Integrated Photonic Ring Resonator for Application in Optoelectronic Oscillator

MTech Thesis

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Integrated Photonic Ring Resonator for Application in Optoelectronic Oscillator

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of

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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Integrated Photonic Ring Resonator for Application in Optoelectronic Oscillator** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period from June 2023 to June 2024 under the supervision of Prof. Mukesh Kumar, Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

28/5/2024

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

28/05/24

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Abstract

As most of the improvements in silicon photonics, high quality factor Micro Ring Resonators are widely used in the integrated microwave photonic systems. Silicon photonics is advanced technology for the photonic integrated circuits (PIC) which has many applications in various fields. Now silicon-on-insulator (SOI) is mostly used platform for silicon photonics because of various optical and material characteristics of crystalline silicon. Silicon di Oxide(SiO_2) is used as the integration platform to realize the OEO. Optoelectronic Oscillators are designed to produce high quality spectrally pure RF signal and mm wave signals by introducing a high-quality factor Ring Resonator of 3120 after the Optical Modulator which is realized as a bandpass microwave photonic filter with a 3 dB bandwidth of 100MHz. The optoelectronic oscillator(OEO) can be tunable because it is based on microwave photonic filter which is tunable. While the frequency tuning of OEO the measured side mode suppression ratio(SMSR) is 45dB. The calculated stop band rejection ratio(SRR) is 30dB. The optoelectronic oscillators are used in satellite communication links, wideband tunable frequency generation, aerospace engineering, navigation systems and wireless communication.

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NOMENCLATURE

ϵ	Dielectric Constant
Λ	Wavelength
Ω	Angular Frequency
M	Permeability Constant
Ħ	Reduced Planck's Constant
B	Propagation Constant
Φ	Phase Shift
E_F	Fermi Energy Level
K_o	Free Space Wave Number
ω_p	Plasma Frequency
E	Charge of the Electron
N_e	Electron Density
m_e	Effective mass of Electron
n_{eff}	Effective Refractive Index
L	Propagation Length
A	Transmission Coefficient
Q	Quality Factor
E	Electric Field Intensity
D	Density of States

ACRONYMS

OEO	Optoelectronic Oscillator
PIC	Photonic Integrated Circuit
SMSR	Side Mode Suppression Ratio
WGM	Whispering Gallery Mode Resonator
MDR	Micro Disk Resonator
RTD-PD LD	Resonant Tunneling Diode Photodetector Laser Diode
Q Factor	Quality Factor
FWHM	Full Width Half Maximum
SRR	Stopband Rejection Ratio
FSR	Free Spectral Range
MZI	Mach– Zehnder interferometer
MRR	Micro Ring Resonator
EA	Electrical Amplifier
EDFA	Erbium Doped Fiber Amplifier
MPF	Microwave Photonic Filter

Chapter 1

INTRODUCTION

1.1 Integrated Photonics

Integrated Photonics is the young and advanced technology that combines the principles of optics and electronics. This technology transmit, manipulates and detect light signals. Integrated photonics miniaturizes various components on to a single platform by offering high efficiency, scalability and functionality[1]. By confining light within nanoscale waveguide, using advanced materials and fabrication techniques, integrated photonics enables wide range of applications in telecommunication, sensing, computing and healthcare. This emerging technology overcomes the limitations of electronic industries such as limited bandwidth and high-power consumption. Integrated photonics has already demonstrated its potential in enabling high speed data transmission, ultra sensing capabilities, and compact optical computing. Integrated photonics also known as photonic integrated circuits (PICs)[2]. Integrated photonics accommodates optical components such as lasers, modulators, detectors and waveguides on to a single substrate, made of materials like silicon, silicon nitride or III – V semiconductors. This integration offers various advantages over traditional optics like reduced size, weight, power consumption and cost and simultaneously enhance the parameters such as speed, bandwidth and reliability. The technology in integrated photonics is the concept of optical waveguides. These waveguide structures guide the light and control in a predetermined path. Integrated photonics is also emerging field in quantum computing and quantum communication. Figure 1.1 shows a Photonic Integrated Circuit (PIC) depicting the integration of photonic devices on a single chip with electronics. The elements of PICs are connected via waveguides which confine and direct light. The chip elements can be both passive (for e.g., couplers, filters, and multiplexers) and active (for e.g., modulators, switches, amplifiers, and detectors). These components are integrated and fabricated onto a single substrate, which creates a compact and robust photonic device. This integration dramatically improves the performance and reliability of photonic functions while simultaneously reducing the size, weight, and power consumption[3]. Photonic devices find applications in energy-efficient lighting, high performance computing, environmental monitoring, chemical, and biological sensing and many more.

1.2 Silicon Photonics

Silicon photonics is a cutting-edge technology that combines the areas of photonics and electronics. Essentially, it involves using silicon as a medium to manipulate light for various purposes, including data transmission and processing.

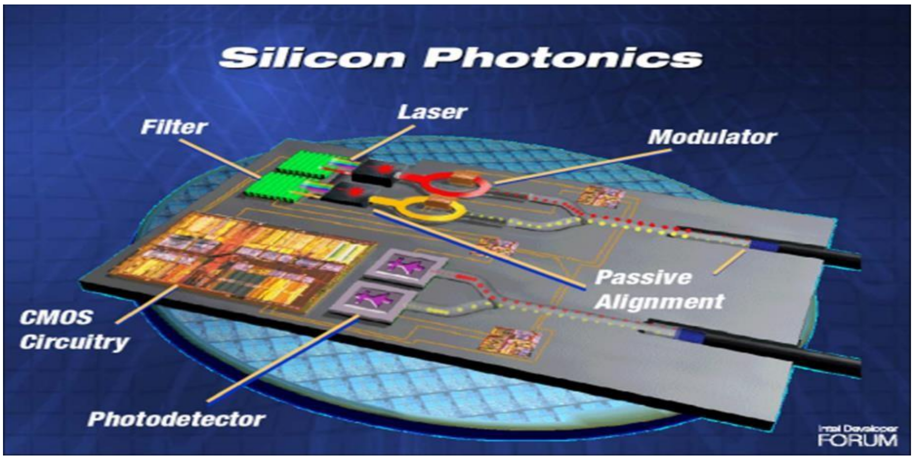


Figure 1. 1 A Si photonic integrated circuit depicting the integration of photonic components with CMOS circuitry[28]

