Faculty of Engineering

SILICON-ON-INSULATOR (SOI) LARGE CROSS-SECTION RIB WAVEGUIDE (LCRW) FOR FIBER-TO-THE-HOME COUPLER DEVICES

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AIDA KHAIRINA BINTI ABDUL RAHMAN

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ABSTRACT

One of the solutions to cater to increasing internet demands is to employ Fiber-to-the-Home (FTTH) access network that mainly uses Gigabit Passive Optical Network (GPON) structure. One of the optical devices used for this network is a 3dB directional coupler using Silicon-on-Insulator (SOI) Large Cross-section Rib Waveguide (LCRW). According to previous research, coupler that uses SOI LCRW can operate in single-mode propagation, has low cost, and it can offer minimal loss. This is ideal for FTTH access network standards. In this thesis, by using the optimum symmetrical and asymmetrical LCRW, the parallel LCRW and S-Bend LCRW were designed and combined to form a 3dB directional coupler. The downstream wavelengths used in the simulation were 1480 nm and 1550 nm which is FTTH compliant. The Soref's formula were used to design LCRW to ensure single-mode propagation for the coupler. Modal field analysis through the beam propagation method (BPM) were used in the simulation by using OptiBPM 9.0 software. The LCRW with highest refractive index (w = 7 µm, H = 7 µm, d = 0.5 µm) were chosen to model the directional coupler. From the results, it was found that the symmetrical SOI LCRW for 3dB directional coupler with total length of 12741 µm with offset spacing of 0.55 µm produced the best results of the normalised output power (NOP) of ~30% at both outputs for both downstream wavelengths. The coupling ratio at output SB3 was 50.66% for 1480 nm signal and 48.98% for 1550 nm signal.

ABSTRAK

Salah satu penyelesaian untuk memenuhi permintaan internet yang semakin meningkat adalah dengan menggunakan rangkaian capaian *Fiber-to-the-Home (FTTH)* yang kebanyakannya menggunakan struktur Rangkaian Optik Pasif Gigabit (*GPON*). Salah satu peranti optik yang digunakan untuk rangkaian ini ialah pengganding arah 3dB yang menggunakan *Silicon-on-Insulator (SOI) Large Cross-Section Rib Waveguide (LCRW*). Menurut penyelidikan terdahulu, pengganding yang menggunakan *SOI LCRW* boleh beroperasi dalam perambatan mod tunggal, mempunyai kos yang rendah, dan ia boleh menawarkan kerugian yang minimum. Pandu gelombang ini sesuai untuk digunakan dalam rangkaian akses *FTTH*. Dalam tesis ini, dengan menggunakan geometri simetri dan asimetri *LCRW* yang optimum, pandu gelombang selari dan pandu gelombang *S-Bend* telah direka dan digabungkan untuk membentuk pengganding arah 3dB. Panjang gelombang hiliran yang digunakan dalam simulasi ialah 1480 nm dan 1550 nm yang mematuhi *FTTH*. Formula Soref digunakan untuk mereka bentuk *LCRW* bagi memastikan perambatan mod tunggal untuk pengganding. Analisis medan modal melalui kaedah perambatan rasuk (*BPM*) digunakan dalam simulasi dengan menggunakan perisian OptiBPM 9.0. *LCRW* dengan indeks biasan tertinggi (w = 7 µm, H = 7 µm, d = 0.5 µm) telah dipilih untuk memodelkan pengganding arah. Daripada hasil simulasi, didapati bahawa *LCRW SOI* simetri untuk pengganding arah 3dB dengan jumlah panjang 12741 µm dengan jarak mengimbangi 0.55 µm menghasilkan keputusan terbaik kuasa keluaran ternormal (*NOP*) sebanyak ~30% pada kedua-dua output untuk kedua-dua panjang gelombang hiliran. Nisbah gandingan pada output SB3 ialah 50.66% untuk isyarat 1480 nm dan 48.98% untuk isyarat 1550 nm.

