SSURJET

Sir Syed University Research Journal of Engineering & Technology
2022, Vol. 12, No. 2,
https://doi.org/10.33317/ssurj.486

Simulation of Silicon Oxycarbide Waveguides for Shorter Band Photonics

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Received April 26, 2022; Revised June 08, 2022; Accepted July 13, 2022

Abstract

In this research paper, we design and simulate the Silicon Oxycarbide (SiOC) channel waveguides and a photonic passive device such as a directional coupler. SiOC channel waveguides are designed for different values of width and height at a shorter wavelength band that is a 1310 nm wavelength window with a refractive index of SiOC (ncore) =2.2 µm and SiO_2 (nclad) = 1.444 µm. TE and TM fundamental modes are achieved at width = 1.5 microns and height = 0.5 microns to understand the single mode operation of SiOC channel waveguides. The minimum bending radius of SiOC waveguide is found to be 30 microns which are large enough to integrate large-scale devices. A directional coupler is designed to measure the coupling power between waveguides with gaps of 0.6, 0.7, and 0.8 microns that give the 3 dB coupling at 20, 40, and 100 microns. In this research, Silicon Oxycarbide (SiOC) is presented as a potential material platform for the highly efficient photonic devices that will be used for shorter wavelength bands instead of the 1550 nm transmission wavelength window where bandwidth demand is increasing every day. Due to this shorter wavelength band is sufficient to develop and design SiOC waveguides to meet the future bandwidth requirement.

Index Terms: *Integrated Photonics, Silicon Oxycarbide, Directional Coupler, Bending Radius, Photonics.*

I. INTRODUCTION

Optical fiber plays an important role in photonics and is the basic component of fiber optic communication. It is used widely because of its low losses, fast speed, and high reliability as compared to electronic communication. Silica is the most commonly used glass for optical fibers such as amorphous Silicon Dioxide (SiO_2) and quartz glass that can be either in pure form or with some other dopants. Optical fibers are mostly used in laser technology that consists of waveguides having a refractive index of core higher than the bounding medium called cladding. An optical waveguide is a building block element in which different devices of an integrated circuit are connected. Whereas, in an electrical integrated circuit, metallic strips are used [1]. Integrated photonics refers to the fabrication of many components onto a single planar substrate. These components constitute the basic building block to fabricate more complex devices when integrated with a planar waveguide that provides better and faster communication [2]. For waveguides, dielectric technologies are used that have low losses including Silicon Nitride (SiN) and Silicon Oxy-Nitride (SiON).

There are various material platforms in the field of photonics that ranges from semiconductor [3], and polymers [4] to different dielectric material platforms. Semiconductors are mostly used in different kinds of applications that include transistors, diodes, optical sensors, and lasers. Polymers are used as photo resistance material in the photolithography method, widely used in LEDs and optical storage devices. In Photonic Integrated Circuits (PICs), it can be used as substrate material. Most of the dielectric technologies such as silica [5], silica nitride [6], silicon oxy-nitride, and the most-novel material that is silicon oxy-carbide are used for the fabrication of optical waveguides and devices due to their appealing optical characteristics. All the compounds have their different characteristics and are used for the fabrication of photonic devices.

In PICs, materials that have a high refractive index or one which have a tunable refractive index are used for large-scale integration. In high index contrast waveguides, the mode remains confined to the core leading to a small bending radius. For this purpose, SiOC dielectric material is designed in this research paper. It is a novel material made up of ceramic glass that contains silicon, oxygen, and carbon atoms between silica and silica carbide with different ratios [7]. It has optical characteristics and has found major applications in different fields of technologies to become an enabling material in the field of photonic integrated circuits. These application includes lithium-ion batteries [8], light emitters [9], filters [10], interlayer dielectrics [11], and [12], photoluminescence [13], Plasmonics [14] and others [15], and [16]. The most enabling characteristic of SiOC is that it has a widely tunable refractive index that ranges from 1.45 to 3.2 [17], and [18]. The refractive index is defined as how fast light is travelling through a medium. The advantage of its tunable refractive index is that we can design integrated circuits according to the application requirements. If we want large-scale integration for photonic devices, we will acquire a higher refractive index by using the same material that is SiOC. It can be integrated into a photonic platform and have low loss at telecom wavelengths. Chemical vapor deposition [19], and sol-gel pyrolysis methods are generally used for deposition of SiOC material [20] but recent studies suggested Radio Frequency Sputtering or RF Sputtering process for deposition of SiOC waveguides that contain low losses [21]. In recent research work, SiOC is presented as potential dielectric material in which optical and structural properties of SiOC thin films deposited by reactive RF-Magnetron Sputtering are investigated at 1550 nm.