Photonics deals with the study and manipulation of photons, which are particles of light. In traditional electronics, information is carried and processed using electrons. In photonics, however, light is used instead. Light can carry information incredibly quickly and over long distances with minimal loss, making it ideal for high-speed communication. Silicon, a material commonly used in electronics, turns out to be highly compatible with photonics as well. This is because silicon has properties that allow it to manipulate light effectively. By fabricating intricate structures on a silicon substrate, such as waveguides and modulators, researchers can control the propagation and characteristics of light. One of the key advantages of silicon photonics is its compatibility with existing silicon-based electronics manufacturing processes. This means that photonic components can be fabricated alongside electronic ones on the same silicon chip, enabling seamless integration of photonics and electronics on a single platform. This integration is crucial for developing advanced technologies such as high-speed data communication, optical interconnects, and even quantum computing. Silicon photonics has a wide range of applications across various industries. In telecommunications, it enables faster and more efficient data transmission over optical fibers, leading to higher bandwidth and lower latency networks. In data centers, silicon photonics can be used for interconnecting servers and switches, improving the overall performance and energy efficiency of the infrastructure. It also holds promise for emerging fields such as biomedical sensing, environmental monitoring, and quantum information processing. Overall, silicon photonics represents a significant advancement in both the fields of photonics and electronics, offering new opportunities for high-performance computing, communication, and sensing applications. Its integration with existing silicon-based technologies makes it a particularly promising platform for driving innovation in the digital age[4]. The applications of silicon photonics span across various sectors. In telecommunications, it facilitates the transmission of data at blazing speeds over optical fibers, driving the evolution of 5G networks and beyond. Data centers leverage silicon photonics for intra and interconnectivity, enabling efficient communication between servers and reducing latency.

1.3 Optoelectronic Oscillator (OEO)

An optoelectronic oscillator (OEO) is a sophisticated device that combines the principles of optics and electronics to generate stable microwave or radio-frequency signals. Unlike traditional electronic oscillators, which rely solely on electronic components like capacitors and inductors, an OEO employs optical feedback to sustain oscillations. This unique hybrid architecture offers several advantages, including high-frequency stability, low phase noise, and immunity to electromagnetic interference. At its core, an OEO consists of an optical loop containing a modulator, an optical delay line, and a photodetector. The modulator impresses an electrical signal onto an optical carrier, which is then circulated within the loop. The optical delay line ensures that the signal travels a specific distance before being converted back to an electrical signal by the photodetector. This feedback loop introduces a delay, which is crucial for sustaining oscillations. By controlling the parameters of the optical loop, such as the length of the delay line and the modulation frequency, an OEO can generate stable microwave or RF signals with spectral purity and frequency stability.

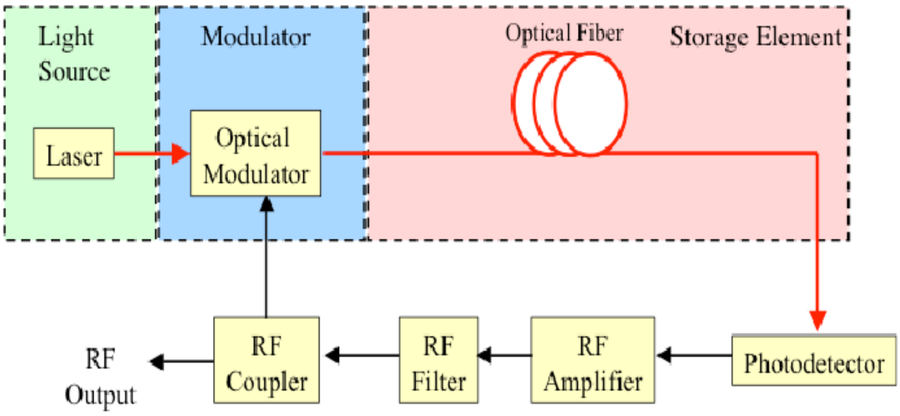


Figure 1. 2 Conventional optoelectronic oscillator[5]

1.3.1 Optical Modulator

An optical modulator is a component in modern telecommunication systems and optical signal processing. It's used to modulate or manipulate the characteristics of light waves, typically in the form of photons, to encode information for transmission. This modulation can involve varying properties of the light wave such as intensity, phase, polarization, or frequency.

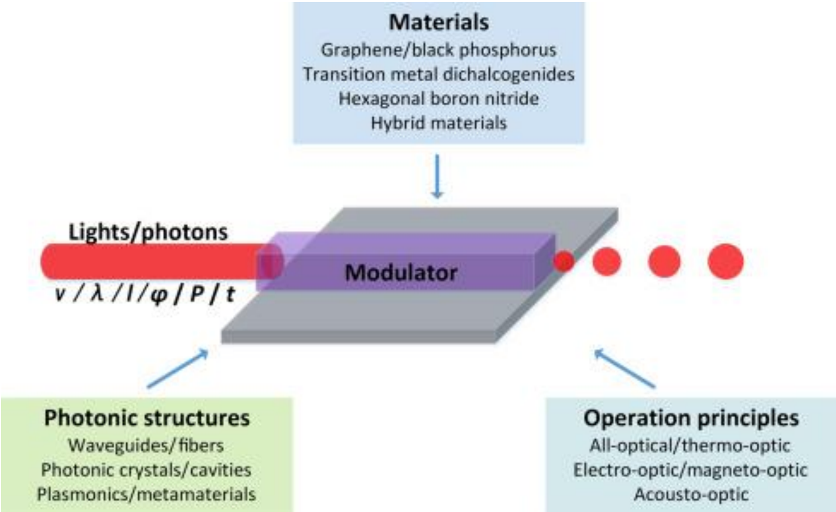


Figure 1. 3 Optical Modulator

There are several types of optical modulators, each with its own mechanism of operation. One common type is the electro-optic modulator, which relies on the electro-optic effect to change the refractive index of a material in response to an applied electric field. This change in refractive index alters the phase of the light passing through the material, allowing for modulation of the optical signal. Another type is the acousto-optic modulator, which utilizes acoustic waves to change the refractive index of a material, thereby modulating the phase or amplitude of the incident light. This modulation is achieved by the interaction between the acoustic wave and the optical wave within the modulator. Additionally, there are optical modulators based on other principles such as the magneto-optic effect, quantum dot modulation, and micro-electromechanical systems (MEMS) technology. These modulators offer unique advantages and are used in specific applications based on their performance characteristics. Overall, optical modulators play a crucial role in various optical communication systems, including fibre optic networks, laser systems, and optical sensors. They enable the encoding of information onto light waves, facilitating high-speed data transmission and signal processing in modern telecommunications.

1.3.2 Photodetector

Photodetectors are essential components in various electronic devices and systems, particularly in applications where the detection and measurement of light are necessary. They convert light signals into electrical signals, allowing for the manipulation, processing, and transmission of optical information in electronic circuits.