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LIST OF ABBREVIATIONS

BPM	:	Beam Propagation Method
3D-FDTD	:	Three-dimensional Finite-Difference Time Domain
COVID-19	:	Coronavirus
FDH	:	Fiber Distribution Hub
FTTH	:	Fiber-to-the-home
FTTX	:	Fiber-to-the-X
GaAs	:	Gallium Arsenide
GPON	:	Gigabit Passive Optical Network
HOM	:	Higher Order Mode
ISP	:	Internet Service Provider
LCRW	:	Large Cross-section Rib Waveguide
LED	:	Light-emitting diode
$LiNbO_3$	:	Lithium Niobate
MMF	:	Multimode Fiber
NFCP	:	The National Fiberisation and Connectivity Plan
NOP	:	Normalized Output Power
OLT	:	Optical Line Terminal
ONT	:	Optical Network Terminal
ONU	:	Optical Network Unit
PIC	:	Photonics Integrated Circuit
PLC	:	Planar Lightwave Circuit
PON	:	Passive Optical Network
RF	:	Radio wave

SiO_2	:	Silicon dioxide
SMF	:	Single Mode Fiber
SOI	:	Silicon-On-Insulator
TE	:	Transverse Electric
TM	:	Transverse Magnetic
WDM	:	Wavelength Division Multiplexing

LIST OF SYMBOLS

λ	:	Wavelength
d	:	Etch depth of rib waveguide
D	:	Lateral offset of s-bend waveguide
H	:	Height of centre rib
h	:	Height of slab region
L	:	Transition length of s-bend waveguide
L_C	:	Coupling length of parallel waveguide
P_1	:	Power at Port 1
P_3	:	Power at Port 3
P_4	:	Power at Port 4
P1	:	Parallel waveguide 1
P2	:	Parallel waveguide 2
r	:	Ratio of height of slab region to the height of centre rib
s	:	Spacing gap between cores of parallel waveguide
S1	:	Structure 1 with H = w = 5 um
S2	:	Structure 1 with H = w = 6 um
S3	:	Structure 1 with H = w = 7 um
SB1	:	S-Bend waveguide 1
SB2	:	S-Bend waveguide 2
SB3	:	S-Bend waveguide 3
SB4	:	S-Bend waveguide 4
w	:	Width of rib centre waveguide

CHAPTER 1

INTRODUCTION

1.1 Background

Information transmission continues to be developed at a fast pace due to the high demand for communication between devices or users to be faster. Internet access which used to be a luxury has become a necessity as declared by United Nations in 2016 [1] that internet access is a human right. This has become more obvious when Coronavirus (COVID-19) diseases were discovered and most were forced to stay at home, a lot of activities started to rely a lot on network connections. After COVID-19 was declared as a pandemic, people started to adapt to the new normal where students must undergo online classes, workers must work from home, and government must disperse information efficiently regarding government aid and COVID-19's developments via television, radio, and social media. This goes to show that most of us are starting to rely heavily on network connections to gain the latest information. Online gaming is another example of how faster and more reliable network connections are in demand as online gaming becomes a growing industry, especially during the pandemic [2]. As a result of increasing demand, internet service providers (ISPs) continue to pursue affordable broadband that offers both higher bandwidth and faster data throughput which is solvable by deploying optical networks like Passive Optical Networks (PON). Another driver that led to an increase in demand for optical networks in Malaysia is the government's initiative to improve broadband quality and coverage and provide accessible and affordable internet connection through the implementation of a five-year plan named The National Fiberisation and Connectivity Plan (NFCP) [3].

One of the ways to meet this need is by establishing an optical fiber connection to be closer to the consumer. This can be done by implementing a fiber-to-the-home (FTTH) network whereby this architecture allows connections of fiber links from the central office to the end user's home. There is multiple optical fiber network architecture such as Point-to-Point (P2P), Active Optical Network (AON), and Passive Optical Network (PON).

However, the most suitable network architecture for FTTH is PON mainly because it addresses the cost issues presented in P2P and AON architectures, and it is also simpler compared to the other two [4]. PON architecture mainly consists of three parts which are Optical Line Terminal (OLT), a Fiber Distribution Hub (FDH) which houses optical splitters, and an Optical Network Terminal (ONT) as shown in Figure 1.1.

