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Investigation on Electro-Absorption Modulators

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Abstract— **With an increase in internet traffic, both long distance fiber networks and short-reach interconnections in data centres demand large-capacity optical transceivers. To achieve the proper transmission distances, symbol rates, and modulation formats in optical transceivers, directly modulated lasers, Electro- Absorption Modulators (EAM), and Mach-Zender Modulators (MZM) are, respectively needed. Because it offers a small footprint, high bandwidth, and low power consumption, the EAM is a crucial component for data centre applications. The Multiple Quantum Well (MQW) based structures has applications in op- tical modulators and switches. How to make optical transceivers with EAMs smaller and less expensive is a crucial concern. In this paper various EAM is investigated. The Insertion Loss (IL) and Extinction Ratio (ER) is also investigated for various EAMs. The applications based on EAM is also presented.**

Index Terms— **Electro-Absorption Modulator, External Modulation, Extinction Ratio, Insertion Loss**.

I. Introduction

Optical modulation is a technique for controlling an optical wave or encoding information on a carrier optical wave. De- modulation is the inverse procedure that restores the encoded information. There are several forms of optical modulation, which may be classified in a variety of ways. In general, there are two ways for modulating an optical signal. These two techniques are classified as Direct Modulation and External Modulation.

Direct Modulation is a modulation technique in which the data to be communicated is directly put over a light stream generated by the source. Simply altering the driving current of a light source, i.e.; the laser, with the electrical information signal generates a changing optical power signal in this manner. As a result, individual optical modulators are not required for optical signal modulation. The main disadvantage of this modulation approach is related to the carrier duration for spontaneous and stimulated emission, as well as the photon lifetime of the source.

The laser turns on and off in accordance with the electrical signal or the driving current while conducting direct modulation with the laser transmitter. But in this instance, the laser line width is increased in some manner. This increase in laser line width is referred to as chirp. External modulation employs independent optical modulators that modify optical signals to alter signal properties. After the light is produced, external modulation is carried out. A dc current is used to power the laser, and modulation is performed independently after that. Here, chirping is reduced and requires low driving voltage and is faster in processing. The Electro-Optic Modulation and Electro-Absorption Modulation are examples.

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II. ELECTRO-ABSORPTION MODULATOR (EAM)

An optical modulator known as an Electro-Absorption Modulator is a semiconductor-based device that can change the intensity of a beam of light by using an external electric voltage. The Franz-Keldysh Effect (FKE), which states that a change in the bandgap energy is produced by the applied electric field, forms the foundation of an EAM. Modulators with low modulation voltages and compact dimensions are preferred in telecommunications. For this sort of external modulation technology, the EAMs are suitable. Bulk semi-conductor materials, materials with many quantum dots, or materials with wells can be used to create these modulators. The majority of EAMs are constructed in waveguide form with electrodes to provide an electric field perpendicular to the modulated light beam. In a quantum well structure, the Quantum-Confined Stark Effect (QCSE) is frequently utilized to obtain a high extinction ratio. In comparison to an Electro Optic Modulator (EOM), an EAM may operate at substantially lower voltages (a few volts instead of ten volts or more). Due to their ability to operate at extremely high speeds and achieve modulation bandwidths of tens of gigahertz, these devices are useful for optical fiber communication.

A valuable feature is the ability to merge an EAM and distributed feedback laser diode on a single chip to produce a photonic integrated circuit that acts as a data transmitter. In comparison to direct modulation of the laser diode, higher bandwidth and less chirp may be produced. Interest in the study of self-organized quantum dots has recently increased due to developments in crystal growth. The ability to fabricate quantum dots with improved electro-absorption coefficients makes them interesting for this application since the EAM needs compact size and low modulation voltages

III. BASIC OPERATING PRINCIPLES OF EAM

The practical EAM is semiconductor devices based on FKE, in case of a bulk semiconductor. EAM also known as Quantum Well (QW) Modulator works based on the principle of QCSE. Stark Effect is simply the shift in the absorption spectrum. That is shift in the absorption lines in presence of applied electric field.

A. Franz-Keldysh Effect (FKE)

The FKE describes how absorbing a photon with energy below the band gap can allow an electron in a valence band to be excited into a conduction band. When the photon energy is below the bandgap, tunnelling permits the electron and hole wave functions to overlap.

