Design and Numerical Analysis of 45-degree Polarization Rotator for Quantum Cryptography

Salwa Marwan Salih, and Shelan Khasro Tawfeeq

Abstract—**Polarization manipulation in visible wavelengths has an important role in many applications, such as free-space quantum communication and quantum cryptography. In this study, a polarization rotator based on a tilted slot waveguide by 45-degree is proposed and designed. Its principle is to rotate a +45°/-45° input polarized light to TM0/TE0 output polarized light. The simulation results show an extinction ratio of 45.23 (41.17) dB and insertion loss below 0.62 dB at 700 nm wavelength. The bandwidth for an extinction ratio higher than 20 dB is 40 nm. In addition, the device tolerance is analyzed.**

Index Terms—**Polarization rotator, hybrid modes, visible wavelength, extinction ratio, 45-degree**

I. INTRODUCTION

Integrated photonics holds great promise for the advancement of quantum communication devices in terms of their complex nature, resilience, and scalability [1]. A particular area of focus within this field is silicon photonics, which serves as a prominent platform for quantum photonic technologies [2]. Further benefits it offers miniaturization, low-cost device manufacturing, and compatibility with CMOS microelectronics [3].

Polarization control is essential in numerous applications such as telecommunication, quantum cryptography based on photon polarization encoding, and biosensing [4-7]. Photonic integrated circuits (PICs) have faced significant challenges because of the high confinement and large index contrast that often cause waveguides and devices to be polarization-dependent [8]. The high index contrast, on the other hand, adds significant birefringence to the devices, resulting in polarization-dependent losses or polarization wavelength characteristics [9,10]. As a result, polarization diversity devices such as polarization beam splitters and polarization rotators are required to manipulate the polarization states [11, 12].

The conventional Polarization rotator (PR) waveguides allow the conversion between the orthogonal transverse electric and magnetic modes (TE-TM) [13]. Different structures based on mode evolution, mode hybridization, and surface plasmon effect mechanisms have been reported in [14-16]. Recently, PICs have significant development at a visible wavelength that demands polarization control for chip-scale atomic systems and free-space quantum communication [17]. However, a reduction in wavelength implies a reduction in waveguide size, which requires high manufacturing precision [18]. In quantum communication subsystems, including quantum cryptography repeaters, transmitter and receiver chips, polarization control components are crucial [19, 20]. In addition, shorter wavelength operation would enable polarization rotators more compatible with a variety of single photon emitter sources and several free space transmission systems [21,22]. To the best of our knowledge, few works introduced ±45 polarized light rotators that are very important in QKD protocols. Most of the structures mentioned in the introduction and literature operate at 1550 nm wavelength, while our designed structure operates in the visible region.

The position of the slot has a significant effect on the rotation angle of the polarization rotator. For conventional rotation by 90 degree, the slot position was at 46 nm shifted from the upper corner of Gallium-Phosphide waveguide [12]. While in this structure, the slot is positioned at 19.7 nm.

Salwa Marwan Salih with University of Baghdad, Al-Khwarizmi College of Engineering (e-mail: salwa.m@kecbu.uobaghdad.edu.iq)
Shelan Khasro Tawfeeq with University of Baghdad, Institute of Laser for Postgraduate Studies (e-mail: shelan.khasro@ilps.uobaghdad.edu.iq)

II. DESIGN PRINCIPLE AND NUMERICAL RESULTS

FIGURE 1(A) shows the 3D view of the proposed structure consisting of three parts. The input and output parts are regular Gallium-Phosphide (GaP) strip waveguides with a thickness of 250 nm. The rotation cross-section of the waveguide is shown in Fig. 1(b), which is formed by a horizontal slot of Hydrogen Silsesquioxane (HSQ) tilted by 45º to break the symmetry of the waveguide. To simplify the structure design, the width of the slot (w_{slot}) was fixed to 20 nm and shifted by 19.7 nm from the upper left corner of the rotator waveguide. The width (w) and the height (h) of the GaP waveguide are 197.5 and 200 nm, respectively. The structure is designed by using COMSOL Multiphysics based on a silicon on an insulator platform and covered by air. The refractive indices of GaP, HSQ, and air are 3.2543, 1.41, and 1, respectively, for a wavelength of 700 nm. The 2D simulation framework is truncated by first-order scattering boundary conditions with an extremely fine mesh element size. While in a 3D framework, first-order scattering boundary conditions, in addition to perfect magnetic conductors, are used.