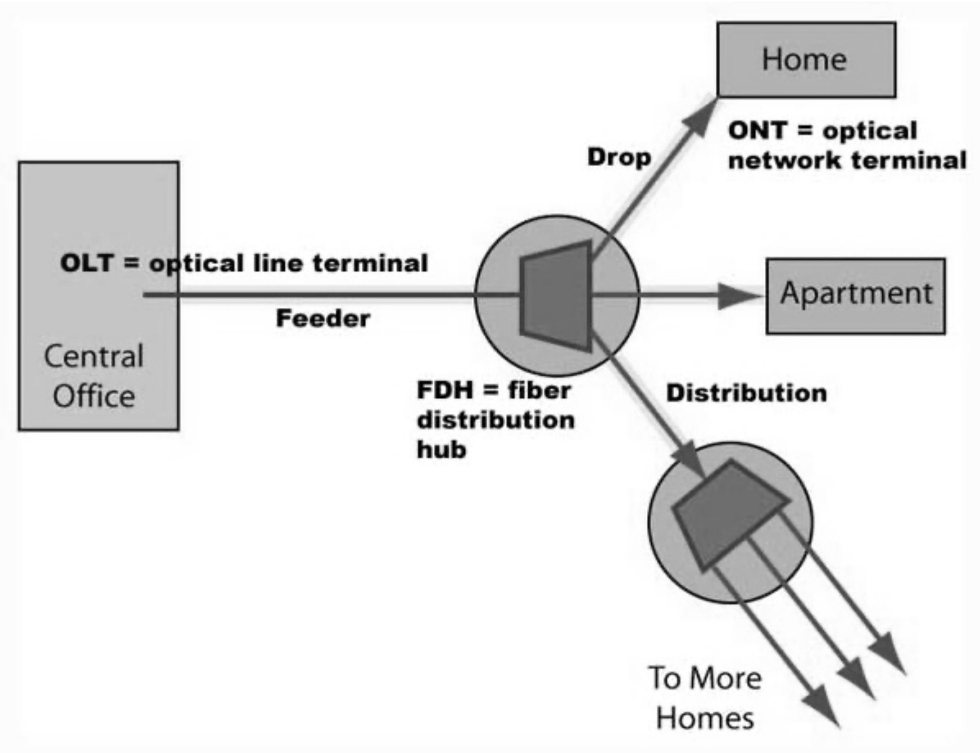

Figure 1.1: Passive Optical Network (PON) Architecture [5]

Nowadays, there is various research being conducted to integrate optical components onto silicon substrates. This field of research is known as silicon photonics and in this field, the study of the optical properties of silicon and the design and construction of devices for optical components are explored. One of the ongoing studies in silicon photonics is the Silicon-On-Insulator (SOI) platform which is usually used in integrated optical circuits also known as Photonics Integrated Circuit (PIC). For this technology, coupling light efficiently is critically important to ensure low losses. However, it is difficult to achieve high coupling efficiency due to the volume mismatch between silicon waveguide and optical fiber [6].

1.2 Problem Statement

Nowadays, a faster and more secure network operation is in demand by the general masses. Corporations also seek a network system that has larger capacity communication systems. One of the solutions for this demand is to deploy Fiber-to-the-X (FTTX) architecture. In this project, FTTH architecture is the focus where the optical fiber is connected all the way to the home. As more demands for network communication to offer affordable options that provide higher bandwidth and faster data throughput, a lot of new technology are invented day by day. The same can be said for coupler devices as researchers are eager to develop a coupler device that offers higher coupling efficiency. As mentioned in the previous section, the coupling efficiency is very important to ensure less loss. The different geometry between optical fiber and waveguide poses a challenge in ensuring that the coupling efficiency is high. The loss budget for all optical components in the implementation of ITU-T G.984 standards are also considered as strict as the standard for Class B+ is at a total of 13 dB at a minimum and 28 dB at maximum for both wavelengths operating at region 1310 nm and 1490 nm [7]. This means that the loss budget is strict when deploying FTTH network. So, it is very important to ensure that the optical components designed operate at minimal loss. Hence, one of the focuses of this project is to ensure that the coupler devices that will be designed operate with minimal loss.