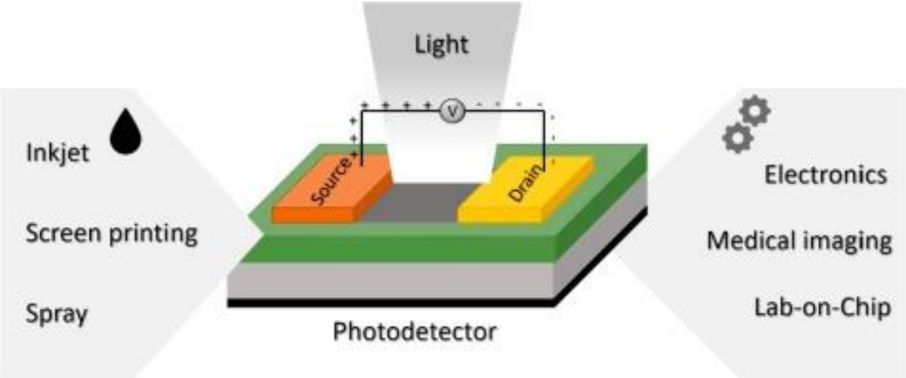


Figure 1. 4 Mechanism of Photodetector[6]

Basic Principle: At its core, a photodetector operates based on the photoelectric effect, where incident photons of light are absorbed by a material, leading to the generation of free charge carriers (electrons and holes). These charge carriers create an electrical current or voltage proportional to the intensity of the incident light.

Types of Photodetectors:

Photodiodes: These are semiconductor devices that convert light into current or voltage. They consist of a p-n junction where light-generated carriers are swept by an electric field. Photodiodes are widely used in various applications due to their high sensitivity and fast response times.

Phototransistors: Similar to photodiodes, phototransistors also convert light into current, but they provide higher gain due to the transistor amplification effect. They are commonly used in applications requiring higher sensitivity.

Avalanche Photodiodes (APDs): These are photodiodes operated in reverse bias at a voltage close to the breakdown voltage. They provide internal amplification through avalanche multiplication, offering higher sensitivity and lower noise compared to standard photodiodes.

Performance characteristics:

Responsivity: The ratio of output electrical signal (current or voltage) to incident optical power, typically expressed in amps per watt (A/W) or volts per watt (V/W).

Spectral Response: The range of wavelengths over which the photodetector is sensitive to light

Dark Current: The current flowing through the photodetector in the absence of light, typically due to thermal generation of carriers.

PIN Photodetector: A PIN photodetector is a type of photodetector widely used for detecting optical signals in various applications, including fibre optic communication, remote sensing, and photometry. A PIN photodetector consists of three main regions: a lightly doped (or intrinsic) semiconductor layer sandwiched between two heavily doped semiconductor layers. The acronym PIN stands for the p-type, intrinsic, and n-type layers, respectively. The intrinsic layer is typically made of materials like silicon, germanium, or III-V compounds.

Operation Principle: When photons of light strike the intrinsic layer of the photodetector, they generate electron-hole pairs through the photoelectric effect. The electric field established by the reverse bias voltage applied across the p-n junction accelerates these charge carriers towards the respective electrodes.

Absorption Region: The intrinsic layer serves as the absorption region where the incident photons are absorbed, generating electron-hole pairs. The thickness of this region determines the absorption characteristics of the photodetector, including its sensitivity to different wavelengths of light.

Applications:

Optical Communication: Photodetectors are used in fibre optic communication systems for receiving optical signals and converting them into electrical signals for further processing.

Remote Sensing: They are employed in applications such as lidar (light detection and ranging), laser rangefinders, and photometry for measuring distances, detecting objects, and monitoring environmental parameters.

Photovoltaic Devices: PIN photodetectors are also employed in photovoltaic devices such as solar cells and photodiodes for converting light energy into electrical energy.

High Sensitivity: PIN photodetectors exhibit high sensitivity due to their large absorption region and efficient collection of charge carriers.

Low Noise: They offer low noise characteristics, making them suitable for applications requiring high signal-to-noise ratios.

Fast Response Time: PIN photodetectors typically have fast response times, enabling rapid detection and processing of optical signals.

1.3.3 Applications of Optoelectronic Oscillator

Optoelectronic oscillators (OEOs) are devices that convert optical signals into electrical signals, offering high-frequency and low-phase-noise signal generation. They have several significant applications:

High-Precision Signal Generation: OEOs are widely used in generating stable and precise microwave and millimetre-wave signals. This is critical for radar systems, communication networks, and electronic warfare where signal accuracy and stability are important.

Optical Communication Systems: In optical fibre communications, OEOs help in signal processing and improving the performance of data transmission. They enable the generation of ultra-pure carrier waves, which enhance the modulation and demodulation processes, leading to higher data rates and improved signal quality.

Metrology: OEOs are used in precision measurement systems, including time and frequency metrology. They provide highly stable reference signals that are essential for accurate measurements in scientific and industrial applications.

Sensors: They play a role in various sensing technologies, such as fibre optic sensors, where they enhance the detection capabilities and sensitivity. This is particularly useful in environmental monitoring, structural health monitoring, and medical diagnostics.

Phase-Locked Loops (PLLs): OEOs are integral in designing phase-locked loops, which are crucial components in many electronic systems, including signal synthesis, clock generation, and frequency modulation systems.

Microwave Photonics: In the field of microwave photonics, OEOs are used to convert and process microwave signals optically. This allows for the integration of optical and microwave technologies, leading to advancements in high-frequency signal processing and communication systems.

Radar Systems: OEOs enhance the performance of radar systems by providing low-phase-noise oscillations, which are essential for accurate target detection and resolution.

High-Frequency Testing and Measurement: They are used in the testing and measurement of high-frequency electronic components and systems, providing precise signal sources that are necessary for evaluating performance and reliability.

1.4 Whispering gallery mode resonator (WGM)

Whispering gallery mode (WGM) resonators are fascinating structures that harness the principles of wave behaviour to confine light or sound within a circular or spherical boundary. These resonators derive their name from the whispering galleries in some architectural wonders, where whispers travel along curved walls seemingly indefinitely due to multiple reflections. Similarly, in WGM resonators, light or sound waves circulate around the perimeter of the structure, creating standing waves that can persist for extended periods. These resonators find applications across various fields, including optics, photonics, acoustics, and telecommunications, owing to their ability to store and manipulate electromagnetic or acoustic energy with high efficiency. The unique properties of WGM resonators, such as high quality (Q) factors and small footprints, make them valuable components in a wide range of devices, including sensors, lasers, filters, and frequency converters. In this introduction, we looked into the fundamental principles behind WGM resonators, explore their applications, and discuss recent advancements in their design and fabrication techniques.

1.4.1 Working Principle of WGM

Whispering gallery mode (WGM) resonators operate based on the principle of total internal reflection, which allows waves to propagate along a curved surface with minimal loss. Imagine a circular or spherical structure, like a ring or a sphere, made of a material with high refractive index, such as glass or crystalline material. When a wave, whether it be light or sound, enters this structure at a shallow angle, it bends along the curve due to the change in medium, just like light bending when it enters water from air.