The physical principle of the proposed structure is to rotate an input linear polarized light of +45º/-45º into TM_0 /TE_0 mode. The amplitude of the input (E_{xin}, E_{yin}) and output (E_{xout}, E_{yout}) modes can be expressed by John's matrix as [23],

$$\begin{bmatrix} E_{xout} \\ E_{yout} \end{bmatrix} = J \begin{bmatrix} E_{xin} \\ E_{yin} \end{bmatrix} \quad (1)$$

DOI: 10.36244/ICJ.2026.2.4

Where J is the general John's matrix for a rotator that is [cosθ -sinθ; sinθ cosθ], θ is the rotation angle. For conventional rotators (θ = 90°), i.e., the Johns matrix is defined as [0 -1; 1 0]. This means the fundamental mode TE_0 represented by the vector [1;0] will be completely rotated by 90º into TM_0 mode represented by [0;1]. The same process is applied for rotating the input TM_0 mode to TE_0 mode.

For a special case of an incoming input of 45º linear polarized light represented by 1/√2 [1;1]. To obtain an output of TM_0 mode, the rotation angle should be (θ =45º) with J=1/√2 [1 -1; 1 1]. Accordingly, when a +45º polarized light is launched into the proposed waveguide, two hybrid orthogonal modes are excited with electric field components $E_x < E_y$ for the first mode and $E_x > E_y$ for the second at half of the conversion length (L_c). After complete propagation through the waveguide with an integer number of L_c, it can be completely converted to TM_0 mode. The conversion length (L_c) can be expressed as [24]

$$L_c = \frac{\lambda}{2(n_{eff1} - n_{eff2})} \qquad (2)$$

Where λ is the operating wavelength and n_{eff1} and n_{eff2} are the effective refractive indices of the two hybrid modes.
The rotation angle of the optical axis (φ) caused by modal hybridity is defined as [24]

$$\tan\varphi = \frac{\iint n(x,z)E_x^2(x,z)\,dx\,dz}{\iint n(x,z)E_y^2(x,z)\,dx\,dz} \qquad (3)$$

Where n(x,z) is the refractive index distribution and $E_x(x,z)$ and $E_y(x,z)$ are the horizontal and vertical electrical field components of two orthogonal hybrid modes.
Fig.1(c, d) shows the magnetic field distribution of two hybrid fundamental orthogonal modes at half of L_c. The first mode is with an angle of -67.47º relative to a normal line at the xz-plane, and the second mode is with an angle of 22.49º.

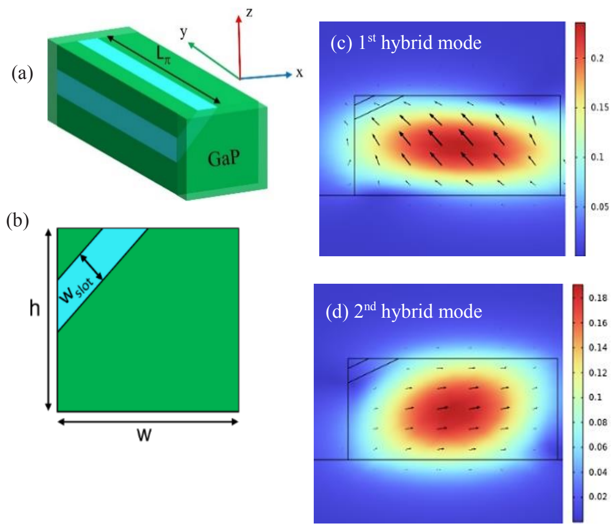


Fig. 1 (a) 3D-view of the polarization rotator (b) cross-section of the rotation region with w and h as the width and the height of the waveguide (c) magnetic field distribution of 1st hybrid mode (d) magnetic field distribution of 2nd hybrid mode. Arrows represent the electric field direction.