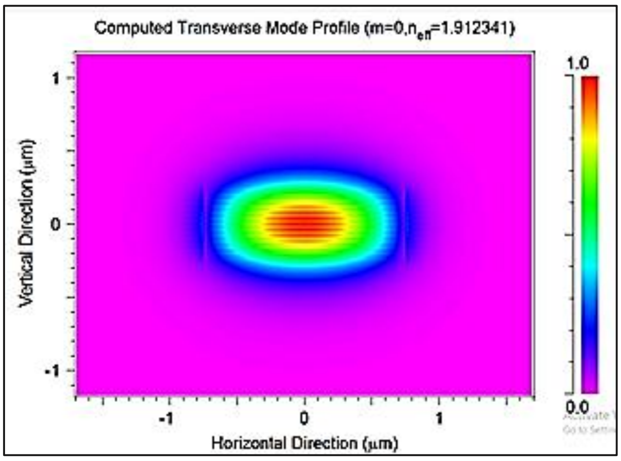
The chemical and structural properties of SiOC are described in the literature [22-24]. Therefore, in this research paper, SiOC material is used to design channel waveguides and a passive device such as a directional coupler. It is used to measure the power that is transferred between two waveguides. The coupled power of waveguides can be controlled by adjusting the coupler length or by varying the gap between waveguides [25].

In this paper, we have reported the simulation results of SiOC channel waveguides designed at O-Band, i.e. 1310 nm window [26]. The waveguides are designed at different parameters to know the effect of varying parameters on waveguide design.

The paper is divided into three sections. After giving a brief introduction, the section contains the methodology for designing the channel waveguides and directional coupler. Later, the simulation results discussed that were obtained by implementing the methodology. In the end, the last section is of conclusion that defines the approach to fabricating waveguides at O-Band.

II. SIMULATION DETAILS

The 'RSoft Beamprop' simulation tool is used to design channel waveguides at different geometry parameters. It is a 'CAD' tool that is commercially available and is used for designing photonic integrated circuits that give a fast and accurate design of waveguides. This paper is used for the design of SiOC channel waveguides and a photonic device called a directional coupler. The core of the waveguide is SiOC, having a refractive index = 2.2 µm, and the clad of the waveguide is silica having a refractive index = 1.444 µm. The single mode of channel waveguide is achieved by setting the parameters at different values of width and height and keeping the other parameters constant such as wavelength and refractive index of core and cladding. After that, the effective index of traveling mode is analyzed. The computed Transverse Electric (TE) and Transverse Magnetic (TM) fundamental mode is achieved at width = 1.5 µm and height = 0.5 µm. The effective refractive index (neff) of TE mode is 1.912341 and that of TM mode is 1.709711 as shown in figure I(a) and figure I(b). In TE mode the electric field is orthogonal to the direction of propagation while in TM mode, the magnetic field is orthogonal to the propagation direction. Further TE mode is confined horizontally within the waveguide which means increasing the width of a waveguide can result in a better confinement factor. On the other hand, TM mode is vertically oriented and confinement can be improved by increasing the height of the waveguide.



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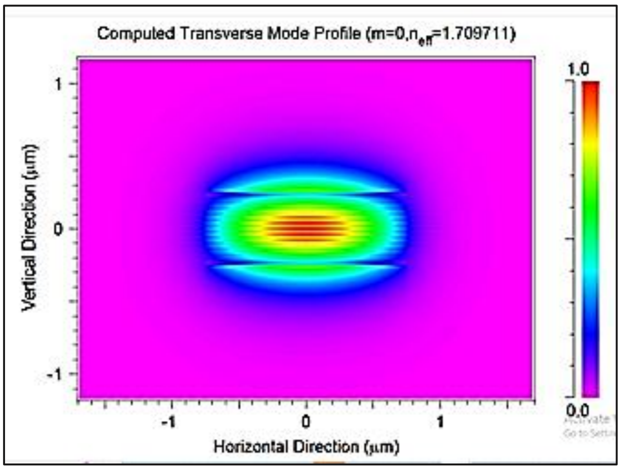