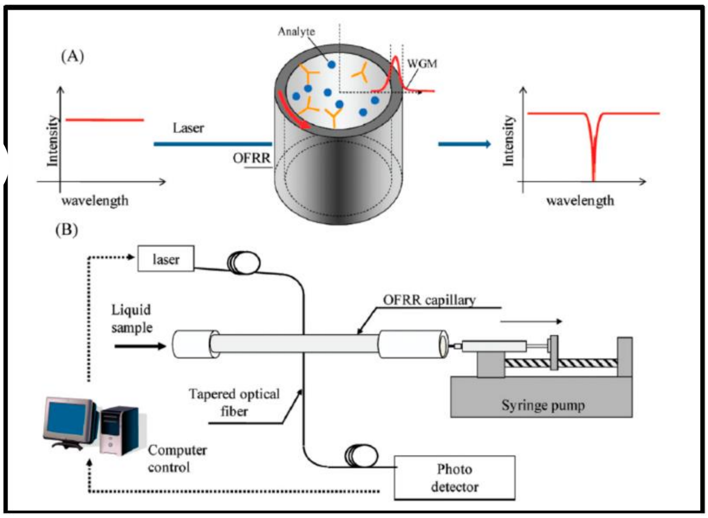


Figure 1. 5 Whispering gallery mode resonator[7]

Once inside, the wave undergoes multiple reflections along the inner surface of the structure. These reflections occur at angles that ensure the wave remains trapped within the resonator, unable to escape due to total internal reflection. As a result, the wave circulates around the perimeter of the structure, continuously interfering with itself and forming what are known as whispering gallery modes. These whispering gallery modes are standing wave patterns characterized by regions of constructive and destructive interference. In optical WGM resonators, for instance, light waves form these modes, leading to intense electromagnetic fields localized near the surface of the resonator. Similarly, in acoustic WGM resonators, sound waves exhibit similar behavior, circulating within the structure and forming standing wave patterns. The key to the functionality of WGM resonators lies in their ability to confine and sustain these modes for extended periods with minimal energy loss. This is quantified by the quality factor (Q-factor) of the resonator, which represents the ratio of the energy stored in the resonator to the energy lost per cycle. WGM resonators typically exhibit very high Q-factors, making them efficient at storing and manipulating energy. WGM resonators are known for their exceptionally high Q-factors, indicating minimal energy loss per cycle. This property allows for efficient energy storage and prolonged resonance, essential for various applications requiring stable and long-lasting operation. Due to their ability to confine waves within a compact volume, WGM resonators can achieve high resonant frequencies in relatively small structures. This compact size is advantageous for applications where space is limited, such as integrated photonics and miniaturized sensors.

WGM resonators are highly sensitive to changes in their surroundings. Small variations in parameters such as refractive index, temperature, or pressure can induce measurable shifts in the resonant frequency or linewidth of the modes. This sensitivity makes WGM resonators valuable for sensing applications, including bio-sensing, environmental monitoring, and chemical analysis.

WGM resonators exhibit strong nonlinear optical and acoustic effects due to the high intensity of the electromagnetic or acoustic fields within the resonator. These nonlinearities enable applications such as frequency conversion, parametric amplification, and generation of non-classical states of light or sound.

Integration with Other Components: WGM resonators can be seamlessly integrated with other optical or electronic components, facilitating the development of complex photonic or acoustic circuits. This integration capability enables the creation of multifunctional devices and systems with enhanced performance and functionality.

Low Power Consumption: The efficient energy storage and propagation characteristics of WGM resonators contribute to low power consumption in devices and systems utilizing these resonators. This energy efficiency is particularly advantageous in applications where power consumption is a critical factor, such as portable sensors or battery-operated devices.

1.4.2 OEO based on Micro Disk Resonator

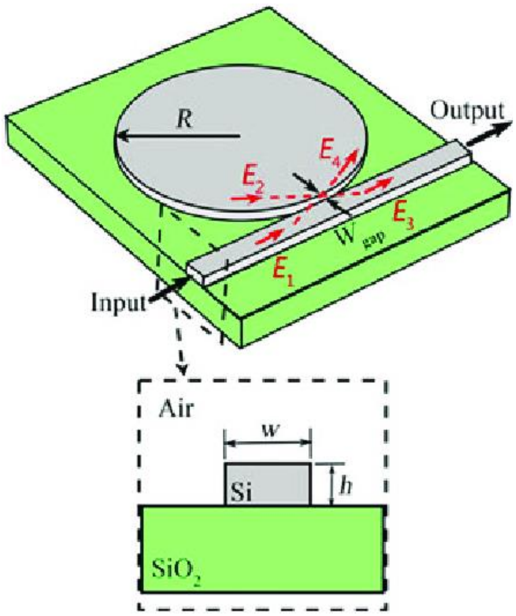


Figure 1. 6 Design of micro disk resonator[8]

Label-free biomedical sensors offer the capability to deliver real-time quantitative data concerning the advancement of biochemical reactions. Among these sensors, optical micro-resonators utilizing silicon-on-insulator (SOI) technology exhibit compelling features for label-free sensing tasks. They possess advantageous traits in comparison to sensors built using alternative methodologies. In contrast to sensors based on straight waveguides, those utilizing micro-resonators offer a reduced footprint without compromising on detection limit (DL) thanks to the high-quality (Q) factor inherent to micro-resonators. Moreover, biochemical sensors based on micro-resonators present notable advantages, including heightened sensitivity, compact form factor, straightforward manufacturing processes, surface functionalization capabilities, and the ability to perform multiplexed analyses. micro-resonators based on SOI are susceptible to temperature fluctuations. This susceptibility is exacerbated by the high thermo-optic coefficient of silicon and the wavelength sensitivity inherent to micro-resonators. While this temperature sensitivity renders micro-resonators suitable for temperature sensing applications, it poses a drawback for other optical devices, such as refractive index (RI) sensors relying on micro-resonators. To mitigate the temperature effect, various sensing schemes have been proposed, including the integration of a reference micro ring. Another approach involves combining a ring resonator with a Mach-Zehnder interferometer to minimize the impact of environmental temperature. Additionally, a dual – micro ring scheme with resonance splitting has been employed to diminish the temperature dependence of micro-resonators. However, these additional reference configurations contribute to increased device size, which is detrimental to device integration efforts. Furthermore, temperature control mechanisms utilized for temperature compensation necessitate integrated heaters and photodetectors, leading to elevated power consumption. A novel optical micro disk resonator featuring two Whispering Gallery Mode (WGM) resonance peaks is introduced for simultaneous measurement of changes in surrounding refractive index (RI) and temperature. The mode characteristics and transmission responses of the two WGMs are analysed using the 3-D Finite Element Method (3D-FEM). Investigations into the Quality Factor (Q factor) and Extinction Ratio (ER) of the two WGM resonance peaks are conducted under varying coupling media and gap sizes. Furthermore, manufacturing tolerances of the micro disk resonator are deliberated upon to showcase the precision and reliability of the proposed sensor.

1.4.3 Applications of MDR - OEO

Telecommunications: Micro disk resonator-based optoelectronic oscillators play a crucial role in telecommunications systems, offering stable and high-frequency microwave and milli meter-wave signals. These signals are utilized in optical communication networks for tasks such as signal generation, synchronization, and frequency conversion.