The purpose of the structure is to design a polarization rotator that provides a rotation angle of 22.5º at half of L_c so that the input polarized light will be rotated by 45º at L_c. By choosing the appropriate dimensions (w=197.5 nm and h=200 nm), two orthogonal fundamental modes can be fully hybridized as shown in Fig.1 (c and d). The polarization of an incoming +45º polarized light is therefore rotated by 45º into TM_0 mode. In addition, the structure is investigated for rotating -45º input polarized light into TE_0 mode. In Fig.2, the electric field distribution of E_x and E_z components of +45/-45 input polarized light along the rotator waveguide is observed.

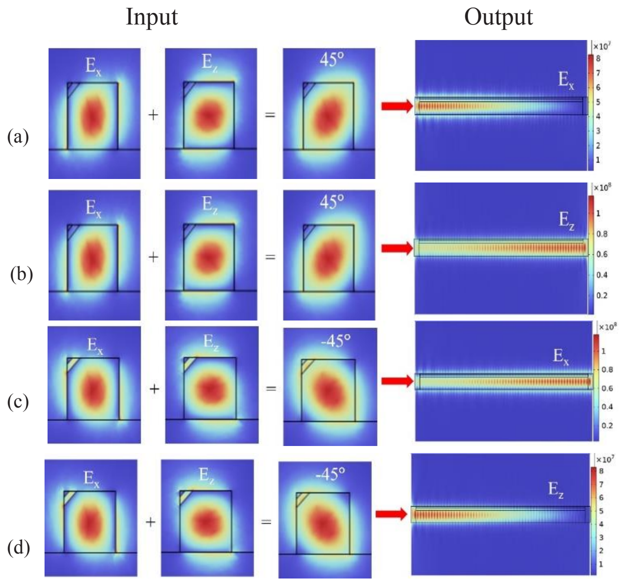


Fig. 2 The electric field distribution of E_X and E_Z components along the rotator waveguide. (a) E_X output when +45º as input (b) E_Z output when +45º as input (c) E_X output when -45º as input (d) E_Z output when -45º as input

The performance of the polarization rotator for input +45º/-45º polarized light is determined by the Polarization Conversion Efficiency (PCE), Extinction Ratio (ER), and Insertion Loss (IL) that can be defined as [25]

$$PCE = \frac{P_{TM-out}}{P_{TE-out} + P_{TM-out}} \qquad (3)$$

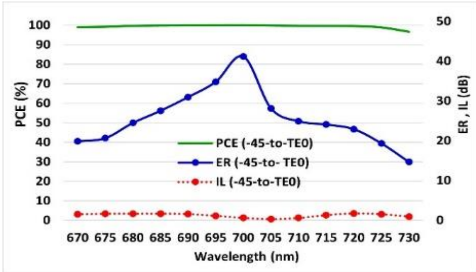
$$ER = 10\log\left(\frac{P_{TM-out}}{P_{TE-out}}\right) \qquad (4)$$

$$IL = -10\log\left(\frac{P_{TM-out}}{P_{in}}\right) \qquad (5)$$

Where P_{TM-out} and P_{TE-out} are the output power for TE and TM modes, respectively, and P_{in} is the input power, which is represented by (P_x+P_z).

The wavelength dependence transmission spectra, PCE, ER, and IL of the polarization rotator are illustrated in Fig. 3. The solid lines (blue and red) shown in Fig.3-a represent the transmission for the rotated input light of +45º/-45º polarization to TM_0/ TE_0, respectively. While Fig.3 (b and c) shows the PCE of 99.99% with a maximum ER 45.23 (41.17) dB for the rotation from +45º/-45º linear polarized light to TM_0/TE_0, respectively. The IL is 0.62 dB at 700 nm wavelength. The bandwidth achieved for ER above 20 dB is 40 nm.

Table (1) shows a comparison between the designed and other structures mentioned in the literature.