(b)

Figure I: (a) Mode Profile Image of TE Fundamental Mode; (b) Mode Profile Image of TM Fundamental Mode

A. Coupling Efficiency (C.E) and Confinement Factor (C.F)

Coupling Efficiency (C.E), is defined as the power transfer between the two optical components. It is obtained by setting up the monitor value of fiber mode power by using the 'Beamprop' simulation tool. Here, one optical component is an optical waveguide and another one is lensed optical fiber. The diameter of the small core fiber is about 6 micrometers but if we use lensed optical fiber its diameter will depend upon the distance between the optical lensed fiber tip and the chip of the waveguide. The Mode Field Diameter (MFD) of lensed optical fiber is selected from 1 to 5 microns to know the effect of coupling efficiency at different waveguide parameters. By knowing the Coupling Efficiency (C.E), we can get the Coupling Loss (C.L) of the waveguide by mathematical eq. (1):

$$\mathrm{C.L} = -10 \times \log 10 \times \mathrm{C.E} \quad (1)$$

The confinement factor of the silicon oxy-carbide waveguide is achieved by setting the monitor value at different widths and heights using the Beamprop simulator. It is defined as how well the mode is confined in the core region of the waveguide as shown in figure II. If the thickness of the core is larger, the electromagnetic signal will be confined to the core. If core thickness decreases, the electromagnetic signal will radiate out from the core. Hence, there will be a low confinement factor. Here, the electromagnetic signal wavelength is 1.31 microns, and the thickness of the core is determined by different geometry parameters of the waveguide.

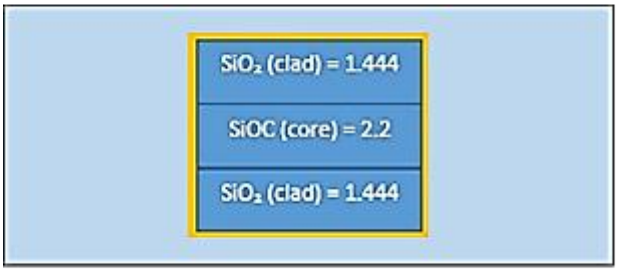


Figure II: Geometry of SiOC Waveguide

B. *Directional Coupler*

A directional coupler is a four-port passive device that couples the power between two waveguides. A coupler can be designed based on coupler length to achieve a coupling ratio of 20:80:50:50, 60:40, and so on [27], and [28]. It can be used as a multiplexer or switch [29], and [30]. Figure III explains the working of the directional coupler.

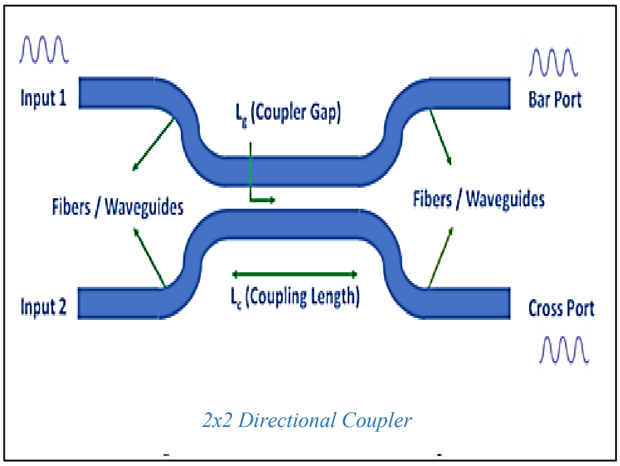


Figure III: 2x2 Directional Coupler

In this paper, SiOC material is used as a core of waveguides of the directional coupler with a refractive index of core = 2.2, and silicon dioxide is used as the upper and lower clad of the waveguide with a refractive index of clad = 1.444.

