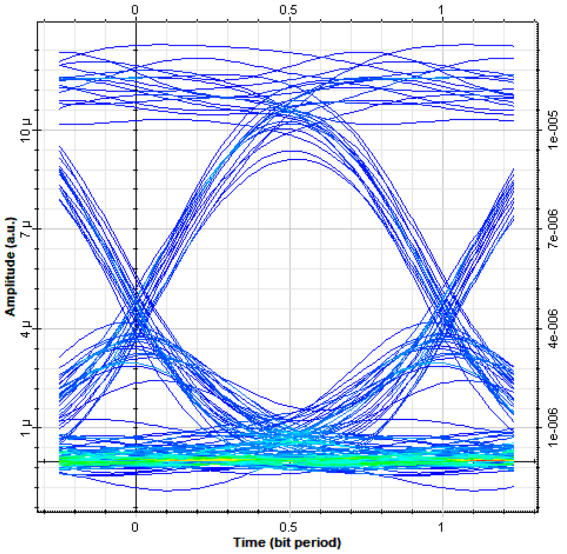

Figure 6. The eye diagram at 60 km

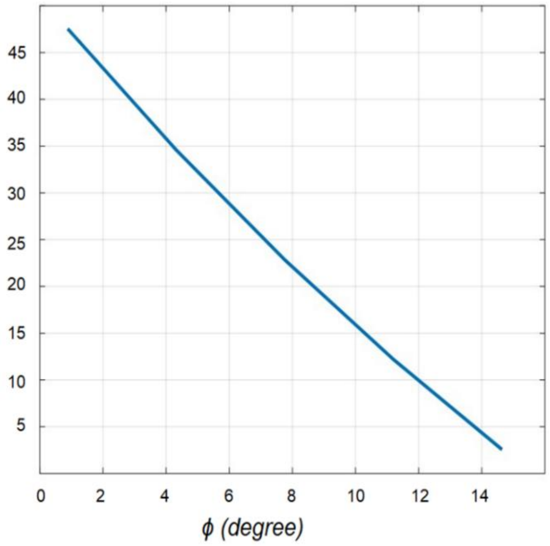

Figure 7. Amplitude against phase shift

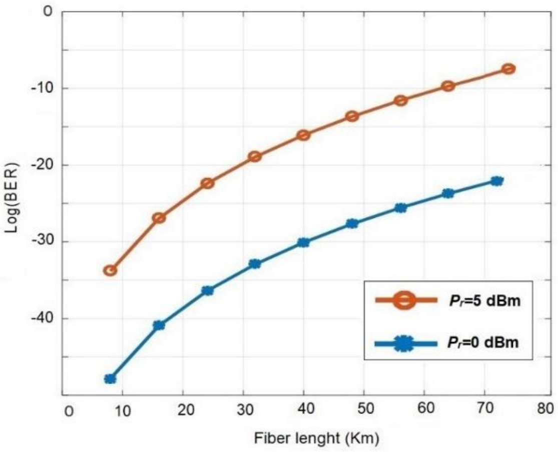

Figure 8. BER versus fiber length

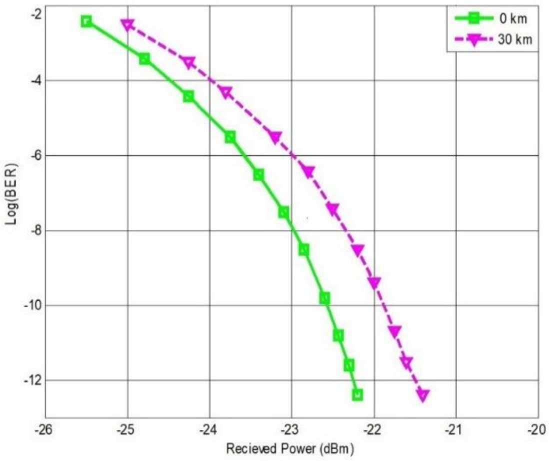

Figure 9. BER versus received optical power

4. CONCLUSION

PONs will play a critical role in the 5G era. Implementing a simple optical transmitter is one strategy for increasing PONs capacity. This work provides a simple and cost-effective optical transmitter architecture based on two parallel SEMZMs and evaluates its performance numerically and via simulation. The effects of phase shift variation on the amplitude of the sideband suppression ratio, variation of fiber length, and received power on the BER were all explored. At the receiver, clear eye patterns could be seen. Based on the article findings, the proposed optical transmitter has enhanced performance, a low cost, and a simple configuration.

REFERENCES

[1] M. Patzold, "5G readiness on the horizon [mobile radio]," *IEEE Vehicular Technology Magazine*, vol. 13, no. 1, pp. 6–13, Mar. 2018, doi: 10.1109/MVT.2017.2776668.