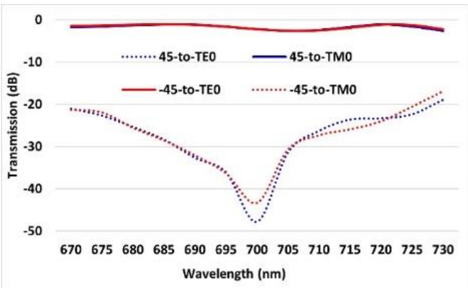


(c)

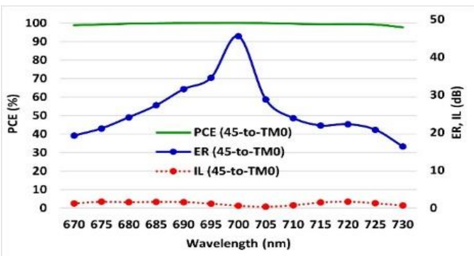
Fig.3 Continued

TABLE I:
A COMPARISON BETWEEN THE DESIGNED STRUCTURE AND VARIOUS PRS

Structure	Input-to-output mode	λ(nm)	PER (dB)	IL(dB)	Lc(μm)	B.W(nm)	Simulation /experimental work
45 deg. W-slot dual-stair waveguide [15]	TE (TM)-to-TM (TE)	1550	>17	<0.4	4.3	300	both
Twisted PR [18]	TE (TM)-to-TM (TE)	1550	---	0.09	150	300	both
Asymmetric slot-waveguide [24]	TE (TM)-to-TM (TE)	1550	25.9	1.19	8	77 TE-to-TM 66 TM-to-TE	simulation
Off-axis PR design [17]	TE (TM)-to-TM (TE)	422	20.7	---	111	---	both
Silicon nitride waveguide PR [19]	TM_0 -to-TE1	780	>20	<1	---	100	both
Our work	±45 to TE_0 (TM_0)	700	> 40	0.62	8.5	40 for PER>20	simulation



(a)



(b)

Fig.3 (a) Transmission spectra for +45º/-45º linear polarized light to TM_0 /TE_0. The PCE, ER, and IL for rotation of (b) 45º linear input polarized light to TM_0 mode (c) - 45º linear input polarized light to TE_0 mode

The performance of the device is affected by the variation in dimensions that occur during the fabrication process. These fabrication errors cause degradation in the device performance, such as PCE and ER. Therefore, it is necessary to study the fabrication tolerance of the rotator waveguide. These fabrication errors have been investigated by varying one parameter, i.e., L_c, and keeping the other parameters fixed at their optimum values. The fabrication tolerance analysis for rotating +45º into TM_0 and -45º TE_0 modes for ER higher than 20 dB is within (ΔL_c = 1μm) shown in Fig.4 and Fig. 5, respectively. The variation in the width of the slot (Δw_{slot}), the width (Δw) and the height (Δh) of the waveguide are listed in Table (2) to obtain ER higher than 15.

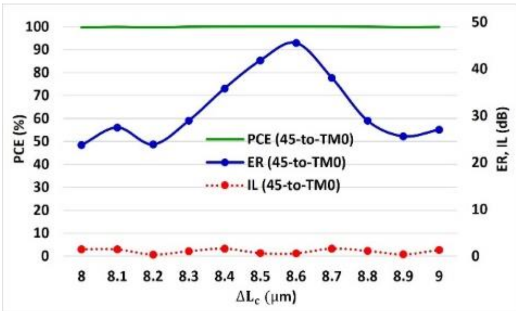
TABLE II
VARIATION OF THE DESIGNED STRUCTURE DIMENSIONS

Mode rotation	Variation		
	Δw_{slot}	Δw	Δh
45° to TM_0	±1	±1	±1
-45° to TE_0	-1 to +2	±1	±1

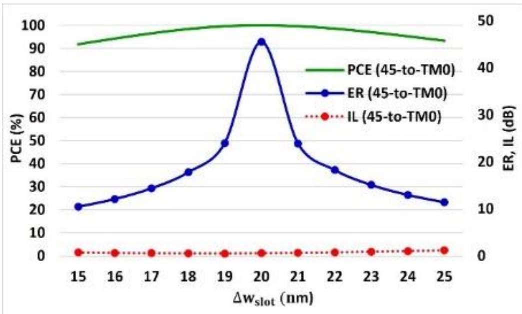
According to Table (2), and Fig. 4 and Fig.5, the results show that the tolerance of Δw_{slot}, Δw and Δh is very tight compared to ΔL_c.