Radar Systems: Radar systems benefit from the precise and stable signals generated by micro disk resonator optoelectronic oscillators. These signals are utilized for radar signal processing, target detection, tracking, and imaging applications, contributing to enhanced radar performance and accuracy.

Sensing and Metrology: Micro disk resonator optoelectronic oscillators find applications in sensing and metrology, where their high sensitivity and stability enable precise measurements. They are utilized in label-free biochemical sensing, environmental monitoring, and precision measurement of physical parameters such as temperature, pressure, and strain.

Frequency Synthesis: Micro disk resonator-based oscillators are employed in frequency synthesis applications, where stable and tunable microwave and milli meter-wave signals are required. They are used in synthesizers for wireless communication, satellite communication, and instrumentation systems, facilitating frequency generation and modulation with low phase noise.

Quantum Technologies: In emerging fields such as quantum information processing and quantum communication, micro disk resonator optoelectronic oscillators play a role in generating and manipulating quantum states of light[9]. They are utilized in quantum key distribution (QKD) systems, quantum metrology, and other quantum technologies, facilitating the development of secure communication and precise measurements at the quantum level.

1.5 Resonant Tunneling Diode-Photodetector-Laser Diode

A different type of integrated OEO utilizes a resonant tunneling diode-photodetector-laser diode (RTD-PD-LD) or an electro-absorption modulated laser (EML). While this design offers the advantage of simplified structure, as it combines light generation, modulation, and photodetection within a single device, it still necessitates a long optical fibre loop spanning several kilometres. Following Ikeda's pioneering work on bifurcation phenomena in systems with delayed-feedback, numerous experimental and numerical investigations involving time-delay have been conducted. Notably, optoelectronic oscillator (OEO) systems with time-delay have garnered significant attention. An OEO comprises a nonlinear system with a feedback loop incorporating a time-delay, capable of operating across a frequency spectrum ranging from tens of GHz to a few kHz. These systems find applications across diverse fields including biology, chemistry, optics, and electronics. Recent developments have seen the realization of delayed-feedback optoelectronic oscillators for use as high-quality microwave sources. The integration of time-delay loops into optoelectronic oscillators introduces complexity into their dynamics, leading to a diverse range of dynamical behaviour. Of particular interest is the utilization of delayed-feedback OEOs for generating high-dimensional chaotic waveforms, for chaos control, and for enhancing security in communication systems. In earlier studies, we presented innovative optoelectronic chaotic generators utilizing resonant tunneling diode (RTD) voltage-controlled oscillators (VCO). The RTD, characterized by its negative-resistance behaviour, operates efficiently at very high frequencies owing to its broad bandwidth negative differential resistance (NDR). Coupled with a laser diode, the RTD-VCO system offers a straightforward method for converting microwave signals into optical sub-carriers.

The overall nonlinear dynamics of the RTD-VCO laser diode system are effectively captured by two sets of differential equations. One set describes the electrical circuit oscillator system, influenced by external electrical and optical injection. The second set encompasses the laser's single-mode rate equations, detailing photon and carrier densities. More recently, our experimental realization of a low-phase noise OEO built upon an RTD integrated with a photodetector, a laser diode, and an optical fibre delay line.

1.5.1 Working of RTD-PD-LD OEO

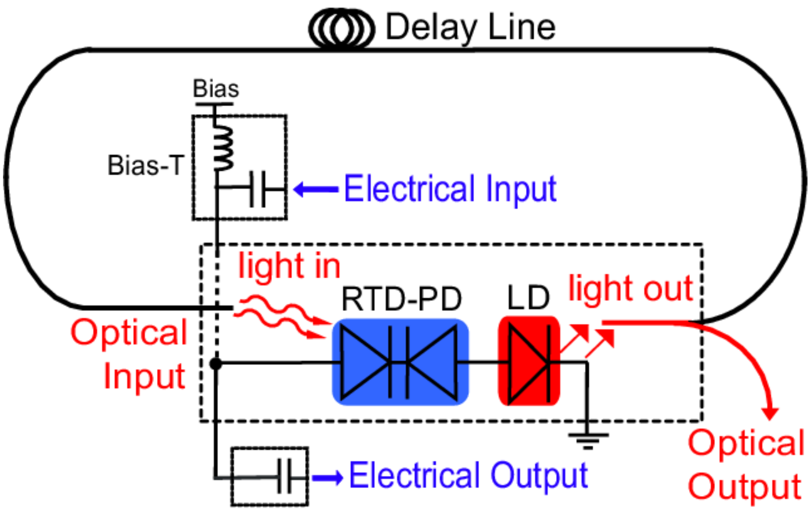


Figure 1. 7 Resonant tunnelling photodetector[10]

The delayed-feedback nonlinear oscillator derived from the RTD-OEO system, employing delay differential equations (DDE) representing the Lienard oscillator coupled with laser rate equations. The RTD-OEO system under time-delayed feedback scrutiny here is governed by DDEs rather than ordinary differential equations (ODEs). Through numerical simulations, our model affirms the capability of the RTD-OEO system to exhibit both highly stable microwave oscillations and intricate oscillatory behaviour contingent upon the control parameters of time-delay and feedback strength. Notably, the RTD-OEO demonstrates the capacity to generate robust and high-dimensional signals. The Resonant Tunneling Photodetector-Laser Diode (RTD-PD-LD) based Optoelectronic Oscillator (OEO) is a device that generates stable microwave or millimetre-wave signals by utilizing the properties of resonant tunneling diodes (RTDs), photodetectors, and laser diodes. At the core of the RTD-PD-LD OEO is the RTD, a semiconductor device with a quantum well structure that allows electrons to tunnel through potential energy barriers. RTDs exhibit negative differential resistance (NDR) behaviour, meaning that their current decreases as the voltage across them increases beyond a certain threshold. This property is crucial for generating microwave oscillations. The photodetector in the system detects the optical output from the laser diode and converts it into an electrical signal. This signal is then fed back into the RTD as part of the feedback loop. The laser diode serves as the light source in the system. It emits optical radiation, which is modulated by the electrical signal generated by the RTD. This modulation can occur through various means, such as direct modulation or external modulation techniques.

The RTD-PD-LD OEO operates based on a feedback loop. The electrical output from the photodetector is fed back into the RTD, introducing a time delay in the system. This time delay, combined with the nonlinearity of the RTD's current-voltage characteristics, leads to the generation of stable microwave or millimetre-wave signals.

1.5.2 Advantages of RTD-PD Laser Diode

The Resonant Tunneling Photodetector-Laser Diode (RTD-PD-LD) based Optoelectronic Oscillator (OEO) offers several advantages, making it a valuable component in various applications.

High Frequency Stability: RTD-PD-LD OEOs exhibit high-frequency stability, making them suitable for generating precise microwave or milli metre-wave signals used in telecommunications, radar systems, and wireless communication networks. This stability ensures reliable signal transmission and processing.