B. Quantum Confined Stark Effect (QCSE)

The QCSE defines the impact of an external electric field on a QW light emission or absorption spectrum. Electrons and holes inside the quantum well are only able to occupy states within a specific range of energy sub-bands in the absence of an external electric field. This lowers the frequency of emission or absorption of light that are allowed. The overlap integral decreases as a result of the external electric field's shifting of electrons and holes to the opposing sides of the well, which also lowers the system's efficiency of recombination.

IV. WORKING OF EAM

The Electro-Absorption Effect is the change of a material's absorption coefficient (α) resulting from an external electric field. The intensity of a light beam flowing through the material may be controlled directly using this effect. A Multi- Quantum Well (MQW) structure is made up of alternating small and big bandgap semiconductor layers. The applied electric field alters the energy levels in these structures, causing the absorption edge to move towards lower frequencies or higher wavelengths (QCSE).

When no electric field is applied, light is passed via the modulator. When the electric field is raised, the absorption spectrum moves towards lower frequency/higher wavelength (red shift), and the modulator transforms from transparent to highly absorbing, lowering the intensity of the transmitted light. The intensity of the output light can be calculated using the equation 1.

$$I_o = I_{in} \times e^{(-\alpha L)} \tag{1}$$

where; "I_o" is the intensity of output beam, "I_{in}" is the intensity of input beam, "α" is the absorption coefficient and "L" is the length of the modulator.

Absorption Coefficient(α) specifies how far a substance can penetrate before absorbing light of a specific wavelength. For various semiconductors, the absorption coefficient varies. It depends on wavelength (λ), mole fraction (x), length of modulator (L) and field applied (F).

Insertion Loss (I.L) is the power loss due to insertion of a device. In order to maximize performance and power efficiency, it should be minimized. The insertion loss of EAM is calculated using equation 2. The insertion loss in dB is calculated using equation 3. The insertion loss can be as good as 1 dB.

$$I.L = 1 - e^{(-\alpha_0 L)} \tag{2}$$

$$I.L(dB) = 4.343[1 - e^{(-\alpha_0 L)}] \tag{3}$$

Extinction Ratio (E.R) is the ratio between the optical power at maximum absorption to optical power at minimum absorption. The equation is as shown in equation 4.

$$E.R(dB) = 4.343[\alpha_{(V)} - \alpha_{(0)}]L \tag{4}$$

V. WORKS RELATED TO EAM

Chin *et al.* [1] proposed that for optical on-off modulators, low insertion loss, high Contrast Ratio (CR), low drive power, and high bandwidth or bit-rate are necessary. Here, based on the QCSE, is a methodical way to improve the overall performance of these modulators. The strategy involves lowering the power-bandwidth ratio to fulfill a specific CR and insertion loss. With a thin buried active layer, this concept combines a large-core multimode passive waveguide.

P.L. Souza *et al.* [2] put forward the idea that the basic equipment for long-distance communication are amplitude modulators. Their research began with the FKE or electro-absorption of bulk material. Attention has been focused on multiple QW designs where the QCSE might enhance device performance at high data rates since high- frequency applications required bigger absorption variations with the electric field. This paper clearly shows that the quantum well width cannot be increased further to reduce the applied electric voltage.

Wight *et al.* [3] proposed a 390 μm wide waveguide modulator developed with corresponding insertion loss less than 10% (0.4 dB) and extinction ratio more than 29 dB with regard to an optical bandwidth and evident that these modulators, when inserted into waveguides. Also suggested that these will be perfectly suitable with micro-electronic circuits and offer novel features and improved capabilities up to and possibly beyond the limiting bandwidths currently anticipated in GaAs high speed electronics. Additionally, these modulators also serve as voltage activated detectors.

L. Ji *et al.* [4] proposed that the length of a device has a significant impact on the extinction ratio and insertion loss of EA modulators. And shown that the suggested modulator's extinction ratio and insertion loss rely heavily on the graphene length of L. The length of 120 µm is used to achieve an extinction ratio of 28 dB as well as an insertion loss of 1.28 dB.