A directional coupler has two input and output ports as shown in figure III. It consists of two waveguides. The central parallel length of waveguides is denoted by ‘Lc’ and is called Coupling Length. The separation between two waveguides is denoted by ‘Lg’ and is called Coupler Gap. The coupler width is denoted by ‘W’ and height is denoted by ‘h’. The input and output sides have a significantly bigger distance between them so that the modes passing through the waveguides do not collide and the coupling can readily break. To simulate and extract the values of effective refractive index (neff) of the modes propagating in the middle section of a DC, RSoft Beamprop was used. Single mode operation is obtained by varying the values of height and width of waveguides as multiple modes have more complexity. The parameters that are used to design a directional coupler are the refractive index of core and cladding, width, height, dimension of the waveguide, and others. The width of the waveguide is taken as 1.5 microns and the height is 0.5 microns. The refractive index of core and cladding is given above, having an index difference of 0.756 microns which is the index difference of core and clad. The index contrast is obtained by using eq. (1):

$$\Delta n = \frac{n^2 core - n^2 clad}{2n^2 core} \quad (2)$$

In a directional coupler, the coupled power is based on coupling mode theory in the section of middle straight waveguides. Mode coupling effect in DC is analyzed by knowing the interference pattern between even and odd modes. The coupling power of the central waveguide can be calculated by:

$$P = k \times Lc \quad (3)$$

Here;
k is the field coefficient and Lc is coupler length.

Even neff and odd neff are used to calculate the value of propagation constant β. It can be calculated by using eq. (1):

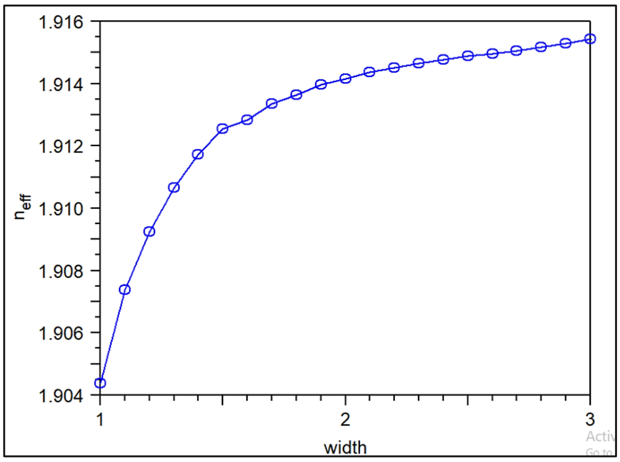
$$\beta = 2\pi\lambda\,(neff) \quad (4)$$

Here;
λ is a free-space wavelength that is 1310 nm.

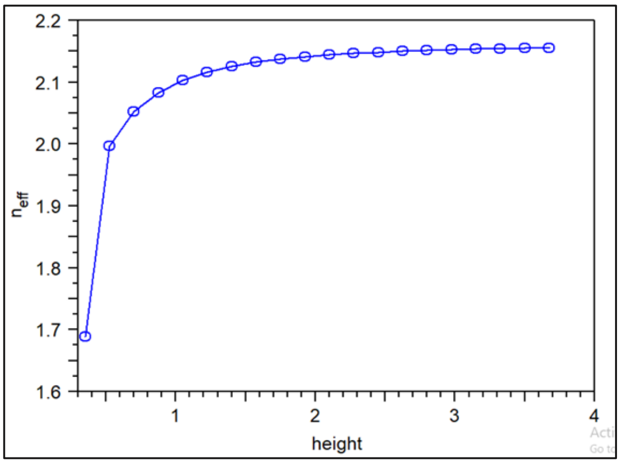
III. RESULTS

Single mode operation for TE and TM polarization of SiOC channel waveguide is obtained at width 1.5 microns and height 0.5 microns as no higher order modes are obtained at these parameters. The graph of neff against width, height, and free-space wavelength is drawn to show the dependency of neff on waveguide design. In figure IV(a), the graph of width shows that if we increase the width of the waveguide, the value of fundamental mode is also increasing by keeping the height and free-space wavelength constant. The starting value of width is 1 micron and the ending value is 3 microns as we can see in graph neff of the fundamental mode is increasing with an increment of 0.1 microns. In figure IV(b), width and free-space wavelength remain constant to show the dependency of neff on height parameters. The starting value of height is 0 microns and the ending value is 4 microns, with the increment of 0.1 microns neff of the fundamental mode is increasing. In figure IV(c), the graph of wavelength shows that if we are increasing the wavelength, the value of the fundamental mode is decreasing. It shows that neff of mode is inversely proportional to free-space wavelength. The starting value of free-space wavelength is 1.25 microns and the ending value is 1.31 microns, i.e., range of shorter wavelength band. Here, width and height remain constant, i.e., 1.5 microns and 0.5 microns respectively.