[2] X. Guan, W. Shi, J. Liu, P. Tan, J. Slevinsky, and L. A. Rusch, "Silicon photonics in optical access networks for 5g communications," *IEEE Communications Magazine*, vol. 59, no. 6, pp. 126–131, May 2021, doi: 10.1109/MCOM.001.2001005.

[3] X. Guan, S. B.-de Villers, W. Shi, and L. A. Rusch, "Overlaying 5G radio access networks on wavelength division multiplexed optical access networks with carrier distribution," *Optics Express*, vol. 29, no. 3, p. 3631, Feb. 2021, doi: 10.1364/OE.415667.

[4] N. Al-Shareefi, S. A. Abbas, M. S. Alkhazraji, and A. A. Sakran, "Towards secure smart cities: design and implementation of smart home digital communication system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 1, p. 271, Jan. 2021, doi: 10.11591/ijeecs.v21.i1.pp271-277.

[5] J. Beas, G. Castanon, I. Aldaya, Aragón-Zavala, and G. Campuzano, "Millimeter-wave frequency radio over fiber systems: a survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1593–1619, 2013, doi: 10.1109/SURV.2013.013013.00135.

[6] A. Delmade *et al.*, "Optical heterodyne analog radio-over-fiber link for millimeter-wave wireless systems," *Journal of Lightwave Technology*, vol. 39, no. 2, pp. 465–474, Jan. 2021, doi: 10.1109/JLT.2020.3032923.

[7] C. Browning, E. P. Martin, A. Farhang, and L. P. Barry, "60 GHz 5G radio-over-fiber using UF-OFDM with optical heterodyning," *IEEE Photonics Technology Letters*, vol. 29, no. 23, pp. 2059–2062, Dec. 2017, doi: 10.1109/LPT.2017.2763680.

[8] F. Paresys, T. Shao, G. Maury, Y. Le Guennec, and B. Cabon, "Bidirectional millimeter-wave radio-over-fiber system based on photodiode mixing and optical heterodyning," *Journal of Optical Communications and Networking*, vol. 5, no. 1, p. 74, Jan. 2013, doi: 10.1364/JOCN.5.000074.

[9] R. T. Logan, "All-optical heterodyne RF signal generation using a mode-locked-laser frequency comb: theory and experiments," in *2000 IEEE MTT-S International Microwave Symposium Digest (Cat. No.00CH37017)*, 2000, vol. 3, pp. 1741–1744, doi: 10.1109/MWSYM.2000.862315.

[10] K. Zeb *et al.*, "Broadband optical heterodyne millimeter-wave-over-fiber wireless links based on a quantum dash dual-wavelength DFB laser," *Journal of Lightwave Technology*, vol. 40, no. 12, pp. 3698–3708, Jun. 2022, doi: 10.1109/JLT.2022.3154652.

[11] L. Chen, Y. Pi, H. Wen, and S. Wen, "All-optical mm-wave generation by using direct-modulation DFB laser and external modulator," *Microwave and Optical Technology Letters*, vol. 49, no. 6, pp. 1265–1267, Jun. 2007, doi: 10.1002/mop.22449.

[12] H. Wen, L. Chen, C. Huang, and S. Wen, "A full-duplex radio-over-fiber system using direct modulation laser to generate optical millimeter-wave and wavelength reuse for uplink connection," *Optics Communications*, vol. 281, no. 8, pp. 2083–2088, Apr. 2008, doi: 10.1016/j.optcom.2007.12.058.

[13] C.-T. Tsai, C.-H. Lin, C.-T. Lin, Y.-C. Chi, and G.-R. Lin, "60-GHz millimeter-wave over fiber with directly modulated dual-mode laser diode," *Scientific Reports*, vol. 6, no. 1, p. 27919, Jun. 2016, doi: 10.1038/srep27919.

[14] D. Yu *et al.*, "Optogenetic activation of intracellular antibodies for direct modulation of endogenous proteins.," *Nature methods*, vol. 16, no. 11, pp. 1095–1100, Nov. 2019, doi: 10.1038/s41592-019-0592-7.

[15] W. Li and J. Yao, "Investigation of photonically assisted microwave frequency multiplication based on external modulation," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 11, pp. 3259–3268, Nov. 2010, doi: 10.1109/TMTT.2010.2075671.

[16] O. G. Morozov, G. I. Il'in, G. A. Morozov, I. I. Nureev, and R. S. Misbakhov, "External amplitude-phase modulation of laser radiation for generation of microwave frequency carriers and optical poly-harmonic signals: an overview," in *Optical Technologies for Telecommunications 2015*, 2016, vol. 9807, p. 980711, doi: 10.1117/12.2231948.