III. Conclusion

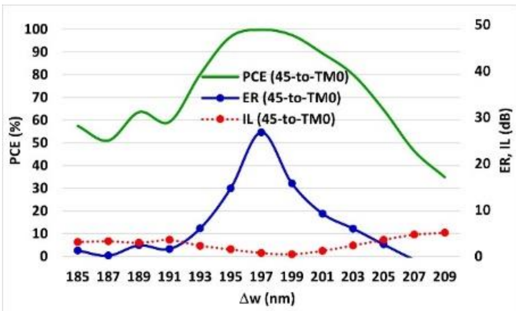
A 45-degree polarization rotator based on a tilted slot waveguide is designed. The device aimed to rotate a +45º/-45º input polarized light by a rotation angle of 45º; to obtain a TM_0/TE_0 polarized output light. The device has ER for the rotation from +45º/-45º linear polarized light to TM_0/TE_0 of 45.23 (41.17) dB, respectively, with IL of 0.62 dB at 700 nm wavelength. Also, the wavelength dependence and fabrication tolerance of the device are analyzed.



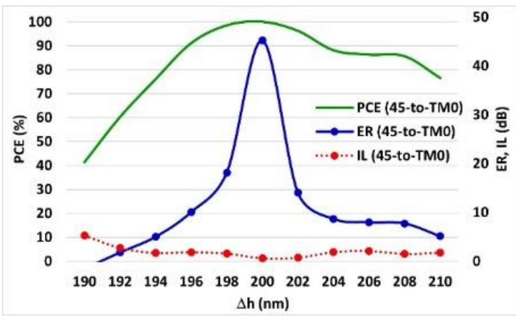
(a)



(b)

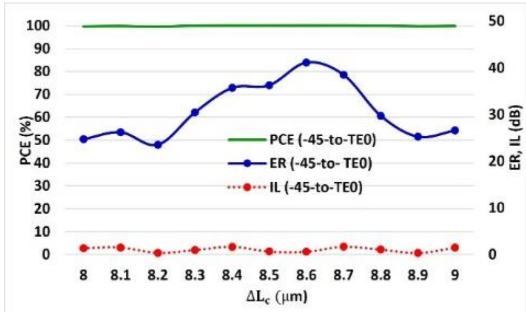


(c)

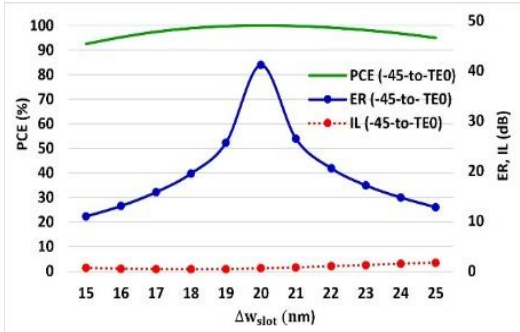


(d)

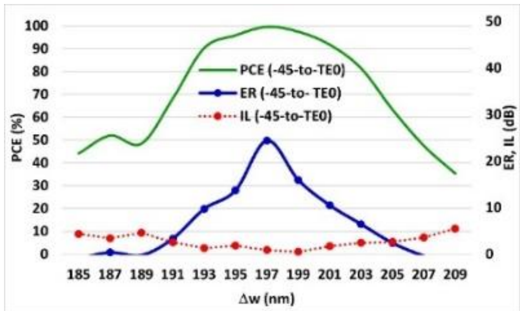
Fig.4 The fabrication error as a function of PCE, ER, and IL for rotating 45º linear polarized light to TM_0 mode (a) ΔL_c (b) Δwslot (c) Δw (d) Δh



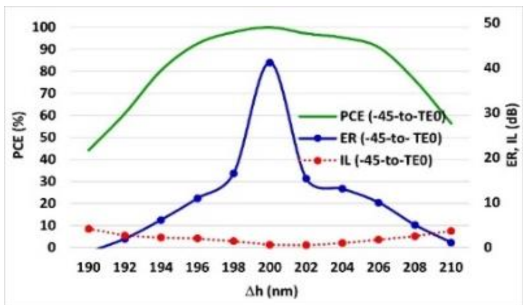
(a)



(b)



(c)



(d)

Fig.5 The fabrication error as a function of PCE , ER and IL for rotating -45º linear polarized light to TE0 mode (a) ΔL_c (b) Δwslot (c) Δw (d) Δh