The coupling efficiency of optical waveguides with lensed optical fiber is determined at different geometry parameters of channel waveguides as shown in table I. If we want to get a good confinement factor of SiOC channel waveguides, then the MFD of lensed optical fiber should be around 1 micron because if the diameter of the tip of lensed optical fiber will be smaller mode will be confined into the core easily. It shows that if the Mode Field Diameter (MFD) of lensed optical fiber is 1 micron, the coupling efficiency will be 90 %. Coupling loss is determined by using the coupling loss formula that gives the coupling loss of 0.1 at waveguide width = 0.5 microns and height = 0.5 microns. If we are increasing the MFD, coupling efficiency will decrease.



(a)



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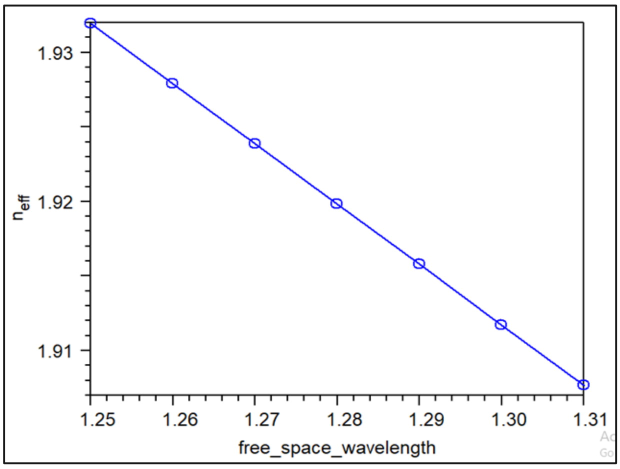

(c)

Figure IV: (a) Graph of neff against Width; (b) Graph of neff against Height; (c) Graph of neff Free-space Wavelength

Hence, there will be more coupling loss as shown in table I. By increasing the waveguide height from 0.5 to 0.75 microns, the coupling efficiency is increasing and coupling loss is decreasing.

Table I: Coupling Efficiency and Coupling Loss of SiOC Waveguide

Width = 1.5 µm Height = 0.5 µm			**Width = 1.5 µm Height = 0.75 µm**			**Width = 1 µm Height = 0.5 µm**		
MFD	C.E (%)	C.L (dB)	MFD	C.E (%)	C.L (dB)	MFD	C.E (%)	C.L (dB)
1	90	0.1	1	91	0.09	1	89	0.11
2	57	0.43	2	64	0.36	2	45	0.55
3	32	0.68	3	41	0.59	3	23	0.77
4	20	0.8	4	29	0.71	4	15	0.85
5	15	0.85	5	23	0.77	5	11	0.89

After getting the coupling efficiency and coupling loss, the confinement factor is calculated by setting the above waveguide parameters. The confinement factor defines how well the electromagnetic field is confined to the core as it is discussed earlier. It is calculated by setting the monitor value of WG power in the Beamprop simulation tool. Table II shows that if we are increasing the waveguide parameters such as width and height, the confinement factor also increases.

Table II: Confinement Factor of SiOC Waveguide

Width and Height of Waveguide	**Confinement Factor (%)**
Width = 1.5 µm Height = 0.3 µm	69
Width = 1.5 µm Height = 0.5 µm	89
Width = 1.5µm Height = 0.75µm	95
Width = 1µm Height = 0.5µm	88
Width = 2µm Height = 0.5 µm	90

The minimum bending radius of the waveguide is determined by using a mathematical formula that is [31]:

$$\text{Rmin} = 5\,\Delta\,n^{-1.5} \qquad (5)$$

The minimum bending radius of SiOC channel waveguide at 1310 nm is found to be 30 microns achieved at width = 1.5 microns and height = 0.5 microns as shown in figure V. It shows that SiOC is a potential material platform for large integration of devices.

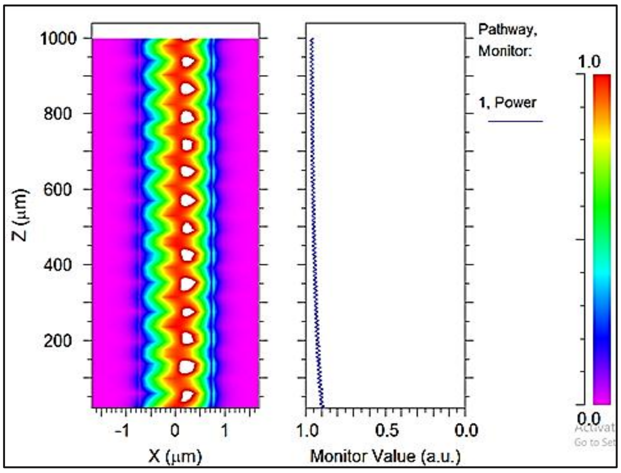

Figure V: Minimum Bending Radius of SiOC Channel Waveguide at Width 1.5 microns and Height 0.5 microns