Wide Bandwidth Operation: RTD-PD-LD OEOs can operate over a wide bandwidth, allowing for the generation of signals across a broad range of frequencies. This versatility makes them adaptable to various communication standards and frequency bands, enhancing their applicability in diverse communication systems.

Low Phase Noise: RTD-PD-LD OEOs typically exhibit low phase noise characteristics, ensuring the stability and accuracy of the generated signals. Low phase noise is crucial for applications requiring precise frequency synchronization and coherent signal transmission, such as in radar systems and wireless communication networks.

1.6 Ring Resonator and its Application

Over the past several decades, optical communication has steadily supplanted electrical transmission, offering numerous advantages such as heightened tolerance to electromagnetic interference, reduced channel losses for high-speed data transmission across extensive distances, and expanded bandwidth capacities per cable. As the demand for communication bandwidth continues to escalate, the superiority of photonics over electronics becomes increasingly evident, particularly over shorter distances. Despite the challenges encountered by short-reach electrical interconnects, the integration of optics in this sector has traditionally lagged due to the substantial number of optical components required per chip and their bulky nature. However, recent advancements in passive silicon waveguide architectures, notably wavelength selective devices and ring resonators, have brought about a significant reduction in waveguide footprint. This innovation is primarily attributed to the remarkable capabilities of photonic waveguides, which can achieve bend radii of less than 5μm owing to the substantial refractive index contrast between silicon and its oxide (or air). Consequently, compact rings can be formed, facilitating on-chip integration of photonic devices. Ring resonators, in particular, play a pivotal role in the advancement of silicon photonics by enabling seamless integration of various photonic components on a single chip.

One notable advantage of integrated ring resonators is their ability to operate without the need for facets or gratings, making them well-suited for seamless integration with other components on a single chip. The basic structure of a micro ring resonator is illustrated in Figure 1.10. MRRs serve various functions in optical systems, including optical sensors, filters, switches, amplifiers, routers, and sources.

1.6.1 Theory of Ring Resonator

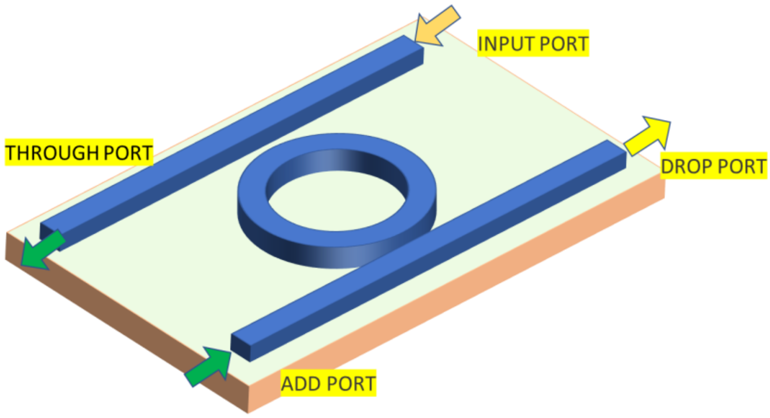


Figure 1. 8 Basic Structure of micro ring resonator

In recent years, integrated ring resonators have emerged as integral components in integrated photonics, finding applications across various fields. A micro ring resonator (MRR) constitutes a resonant cavity formed by coiling a waveguide into a ring structure. These ring resonators employ parallel coupling waveguides to facilitate the transfer of light from a straight waveguide to the circular waveguide. To ensure efficient coupling of the desired frequency into the ring, the distance between the interaction length and the ring is carefully managed. The concept of ring resonators has emerged as a fundamental element in the realm of integrated photonics, representing a pivotal advancement in optical engineering. These resonant structures, typically formed by coiling a waveguide into a circular shape, have garnered significant attention due to their versatile applications across a spectrum of fields. With the ability to efficiently transfer light between waveguides using parallel coupling techniques, ring resonators offer a compact and robust solution for optical signal processing and manipulation. Moreover, their intrinsic properties enable seamless integration into monolithic photonic circuits, eliminating the need for external components such as facets or gratings. This introduction sets the stage for exploring the architecture, functionality, and diverse applications of ring resonators in contemporary optical systems. The MRR's input port to through port transmission coefficient, α is specified by equation (1.1)

$$a = \frac{I_{thru}}{I_{in}} = \frac{a^2 - 2arcos(\varphi) + r^2}{1 - 2arcos(\varphi) + a^2 r^2} \qquad (1.1)$$

where 'a' represents the MRR transmission for one roundtrip, 'r' denotes the bus waveguide's self-coupling, 'k' represents cross-coupling between the bus waveguide and the MRR. $r^2 + k^2 = 1$ as r^2, k^2 are the power splitting ratios of the coupler for a lossless coupling region. The intensities at the input port and through port are I_{input} and I_{thru}. The quantity Φ is equal to the micro ring waveguide's single-pass phase shift, which is specified by $\Phi = \beta L$. β is the propagation constant, which is equal to $2\pi n_{eff}$ (L/λ), and L is the micro ring's round-trip distance. Effective refractive index is n_{eff}. When Φ is a multiple of 2π, the ring is in resonance. For a set of resonant wavelengths, λ0 this condition is met.

$$\lambda_0 = \frac{n_{eff} L}{m} \qquad (1.2)$$

where m = 1,2,3………………

The transfer characteristics of the ring resonator are as shown in Figure 3.4. From in-port to through-port, MRR connected to a bus waveguide functions as a notch filter. Wavelengths that are not on resonance pass by the resonator, whereas wavelengths that are near to the λ0's are caught, and the resonances are periodic in nature. The gap between resonances is called as the free spectral range (FSR) as shown in Figure. and is given by equation (1.3)

$$FSR = \frac{\lambda^2}{n_g L} \qquad (1.3)$$

where n_g is the group index, that accounts for the silicon waveguide's dispersion. When on resonance, equation (1.1) reduces to (1.4)

$$\alpha(\lambda_0) = 1 - A = \frac{a^2 - 2ar + r^2}{1 - 2ar + a^2r^2} = \frac{(a - r)^2}{1 - 2ar + a^2r^2} \qquad (1.4)$$

Once the ring is critically coupled, r = a and α(λ0) = 0 i.e., the power coupled from the bus guide equals the rate of decay of energy owing to losses in the ring.

1.6.2 Applications Of Ring Resonator

Ring resonators are utilized as sensitive detectors in optical sensing applications. Changes in the resonant frequency caused by variations in the surrounding environment, such as refractive index changes or the presence of specific analytes, can be detected with high precision, making them ideal for biosensing, environmental monitoring, and chemical detection.