REFERENCES

[1] Sibson, P., Kennard, J. E., Stanisic, Erven, S., C., O'Brien, J. L., Thompson, M. G.," Integrated silicon photonics for high-speed quantum key distribution," *Optica*, vol. 4, No. 2, pp. 172–177, 2017. DOI: 10.1364/OPTICA.4.000172

[2] Al-mfrji, A. A., Tawfeeq S. K., Fyath, R.S.," Modeling and Analysis of a Miniaturized Ring Modulator Using Silicon-Polymer-Metal Hybrid Plasmonic Phase Shifter. Part I: Theoretical Framework,". I*nternational Journal of Optics and Applications*, vol. 5, no. 4, pp. 121–132, 2015. DOI: 10.5923/j.optics.20150504.03

[3] Du, Y., Zhu, X., Hua, X., Zhao, Z., Hu, X., Qian, Y., Xiao, X., Wei, K.," Silicon-based decoder for polarization-encoding quantum key distribution," *Chip*, vol. 2, no.1, p. 100 039, 2023. DOI: 10.1016/j.chip.2023.100039

[4] Kumar, J., Saxena, V." Cloud Data Security through BB84 Protocol and Genetic Algorithm," *Baghdad Sci. J.*, vol. 19, issue 6, pp. 1445–1453 2022. DOI: 10.21123/bsj.2022.7281

[5] Al Hasani, M. H., Al Naimee, K. A. M.," Quantum Key Distribution and Chaos Bandwidth Effects on Impact Security of Quantum Communications," *Iraqi Journal of Science*, vol. 60 no. 6, pp. 1266–1273, 2019. DOI: 10.24996/ijs.2019.60.6.10

[6] Patton, R. J., Reano, R. M.," Framework for tunable polarization state generation using Berry's phase in silicon waveguides," *Optics Express*, vol. 28 no. 14, p. 20 845, 2020. DOI: 10.1364/OE.384543

[7] Chandra, D., Botsinis,P., Alanis, D., Zunaira Babar, Z., Ng, X.-Z., Hanzo, L., " On the Road to Quantum Communications,", *Infocommunications Journal*, vol. VIX, no. 2, 2022. DOI: 10.36244/ICJ.2022.3.1

[8] Gao, L., Huo, Y., Zang, K., Paik, S., Chen, Y., Harris, J. S., Zhou, Z.," On-chip plasmonic waveguide optical waveplate," *Scientific Reports*, vol. 5, p. 15 794, 2015. DOI: 10.1038/srep15794

[9] Wang, J., Xiao, J., Sun, X.," Design of a broadband polarization rotator for silicon-based cross-slot waveguides," *Applied Optics*, vol. 54 no. 12, pp. 3805–3810, 2015. DOI: 10.1364/AO.54.003805

[10] Xiao, J., Xu, Y., Wang, J., Sun, X., "Compact polarization rotator for silicon-based slot waveguide structures," *Applied Optics*, vol. 53, no. 11, pp. 2390–2397, 2014. DOI: 10.1364/AO.53.002390

[11] Wang, J." Design of a compact polarization beam splitter for silicon-based cross-slot waveguides," *Journal of Modern Optics* vol. 67, no. 15, pp. 1277–1284, 2020. DOI: 10.1080/09500340.2020.1842928

[12] Salih, S. M., Tawfeeq, S. K." Integrated gallium phosphide-waveguide polarization rotator based on rotating a horizontal slot by 45 degree for 700 nm wavelength," *Journal of Optics*, vol. 53, pp. 2168–2173, 2024. DOI: 10.1007/s12596-023-01420-6

[13] Ding, Y., Bacco, D., Llewellyn, D., Faruque, I., Paesani, S., Galili, M., Laing, A., Rottwitt, K., Thompson, M., Wang, J., and Oxenløwe, L. K.," Silicon Photonics for Quantum Communication," in *Proceeding of 21st International Conference on Transparent Optical Networks (ICTON)*, 18994402 2019.