By getting the minimum bending radius of the waveguide, a 2x2 Directional coupler is designed. It shows the power transfer between two waveguides. To calculate the power, a few calculations are done by using the formula of power shown in eq. (3). As mentioned earlier, k is the field coefficient and Lc is the coupler length.
The neff of even and odd TE modes are obtained at Lgap 0.6, 0.7, 0.8, and 1 micron as shown in table III to achieve 3 dB coupling.

Table III: neff Values of Even and Odd Modes

Coupler Gap (Lgap)	neff of Even Modes	neff of Odd Modes
0.6	1.905566	1.913965
0.7	1.9808594	1.913954
0.8	1.910138	1.913689
1	1.911497	1.913013

In figure VI, Lgap is 0.6, 0.7, and 0.8 microns, and the coupler length is 1000 microns. It shows that if we increase the gap between waveguides, the length of the coupler is also increasing. The 3 dB coupling is achieved at 20, 40, and 100 microns as shown in the graph. Similar results were obtained when the gap between waveguides are changed to 0.9 to 1.3 microns.

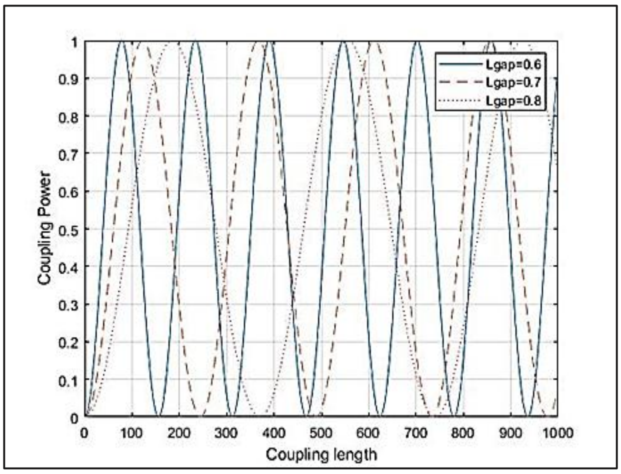

Figure VI: MATLAB plot showing Coupling Power Vs Coupling Length [µm]

IV. CONCLUSION

SiOC is presented as a versatile material platform for the integration of photonic devices. It is demonstrated for the first time for a shorter wavelength band for future photonic applications. SiOC waveguides with different geometry parameters have been simulated in the Beamprop simulation tool for single-mode operation at a shorter wavelength band i.e. 1310 nm. The typical waveguide parameters are found to be width = 1.5 µm and height = 0.5 µm for both TE and TM modes. A further integrated photonic device such as Directional Coupler has been simulated with Lgap = 0.6, 0.7, and 0.8 providing a coupling length of 20, 40, and 100 microns. These all results are helpful for fabricating waveguides at a shorter wavelength band i.e. 1310 nm wavelength window for photonic applications. This research work aims to provide a simulation of SiOC waveguides for a shorter band (1.3 um) and the obtained results can be used for the fabrication of the devices in a clean room environment. From the simulated dimensions of the SiOC waveguide, the authors recommend the use of direct laser lithography and reactive ion etching technology to fabricate the waveguides.

Acknowledgment

Yusra acknowledges the support given by the Telecommunication department and IICT directorate at Mehran University of Engineering and Technology, Jamshoro.

Authors Contributions

The contribution of the authors was as follows: Yusra Daudpota’s contribution to this study was the concept, technical implementation, paper writing, and correspondence. The methodology to conduct this research work along with data validation was proposed by Aftab Ahmed Memon and Faisal Ahmed Memon. Bhawani Shankar Chowdhry’s contribution was project administration.

Conflict of Interest

The authors declare no conflict of interest and confirm that this work is original and not plagiarized from any other source, i.e., electronic or print media. The information obtained from all of the sources is properly recognized and cited below.

Data Availability Statement

The testing data is available in this paper.

Funding

This research received no external funding.

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