R. Dingle *et al.* [5] indicated that Quantum levels associated with carrier confinement in extremely thin, molecular beam-grown $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}$ As. As hetero- structures result in significant structure in the GaAs optical absorption spectrum. Also indicated that the absorption is negligible in case of mole fraction of $Al_xGa_{1-x}As$ less than 0.2 and there should be a higher band-gap energy for better absorption.

Rebecca *et al.* [6] developed an efficient modelling approach called Simple Quantum Well Electro-Absorption Calculator (SQWEAC) that encompasses the numerous significant physical effects found in the Ge QW material system and well fits the first transition (E1-HH1) for a variety of material designs and growth conditions. For ER greater than 5 dB and IL3 dB, the wavelength operating would be 1514 nm to 1550 nm at this design length (60 µm).

Papichaya Chaisakul *et al.* [7] proposed a Ge/SiGe MQW EAM operating at high speed in a waveguide configuration is the subject of this paper. Using a 3 µm wide by 90 µm long Ge/SiGe MQW waveguide, 23 GHz bandwidth is experimentally demonstrated. A high extinction ratio of more than 10 dB is displayed by the modulator over a large spectral range. Additionally, an extinction ratio of up to 9dB can be attained with a swing voltage of 1V between 3 and 4V, with an estimated energy consumption per bit of 108 fJ.

This demonstrates the potential of Ge/SiGe MQWs as a component of silicon-compatible photonic integrated circuits for quick, efficient optical connections. It is inferred that if we reduce the device size and energy consumption can be reduced.

T. Hiraki *et al.* [8] indicated that with increasing Internet traffic, large-capacity optical transceivers are required for not only long-distance fiber links but also short-reach interconnections in data-centers. A membrane InP-based electro-absorption modulator (EAM) is fabricated, in which an InGaAsP-based multiple- quantum-well (MQW) absorption region is buried with an InP layer, on Si-waveguide circuits. By optical coupling between the MQW absorption region and Si core, a low-loss and large-absorption-length (300 µm long) super mode waveguide is designed to suppress electric-field screening at high optical input power.

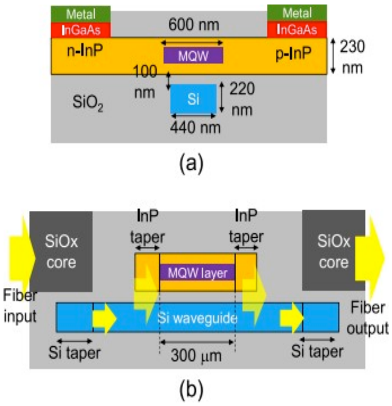

Fig. 1: (a) Cross-sectional and (b) side views of membrane InGaAsP EAM on Si platform [8]

The EAM is fabricated by combining direct bonding of the MQW layer and regrowth of the InP layer on a thin InP template bonded on a Silicon-on-Insulator (SOI) wafer. Figure 1 shows the cross-sectional and side views of membrane InGaAsP EAM on Si platform. The fabricated membrane EAM shows an on-chip loss of less than 4 dB at wavelengths over 1590 nm and temperatures from 25°C to 50°C. Since the membrane lateral p-i-n diode structure is beneficial for reducing the RC time constant of a lumped-electrode InP- based EAM, the EO bandwidth of the EAM is around 50 GHz without a 50-ohm termination up to fiber-input power of 10 dBm. Using the device, clear eye openings for 56-Gbit/s NRZ and 112-Gbit/s PAM4 signals at temperatures from 25 to 50°C is demonstrated.

Zhi Liu *et al.* [9] proposed an idea of developing a high-speed evanescent-coupled Ge waveguide EAM on a Silicon- on-Insulator substrate with a 220 nm top Si layer, with easy manufacturing techniques. Selectively produced Ge with a triangular form was utilized directly for EAM Ge waveguides. In the Ge waveguide, an asymmetric p-i-n junction was built to create a high electric field for the FKE. At 1610 nm, the insertion loss of the Ge EAM was 6.2dB. At 1 V, the EAM demonstrated a high electro-optic bandwidth of 36 GHz. At 1610 nm, clear open 56 Gbps eye diagrams with a dynamic extinction ratio of 2.7 dB was obtained. Potential uses for this EAM include Si-based on-chip optical interconnects with small footprints and low power requirements.