For a 20 km FTTH network, single-mode propagation is preferred due to its nature of having less attenuation at longer distances. Hence, the standards set up by International Telecommunication Union (ITU) for ITU-T G.984 which is normally used in FTTH is in single-mode propagation [7]. Thus, to design an optical coupler for FTTH, the coupler must use be in single-mode propagation. To ensure the coupler propagates in a single mode, a detailed study of the geometry of the waveguides used is done. This is because the geometry of waveguides will affect the mode that will pass through them. In this project, the rib waveguide is the focus. So, the design of the waveguide's geometry must follow certain conditions to ensure that it propagates in a single mode. One of the solutions for this is to use Soref's formula [8] to design a large cross-section rib waveguide (LCRW) operating in single mode.

Lastly, the issue with optical devices is that most were developed using rare materials such as Lithium Niobate ($LiNbO_3$) and Semiconductor III-V Materials such as Gallium

Arsenide (GaAs) are expensive. The usage of rare materials drives up the cost of fabrication of optical devices hence increasing the cost of deploying optical networks. Hence, one of the solutions is to use cheaper materials such as Silicon. As mentioned in an article written by Abate in 2015 [9], the cost to make a wafer of GaAs can cost about $5000 USD, as compared to a silicon wafer that cost $5 USD. Thus, utilising Silicon-on-Insulators (SOI) technology has become one of the solutions to reduce the cost of the fabrication of optical devices. Hence, the coupler devices that will be designed in this project are based on SOI technology.

1.3 Objectives

This project mainly focuses on designing a coupler device for the FTTH network by using SOI LCRW. The objectives of this project are as follows.

- To investigate the effect of using different geometries of SOI LCRW
- To determine the optimum structure parameters for SOI LCRW as a coupler device.
- To design an FTTH coupler by using SOI LCRW.

1.4 Summary

In these thesis, there are five chapters which are Chapter 1: Introduction, Chapter 2: Literature Review, Chapter 3: Methodology, Chapter 4: Results and Discussion, and Chapter 5: Conclusion.

Chapter 1 focuses more on the background of this whole thesis which includes a brief description of the FTTH network and coupler device. Chapter 1 also includes problem statements and objectives.

In Chapter 2, further explanations regarding the thesis were done by reviewing previous studies and exploring theories related to FTTH networks, silicon photonics, and SOI LCRW. From these literature resources, all important parameters in designing the coupler devices were outlined.

Chapter 3 described the procedures taken to execute the project. The process of designing coupler devices by combining both parallel LCRW and S-bend LCRW were done by using OptiBPM 9.0 software tool such as Mode Solver, Waveguide Designer, and 3D Simulations.

Once the simulation was done, the results were obtained, tabulated and relevant graphs were plotted which was include Chapter 4. Analysis for the optimum parameters for symmetrical and asymmetrical LCRW were done, and the results were discussed further. The normalised output power (NOP) was compared to the expected results.

The final findings were concluded in Chapter 5. Limitations of this thesis and recommendations for further research were also discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

To design a coupler device with SOI LCRW that can be deployed in FTTH applications and uses a single-mode propagation, thorough research into the topic must be done to outline any limitations and expectations of this project. Through these literature reviews, the advantages and disadvantages of each element comprised in the coupler design were determined. The designs and methodologies proposed by previous studies were also included in this chapter to aid in the design of couplers in this thesis.

2.2 Optical Fiber Communication

The concept of an optical fiber communication system is similar to the basic concept of any type of communication system. A basic communication system consists of an information source, transmitter, transmission medium, receiver and destination point as shown in Figure 2.1. The transmitter and receiver are also known as modulators and demodulators respectively. The information source is non-electrical messages that have been converted into electrical signals. These signals are then converted into a format that can be transmitted through the transmission medium. Usually, this is achieved by modulating a carrier. The transmission medium carries the signals to be sent to the receiver. This can be done by using a pair of wires, a cable or through the air. Once the receiver receives the signals, the signals were then transformed back into their original electrical information or in other words, they will go through demodulation before being sent to their destination point. The optical fiber communication system can be considered in detail by referring to Figure 2.2 which showed the main components of an optical fiber communications link. The block diagram in Figure 2.1 is the reference for the optical fiber system in Figure 2.2.