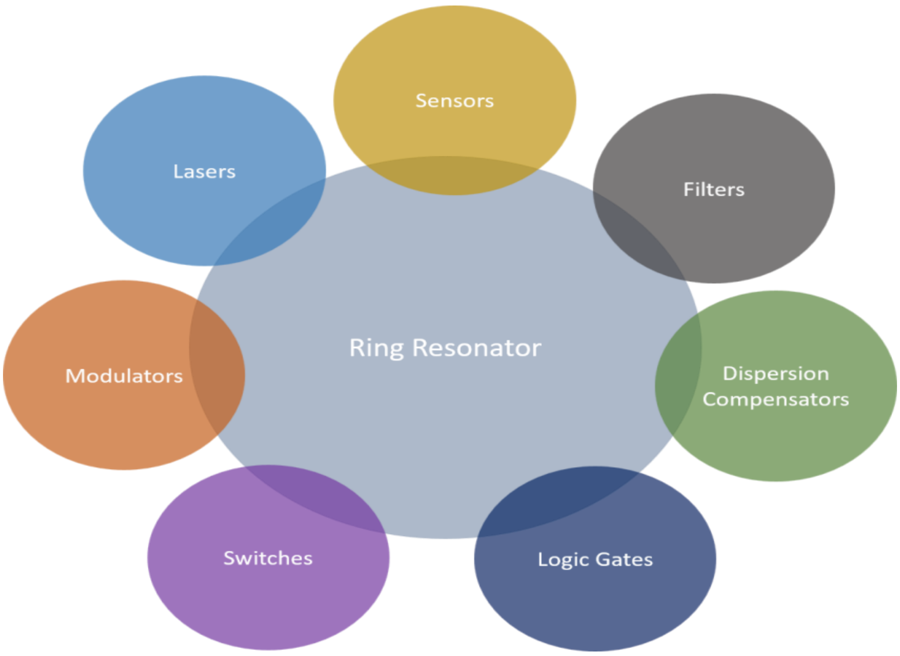


Figure 1. 9 Different application of ring resonator

Ring resonators serve as key components in optical filter designs. By selectively filtering certain wavelengths of light based on the resonance condition of the ring, they enable the creation of narrowband or broadband filters for wavelength-division multiplexing (WDM) systems, spectral analysis, and optical communication networks.

The ability of ring resonators to modulate light transmission based on changes in the resonant condition makes them valuable in optical switching applications. By altering the coupling conditions or the refractive index of the ring material, ring resonators can be employed as optical switches for routing and controlling optical signals in photonic integrated circuits (PICs) and optical networks. In optical amplifiers, ring resonators can enhance the amplification process by providing feedback and resonance enhancement within the cavity. This enables the realization of compact and efficient on-chip amplifiers for boosting optical signals in communication systems and signal processing applications.

Ring resonators used in optical routing and signal routing applications. By exploiting the principles of interference and resonance, they enable the manipulation and redirection of optical signals within photonic circuits, facilitating complex routing schemes and enabling the implementation of reconfigurable optical networks.

1.7 Organization of the Thesis

The thesis is organized in five chapters starting with an introduction and literature survey, one chapter consisting of the original research work followed by the conclusion and the future scope.

Chapter 2 Literature Survey: This literature review covers OEO with WGM, RTD PD Laser Diode, Micro Disk resonators and Ring Resonator configurations. OEO with ring resonator improves performance in generating purity of RF signal. OEO with ring resonator reduces the noise of the signal. It generates signal with good side mode suppression ratio so losses are less.

Chapter 3 Design of Silicon Ring Resonator: Chapter three presents a proposed design of Silicon Ring Resonator and discusses its performance characteristics. The design facilitates the filter, delay and obtains the high-quality factor.

Chapter 4 Optoelectronic Oscillator with Ring Resonator: This chapter discusses the proposed design of OEO utilizing the ring resonator. The design helps to improve the purity of generated radio frequency signal by using high quality factor ring resonator and improves side mode suppression ratio.

Chapter 5 Conclusion and Future Scope: This chapter outlines the thesis and briefly discusses the future scope of the project.

Chapter 2

LITERATURE REVIEW

2.1 Introduction to Optoelectronic Oscillator

A significant advancement in optoelectronic oscillator (OEO) technology emerged with the introduction of a voltage-controlled whispering gallery mode (WGM) resonator, replacing the conventional bulky fibre loop. This innovation enabled the generation of a 34–36 GHz RF signal by manipulating the voltages applied to the WGM. However, despite its promising performance, the fabrication of WGM resonators posed significant challenges, and their integration with other electro-optic devices remained nearly impossible. Subsequent efforts focused on integrated OEO solutions, such as those based on resonant tunneling diode-photodetector-laser diode (RTD-PD-LD) configurations or electro-absorption modulated lasers (EML). While these designs simplified the structure by consolidating light generation, modulation, and photodetection within a single device, they still required long optical fibre loops spanning several kilometres. In recent years, advancements in silicon photonics have spurred the development of silicon-based OEO solutions. For example, silicon micro ring resonators (MRRs) have been leveraged as optical bandpass filters for selecting oscillation modes. Through simple adjustments in the wavelength spacing between the MRR and the laser source, OEO tunability within the range of 6–18 GHz has been achieved. However, the relatively high loss of silicon waveguides (typically 1–2 dB/cm) has limited the quality factor (Q-factor) of the MRR to 8.1 × 10^4, resulting in a phase noise of approximately -50dBc/Hz@10 kHz[11]. the design of a race-track MRR has facilitated the realization of a tunable microwave photonic filter (MPF), leading to the development of an

OEO with a frequency range of 0–20 GHz. However, mitigating loss in these race-track configurations requires increased track widths, consequently complicating both design and fabrication processes. In a recent study, a significant advancement in optoelectronic oscillator (OEO) technology was achieved through the simultaneous integration of a high-speed phase modulator (PM), a thermally adjustable micro disk resonator (MDR), and a high-speed photodetector (PD) on a single silicon-on-insulator (SOI) chip. This integration enabled the development of a miniaturized OEO capable of operating within a frequency range of 3–8 GHz. The micro disk resonator (MDR) featured an impressive quality factor (Q-factor) of approximately 1.1 × 10^5, leading to a remarkable phase noise performance of only -80dBc/Hz@10 kHz for the OEO. Building upon this achievement, a similar tuning principle was applied to propose a broadband tunable OEO utilizing a high-Q silicon nitride MDR. This innovative approach holds promise for extending the frequency tuning range while maintaining high performance characteristics, thus opening new avenues for the advancement of compact and efficient OEO systems.

2.2 Review of OEO with WGM

Since 2008, researchers have utilized a voltage-controlled whispering gallery mode (WGM) resonator to substitute the cumbersome fiber loop in traditional opto-electronic oscillators (OEOs). By adjusting the voltages applied to the WGM, they managed to generate a 34–36 GHz RF signal. It is hard fabricating the WGM is challenging, and its integration with other electro-optic devices remains largely unfeasible.

Ilchenko et.al-2006[12]**:** This review explores the latest advancements in the utilization of whispering gallery mode resonators within the realms of optics and photonics. While we aimed to encompass all recent activities in the field, we acknowledge the rapid pace of growth, which may have caused us to overlook some recent breakthroughs. Whispering gallery modes, intriguing as physical phenomena, are anticipated to experience the most rapid expansion in their practical applications. Devices such as filters, modulators, lasers, and others based on whispering gallery modes offer numerous advantages over their conventional counterparts.