Ning-Ning Feng *et al.* [10] demonstrated an integrated with a single mode 3 µm Silicon-on-Insulator (SOI) waveguide based high-speed Ge EAM. The Ge EAM used a horizontally oriented p-i-n structure. The demonstrated EAM displays a high EA effect in the wavelength range of 1570–1640 nm and has reached 4-7.5 dB ER with 2.5–5 dB total IL, including the transition loss between Si and Ge waveguides, in the wavelength range of 1610–1640 nm.

Marco A. Giambra *et al.* [11] proposed and fabricated the C- band dual-layered graphene (DLG) EAM on a passive SOI platform. The simulation of the proposed EAM was done with the waveguide of 450nm wide and designed to handle a single quasi-Transverse Electric (TE) in-plane polarized optical mode on a 220 nm Si photonic platform. They employed high quality single crystal graphene generated by Chemical Vapour Deposition (CVD) on copper (Cu) foils using deterministic seeded growth for DLG EAM fabrication. Extinction ratios at 10Gb/s range from 1.7 dB to 1.3 dB at 50 Gb/s.

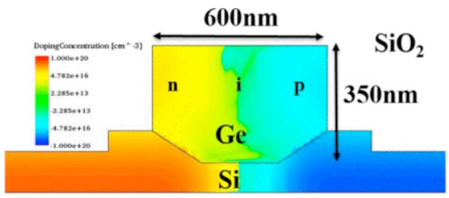

Fig. 2: Cross-sectional schematic of the Ge EAM device integrated on a 220 nm SOI platform [12]

S. A. Srinivasan *et al.* [12] presented a Germanium (Ge) waveguide EAM with an electro-optic bandwidth that is significantly greater than 50 GHz. The device is built using 200 mm SOI wafers with a top Si thickness of 220 nm on a fully integrated Si photonics platform. Figure 2 shows the Cross-sectional schematic of the Ge EAM device integrated on a 220 nm SOI platform. Up to 3.3 dB of ER was observed. And an IL 5.5dB was obtained. At 1610 nm, the device modulates light.

K. Hasebe *et al.* [13] proposed and described the design of a laser with an integrated EAM and lateral-p-i-n-diode structure. When the electric field is applied parallel to the quantum well, broadened exciton absorption peak is observed. The calculated absorption spectrum change is compared for parallel and vertical electric fields. And found that the absorption coefficient change is less for parallel electric field.

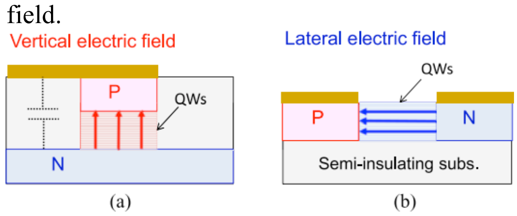

Fig. 3: Typical cross-sectional structures of the EAM using (a) vertical and (b) lateral electric fields[13]

Figure 3 shows the typical cross-sectional structures of the EAM using(a) vertical and (b) lateral electric fields. 200 µm long EAM device is designed and 50-Gb/s operation with clear eye opening is observed. InGaAlAs is used as the well material. This EAM has a static ER of 10 dB over a large wavelength range.

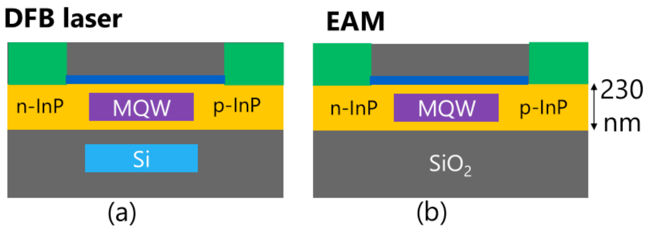

Fig. 4: Schematics of cross-sections of (a) DFB laser and (b) EAM [14]

T. Hiraki *et al.* [14] proposed a membrane InGaAlAs EAM integrated with DFB laser. On a silicon-on-insulator wafer, InP layers are directly bonded to the wafer and are regrown epitaxially. Integration of O-band EAM and laser on SOI wafer is challenging. EAM-integrated DFB laser has clear eye openings for 100 and 112-Gbit/s signals with an ER of 3.8 and 3.2 dB respectively. Figure 4 shows the cross-sections of DFB laser and EAM.