[14] Giordani, T., Hoch, F., Carvacho, G., Spagnolo, N., Sciarrino, F., " Integrated photonics in quantum technologies," *La Rivista del Nuovo Cimento*, vol. 46, pp. 71–103, 2023. DOI: 10.1007/s40766-023-00040-x

[15] Hui, Z., Wen, X., Pan, D., Han, D., Li, T., Gong, J.," Ultrabroadband polarization rotator based on 45 deg W-slot dual-stair waveguide covering S + C + L + U bands," *Optical. Engineering*, vol. 60, no. 12, p. 127 103, 2021. DOI: 10.1117/1.OE.60.12.127103

[16] Khaleel, F. A., Tawfeeq, S. K." On the use of Aluminium as a plasmonic material in polarization rotators based on a hybrid plasmonic waveguide,"*Iraqi Journal of Laser*, vol. 20 issue, 2, pp. 23–41, 2021.

[17] Sneh, T., Hattori, A., Notaros, M., Corsetti, S., Notaros, J." Design of Integrated Visible-Light Polarization Rotators and Splitters," *Proceeding in Frontiers in Optics + Laser Science*, JTu5A.48 2022.

[18] Hou, Z.-S, Hou, Z.-S., Xiong, X., Cao, J.-J., Chen, Q.-D., Tian, Z.-N., Ren, X.-F., Sun, H.-B.," On-Chip Polarization Rotators," *Advanced Optical Materials*, vol. 7 no. 10, p. 1 900 129, 2019. DOI: 10.1002/adom.201900129

[19] Gallacher, K., Griffin, P.F., Riis, E., Sorel, M., Paul, D. J.," Silicon nitride waveguide polarization rotator and polarization beam splitter for chip-scale atomic systems," A*PL Photon*, vol. 7, p. 046 101, 2022. DOI: 10.1063/5.0077738

[20] Jaber, M. S., Tawfeeq, S. K., Fyath, R. S." Design Investigation of 4 x 4 Nonblocking Hybrid Plasmonic Electrooptic Switch," *Photonics*, vol. 6 no. 47, 2019. DOI: 10.3390/photonics6020047

[21] Khaleel, F. A., Tawfeeq, S.K.," The spontaneous emission performance of a quantum emitter coupled to a hybrid plasmonic waveguide with specified output polarization for on- chip plasmonic single-photon source,". *Photonics and Nanostructures – Fundamentals and Applications*, vol. 45, p. 100 925, 2021.
https://doi.org/10.1016/j.photonics.2021.100925

[22] Khaleel, A. I., Tawfeeq, S.K.," Key rate estimation of measurement-device-independent quantum key distribution protocol in satellite-earth and intersatellite links," *International Journal of Quantum Information*, Vol. 16, no. 3, p. 1 850 027, 2018. DOI: 10.1142/S0219749918500272

[23] Pedrotti, F. L., Pedrotti, L. M., Pedrotti, L. S.: "Introduction to optics," (Addison-Wesley, 2006).

[24] Zhang, Z., Tsuji, Y., Masashi, E., . Chen, C.-P, Anada, T., " Design of Polarization Rotator Based on Asymmetric Slot-Waveguide," in *Proceeding Asia Communications and Photonics Conference*. M4A.111, 2019.

[25] Xie, A., Zhou, L., Chen, J., Li, X.: Efficient silicon polarization rotator based on mode-hybridization in a double-stair waveguide. *Opticss Express*, vol. 23, no.4, pp. 3960–3970, 2015. DOI: 10.1364/OE.23.003960

Salwa Marwan Salih earned her B.Sc. degree from the College of Engineering, University of Baghdad, Baghdad, Iraq, in 2013 and the M.Sc. and Ph.D. degrees from the Institute of Laser for Postgraduate Studies, University of Baghdad, in 2019 and 2024, respectively. At present, she is a lecturer at Al-Khwarizmi College of Engineering, University of Baghdad. Her research interest is focused on integrated photonics and optical communication systems.

Shelan Khasro Tawfeeq received a B.Sc. degree from the College of Engineering, University of Baghdad, Baghdad, Iraq, 1990, and the M.Sc. and Ph.D. degrees from the Institute of Laser for Postgraduate Studies, University of Baghdad, in 2001 and 2006, respectively. She is currently an Assistant Professor with the Institute of Laser for Postgraduate Studies, University of Baghdad, and head of Quantum Optics and Electronics Group where she is involved in research in quantum information science and optical communications systems.