[17] S. E. Alavi, M. R. K. Soltanian, I. S. Amiri, M. Khalily, A. S. M. Supa'at, and H. Ahmad, "Towards 5G: A photonic based millimeter wave signal generation for applying in 5G access fronthaul," *Scientific Reports*, vol. 6, no. 1, p. 19891, Apr. 2016, doi: 10.1038/srep19891.

[18] S. Shen and W. Yin, "Photonic generation of high-purity 60 GHz millimeter-wave signal requiring only 10 GHz radio frequency local oscillator," *Optical Review*, vol. 25, no. 6, pp. 684–693, Dec. 2018, doi: 10.1007/s10043-018-0461-0.

[19] N. A. Mohammed, S. I. . Hassan, F. Malek, R. Ngah, and S. A. Abbas, "Optical generation of 60-GHz signal for millimeter wave wireless communication," in *2013 IEEE International RF and Microwave Conference (RFM)*, 2013, pp. 437–440, doi: 10.1109/RFM.2013.6757301.

[20] N. A. Al-Shareefi, S. I. S. Hassan, F. Malek, R. Ngah, and S. A. Abbas, "Optical generation of 60 GHz downstream data in radio over fiber systems based on two parallel dual-drive MZMs," *International Journal of Engineering and Technology*, vol. 6, no. 2, pp. 579–587, 2014.

[21] L. Fan, G. Xia, J. Chen, X. Tang, Q. Liang, and Z. Wu, "High-purity 60GHz band millimeter-wave generation based on optically injected semiconductor laser under subharmonic microwave modulation," *Optics Express*, vol. 24, no. 16, p. 18252, Aug. 2016, doi: 10.1364/OE.24.018252.

[22] D. Bacco *et al.*, "Boosting the secret key rate in a shared quantum and classical fibre communication system," *Communications Physics*, vol. 2, no. 1, p. 140, Nov. 2019, doi: 10.1038/s42005-019-0238-1.

[23] I. N. Cano, A. Lerin, V. Polo, and J. Prat, "Direct Phase Modulation DFBs for Cost-Effective ONU Transmitter in udWDM PONs," *IEEE Photonics Technology Letters*, vol. 26, no. 10, pp. 973–975, May 2014, doi: 10.1109/LPT.2014.2309852.

[24] M. Mohamed, X. Zhang, B. Hraimel, and K. Wu, "Analysis of frequency quadrupling using a single Mach-Zehnder modulator for millimeter-wave generation and distribution over fiber systems," *Optics Express*, vol. 16, no. 14, p. 10786, Jul. 2008, doi: 10.1364/OE.16.010786.

[25] Chun-Ting Lin *et al.*, "Optical millimeter-wave up-conversion employing frequency quadrupling without optical filtering," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 8, pp. 2084–2092, Aug. 2009, doi: 10.1109/TMTT.2009.2015036.

[26] S. Liu, D. Zhu, and S. Pan, "Wideband signal upconversion and phase shifting based on a frequency tunable optoelectronic oscillator," *Optical Engineering*, vol. 53, no. 3, p. 036101, Mar. 2014, doi: 10.1117/1.OE.53.3.036101.

BIOGRAPHIES OF AUTHORS

Sura Adil received the Bachelor of electronic and communication engineering from University of Baghdad/collage of engineering/department of electronic and communication engineering/Iraq/Baghdad/Aljaderiyah, in 2005. The Masters. Degree in electronic and communication engineering from University of Baghdad/institute of laser for postgraduate studies/Iraq/Baghdad/Aljaderiyah, in 2011. She is currently working as an assistant teacher at Department of Communication and Mobile Computing Engineering, faculty of Engineering, University of Information Technology and Communications (UOITC), Baghdad, Iraq. She can be contacted at email: sura.adel@uoitc.edu.iq.

Jaafar A. Aldhaibani is Associate Professor at college of Engineering, University of information technology and communications (UoITC), Iraq. He earned his B.Sc. and M.Sc. in Wireless Communications on 1994 and 2002 from the University of Technology, Baghdad, Iraq and got the Ph.D. degree from University Malaysia Perlis (UniMAP), Malaysia on 2014 and worked with the Motorola Company as a system engineer for communication in terms of RF networks planning, sites configuration. Now he is a head of Mobile Communications and Computing Engineering Department in UoITC, Iraq. Aldhaibani has many interest researches focused on wireless communications, long term evolution networks (LTE) (LTE-A), fourth generation (4G), cooperative communications, heterogeneous network, 5G cellular network, internet of thing (IoT) technology and free space optics communications. He can be contacted at email: dr.jaafaraldhaibani@uoitc.edu.iq.