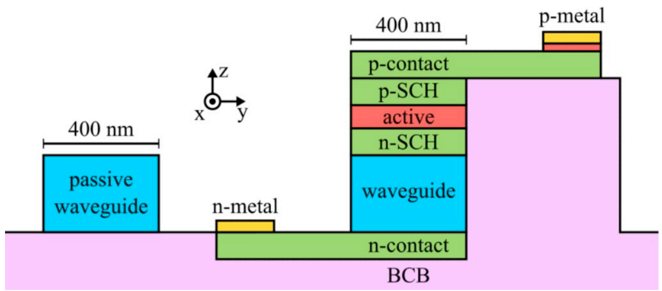

Fig. 5: Cross-section of (left) standard IMOS waveguide, and(right) the simplified device structure [15]

L. Shen *et al.* [15] proposed a novel membrane EAM with high ER and IL for over 100 nm wavelength. Modulator based on IMOS waveguide with 300 nm height and 400 nm width is proposed, designed and simulated. The optical and electrical performance is also evaluated. Modulator based on n- InGaAs with 7.2 dB static ER, 4.4 dB IL, 50 Gb/s modulation speed. proposed a novel membrane EAM and evaluated by simulation. It is based on the electron-concentration-dependent absorption of highly doped n-InGaAs and can be operated over a wavelength range of more than 100 nm. Figure 5 shows the Cross-section of (left) standard IMOS waveguide, and (right) the simplified device structure shows the cross-section of standard IMOS waveguide, and the simplified device structure.

Kambiz Abedi *et al.* [16] proposed EAMs with negative chirp and low insertion loss and numerically designed with Asymmetric Intra-Step-Barrier Coupled Double Strained Quantum Wells (AICD-SQWs) based on InGaAlAs material. The objective of the paper aims to examine how the chirp parameter and the insertion loss in the AICD-SQWs are affected by strain in the well layers. Values of IL up to 2.5 dB are suggested as being preferable for Electro-Absorption Optical Modulators.

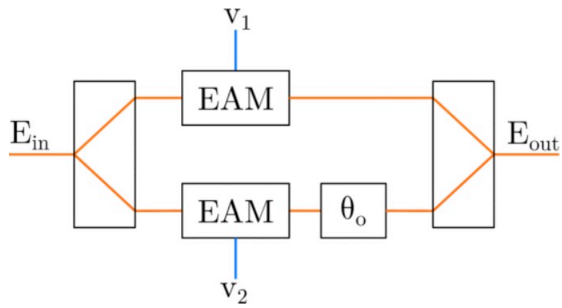

Fig. 6: Block diagram showing the structure of parallel EAMs [17]

J. Declercq *et al.* [17] presented a low-power all-digital RoF transmitter using sigma-delta modulation and a parallel EAM structure to reduce bandwidth requirements and mitigate chromatic dispersion. Experimental results show an Error Vector Magnitude (EVM) of 7.6%. The research aims to reduce the transmitter's sample rate without increasing receiver complexity. A low-power Si-integrated all-digital radio-over-fiber transmitter for operation in the 28 GHz band and beyond, using sigma-delta modulation and parallel EAMs is demonstrated. This transmitter architecture halves the required sample rate and bandwidth, while maintaining the digital nature of sigma- delta modulation. Block diagram showing the structure of parallel EAMs is shown in figure 6.

J. T. Kim *et al.* [18] proposed that Graphene is an interesting optical material for nanoscale photonics, and also proposed a silicon EAM based on a Graphene-hexagonal Boron Nitride hetero-structure. The optical characteristics of the proposed modulator was numerically investigated and optimized to achieve satisfactory modulation characteristics. The anisotropic Graphene model results in a reduction of 7.6 to 4.7 dB in the ILoff of a 50 µm long modulator. For a 10 µm long modulator, ILoff falls from 4.1 to 2.4 dB in the isotropic graphene model. Mode is greatly diminished at the off-state. It's under 5 dB for the C-band (1.530-1.565 µm).

L. Bogaert *et al.* [19] suggested that Silicon photonics is an integrated platform leveraging the microelectronics CMOS industry for low cost, high yield and high-volume capabilities. SiGe EAMs offer low-power, high-speed modulation for data- center interconnects (DCI) transmitters and receivers. Silicon photonics enables the miniaturization of optical systems into integrated circuits [20].

D.Feng *et al.* [21] focused on the development of a GeSi EAM based on the FKE integrated in a 3µm SOI platform. Also indicated the FKE in GeSi, described the EA modulator device design and fabrication, and reported on its performance. The demonstrated modulator has an operational wavelength range of 40 nm, a 3-dB bandwidth of 38 GHz, and a small size of 0.8 µm x 50 µm.

The insertion loss of the modulator is caused by the GeSi material absorption and mode mismatch loss between the silicon waveguide and the GeSi waveguide. The horizontal p-i-n design makes it possible to have a very small intrinsic GeSi area, which lowers the voltage swing needed to produce a significant electric field and a high extinction ratio. Schematic view of a GeSi FK modulator integrated with a 3µm SOI waveguide is shown in Figure 7.

Kaur et al. [22] presented an investigation of the performance at 10 Gb/s of a multi-wavelength converter based on an EAM. The input signal wavelength was seen to convert into fourteen separate wavelengths, with 10 dBm input signal strength combined with 6.99 dBm probe signal power producing the best converted signal quality. The relationship between quality factor, conversion effectiveness, and ER and input signal power was also observed.

Papichaya Chaisakul *et al.* [23] summarized the electro-absorption properties of GeSi and discusses the demonstrated device performance. One of the most promising methods for creating a small, low-energy, quick, temperature-stable, and high-volume optical modulator for short-distance optical inter- connects is electro-absorption from GeSi on Si. Both FKE and QCSE have exhibited high-performance optical modulators. While effective integration of QCSE device with input and output waveguide is still being developed, an FKE modulator but coupled with Si waveguide has been demonstrated with an acceptable performance matrix. Given the current rate of work, significant development can be anticipated during the next few years.

V. CONCLUSION

This paper has presented an overview of different types and applications of EAM. The EAM survey was done on the basis of theoretical, experimental and fabricated works, and applications using EAM. It is inferred that as the length of the modulator increases the IL also increases. By using different materials, the IL and ER was found varying. From the surveyed papers it is noted that new EAM is feasible for membrane photonics platforms. Also, it is noticed that GeSi is a promising material for telecommunication applications due to its high ER.

REFERENCES

[1] M. E. Chin and W. S. C. Chang, "Theoretical design optimization of multiple-quantum-well electro-absorption waveguide modulators," in IEEE Journal of Quantum Electronics, vol. 29, no. 9, pp. 2476-2488, Sept. 1993, doi: 10.1109/3.247705.

[2] P.L. Souza, M.P. Pires, B. Yavich, F. Racedo, C.B. Tribuzy "Amplitude modulators based on the stark effect", in Elsevier Microelectronics Journal, 2002, DOI: 10.1016/S0026- 2692(01)00129-X.

[3] D.R. Wight, A.M. Keir, G.J. Pryce, J.C.H. Birbeck, J.M. Heaton, R.J. Norcross, P.J. Wright, "Limits of electro-absorption in high purity GaAs, and the optimization of waveguide devices", in IEE Proceedings J Optoelectronics, 135(1), 1988. DOI:10.1049/ip-j.1988.0010.

[4] Lanting Ji, Daming Zhang et.al., "Design of an Electro-Absorption Modulator Based on Graphene-on-Silicon Slot Waveguide," in IEEE Photonics Journal, vol. 11, no. 3, pp. 1-11, June 2019, Art no. 7800911, doi: 10.1109/JPHOT.2019.2918314.R.

[5] Dingle, Wiegmann, et.al., "Quantum States of Confined Carriers in Very Thin $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ Heterostructures". Physical Review Letters, 33(14), 827–830, 1984. DOI:10.1103/physrevlett.33.827.

[6] Rebecca, Schaevitz et.al., "Simple Electro-absorption Calculator for De- signing 1310 nm and 1550 nm Modulators Using Germanium Quan- tum Wells" in Quantum Electronics, IEEE Journal of. 48. 187 - 197. 10.1109/JQE.2011.2170961, 2012.

[7] Papichaya Chaisakul "23 GHz Ge/SiGe Multiple Quantum Well Electro- Absorption Modulator", in Optics express, 30 January 2012 / Vol. 20,No. 3 / OPTICS EXPRESS 3219.

[8] T. Hiraki et al., "50-GHz-Bandwidth Membrane InGaAsP Electro- Absorption Modulator on Si Platform," in Journal of Lightwave Technology, vol. 39, no. 16, pp. 5300- 5306, 15 Aug.15, 2021, DOI: 10.1109/JLT.2021.3082710.

[9] Zhi Liu, Xiuili Li, "56 Gbps high-speed Ge electro-absorption Modulator" in Photonics Research, vol. 8, No. 10, October 2020, doi:10.1364/PRJ.401140.

[10] Ning-Ning Feng et.al., "30GHz Ge electro-absorption modulator inte- grated with 3μm silicon-on-insulator waveguide," in Optics Express 19, 7062-7067,2011.

[11] Marco A. Giambra et.al., "High-speed double layer graphene Electro-Absorption Modulator on SOI waveguide," in Optics Express 27, 20145- 20155,2019.

[12] S. A. Srinivasan et al., "56 Gb/s Germanium Waveguide Electro-Absorption Modulator," in Journal of Lightwave Technology, vol. 34, no. 2, pp. 419-424, 15 Jan.15, 2016, doi: 10.1109/JLT.2015.2478601.

[13] K. Hasebe et.al., "High-Speed Modulation of Lateral p-i-n Diode Structure Electro-Absorption Modulator Integrated with DFB Laser," in Journal of Lightwave Technology, vol. 33, no. 6, pp. 1235-1240, 15 March15, 2015, doi: 10.1109/JLT.2014.2383385.

[14] T. Hiraki et al., ``Over-67-GHz-Bandwidth Membrane InGaAlAs Electro-Absorption Modulator Integrated with DFB Laser on Si Platform," in Journal of Lightwave Technology, vol. 41, no. 3, pp. 880-887, 1 Feb.1, 2023, doi: 10.1109/JLT.2022.3221814.

[15] L. Shen et.al., "A Novel Broadband Electro-Absorption Modulator Based on Bandfilling in n-InGaAs: Design and Simulations," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, no. 1, pp. 1-8, Jan.-Feb. 2018, Art no. 3300108, doi:10.1109/JSTQE.2017.2765459.

[16] Kambiz Abedi et.al., "The design of electro absorption modulators with negative chirp and very low insertion loss" in Journal of Semiconductors, Vol. 33, No. 62012, June 2012.

[17] J. Declercq et al., "Low Power All-Digital Radio-Over-Fiber Transmission for 28-GHz Band Using Parallel Electro-Absorption Modulators," in Journal of Lightwave Technology, vol. 39, no. 4, pp. 1125-1131, 15 Feb.15, 2021, doi: 10.1109/JLT.2020.3029105.

[18] J. T. Kim et.al., "Silicon Electro-Absorption Modulator Based on Graphene-Hexagonal Boron Nitride Hetero-structure," in Journal of Lightwave Technology, vol. 34, no. 22, pp. 5293-5299, 15 Nov.15, 2016, doi: 10.1109/JLT.2016.2618371.

[19] L. Bogaert et al., "SiGe EAM-Based Transceivers for Datacenter Inter- connects and Radio Over Fiber," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 27, no. 3, pp. 1-13, May-June 2021, Art no. 6000113, doi: 10.1109/JSTQE.2020.3027046.

[20] B. Jalali and S. Fathpour, "Silicon Photonics," in Journal of Lightwave Technology, vol. 24, no. 12, pp. 4600-4615, Dec. 2006, doi: 10.1109/JLT.2006.885782.

[21] D. Feng et al., "High-Speed GeSi Electro Absorption Modulator on the SOI Waveguide Platform," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 19, no. 6, pp. 64-73, Nov.-Dec. 2013, Art no. 3401710, doi: 10.1109/JSTQE.2013.2278881.

[22] Kaur et.al., "Performance analysis of Electro-Absorption Modulator-based multi-wavelength converter", in Photon Netw Commun 35, 53–64, 2018, doi:/10.1007/s11107-017-0715-y.

[23] Papichaya Chaisakul et.al.,"Recent progress in GeSi Electro-Absorption Modulators", in Science and Technology of Advanced Materials, 03 Dec 2013, doi: 10.1088/1468-6996/15/1/014601