Maleki, L., 2012[13]**:** This paper provides an overview of the advancements made in the Opto-Electronic Oscillator (OEO) field over the past twenty years. It delves into various methodologies employed for realizing the OEO architecture. Recent progress concerning the production of highly pure signals through a compact OEO configuration, leveraging optical whispering gallery mode (WGM) resonators, is examined. Additionally, it explores future iterations of the OEO, which integrate the optoelectronic feedback loop with a Kerr comb frequency generator utilizing a crystalline WGM resonator, based on current developments.

Matsko et.al-2003[14]**:** We conducted theoretical investigations into the characteristics of an optoelectronic microwave oscillator (OEO) utilizing an optical whispering gallery mode lithium niobate disc cavity. Our findings reveal that this device can achieve an oscillation threshold as low as 1mW, with a frequency stability (Allan deviation) potentially reaching as small as $10^{-15}/t^{1/2}$ for practical experimental setups. We contrast the properties of resonant and non-resonant OEOs and present initial experimental findings on the whispering gallery mode OEO.

Nguewou-Hyousse et.al-2021[15]**:** This study explores the stochastic dynamics of a miniature OEO architecture. Initially, we introduced stochastic differential equations governing the system's dynamics under the influence of white noise sources. Subsequently, we developed an analytical framework to ascertain the power of the generated microwave. Additionally, we proposed a stochastic normal form approach to reveal the scaling behavior of the microwave power with increasing gain, both below and above threshold. Our analytical findings demonstrated excellent agreement with numerical simulations. Future endeavors will focus on refining the model to encompass other nonlinear effects in the resonators or optoelectronic components of the feedback loop. Furthermore, the model will be extended to accommodate multiplicative and 1/f noise.

2.3 Review of OEO with RTD-PD Laser Diode

We present and discuss recent advancements in a unique five-port optoelectronic voltage-controlled oscillator that incorporates a resonant tunneling diode (RTD) optical waveguide with a laser diode. This RTD-based optoelectronic oscillator (OEO) features both optical and electrical input and output ports, with an additional port for voltage control. The RTD-OEO can synchronize with reference radio-frequency (RF) sources through optical or electrical injection locking, facilitating remote synchronization and eliminating the requirement for impedance matching with traditional RF oscillators. The RTD-OEO supports various functions including the generation, amplification, and distribution of RF carriers, as well as clock recovery, carrier recovery, modulation, demodulation, and frequency synthesis. Additionally, self-injection locking modes, which feed small portions of the output electrical/optical signals back into the input ports, are proposed. This self-phase locked loop configuration can produce low-noise, highly stable oscillations, independent of the RF source performance and without the need for external optoelectronic conversion.

Romeira et.al-2010[16]**:** This study introduced an innovative optoelectronic oscillator circuit that combines a resonant tunneling diode optical waveguide (RTD-OW) with a laser diode, forming the RTD-OEO. This RTD-OEO is a flexible and straightforward optoelectronic oscillator suitable for microwave-photonic systems, capable of injection-locking, up-conversion, and down-conversion of both electrical and optical reference signals, as well as generating RF and chaotic signals. Future research aims to achieve monolithic integration of an RTD oscillator and a photoconductive region with a laser diode, replacing the current use of separate laser and RTD chips.

This approach could lead to single-chip OEO solutions for high-speed fibre-optic communication systems.

Romeira et.al-2012[17]**:** We have successfully demonstrated a simplified optoelectronic oscillator (OEO) in both single and dual loop configurations, operating in the gigahertz range. This system utilizes resonant tunneling diode (RTD) photo-detectors and laser diodes, eliminating the need for additional electrical amplifiers, photo-detectors, or external modulators. Our OEO achieved a low phase noise of -102.88dBc/Hz at a 10 kHz offset from a 1.12 GHz centre frequency, with a side mode suppression ratio of -60dBc. Further advancements in this RTD-based OEO configuration could enhance the applicability of OEOs across a wide range of microwave photonics applications.

Ironside et.al-2011[18]**:** Optoelectronic oscillators are capable of delivering low noise signals at radio frequencies ranging from 0.5 to 40 GHz. In this paper, we review two newly introduced methods for optoelectronic oscillators, both utilizing an optical fibre feedback loop. The first method employs passively mode-locked laser diodes and can achieve up to a 30 dB noise reduction in a 40 GHz oscillator. The second method utilizes resonant tunneling diode optoelectronic devices, achieving a similar 30 dB noise reduction in a 1.4 GHz oscillator.

Thepi Siewe et.al-2016[19]**:** In this paper, the authors conduct a numerical investigation into the dynamics of a non-linear optoelectronic oscillator (OEO) based on a resonant tunneling diode (RTD) oscillator that incorporates a photo-detector and is coupled to a non-linear electrical circuit. The first part of the study reveals that the RTD-OEO exhibits periodic and quasiperiodic behaviours depending on the parameters of a pulse-like optical signal. In the second part, where the RTD-OEO is coupled with a Van der Pol oscillator, the system demonstrates a range of dynamic states, including bursting, relaxation, and sinusoidal oscillations.

2.4 Review of OEO with Ring Resonator

Cui T et.al-2023[20]**:** This paper introduces a tunable optoelectronic oscillator (OEO) utilizing a silicon nitride high-Q micro ring resonator (MRR) boasting a Q value of 4.36 × 10^5. By integrating the high-Q MRR into a phase-modulated link, an 8–38 GHz tunable microwave photonic filter (MPF) is achieved with a 3-dB bandwidth of approximately 610MHz. Leveraging the tunable MPF, a tunable OEO is established with a frequency range spanning from 14.60 to 25.65 GHz. The measured phase noise of the 25.65-GHz oscillation signal is -88dBc/Hz at a 10 kHz offset.

Yu Y et.al-2019[21]**:** This paper presents a frequency stabilization technique, the measured frequency jitter of the MRR-based OEO is reduced significantly, from 50 MHz to 85 kHz within a span of 10 minutes. Furthermore, the oscillating frequency of the proposed OEO can be adjusted within the range of 0 to 20 GHz. Through the design and fabrication of the MRR with cascaded multi-mode and single-mode waveguides, the measured Q factor reaches an impressive 1.13 × 10^6. This results in a corresponding phase noise of the microwave signal at a 10 kHz offset frequency of -95dBc/Hz, when the microwave signal is at 12.23 GHz. Even during the tuning of the oscillating frequency, the side-mode suppression ratio (SMSR) remains consistently above 50dB. This suggests that the proposed MRR-based OEO, boasting long-term stability, holds promise for monolithic integration.

Do P.T. et.al-2019[22]**:** The proposed OEO functions by creating the microwave signal through the interaction of un-modulated and amplitude-modulated versions of the same laser source. A silicon micro-resonator's drop port is utilized to choose one of the sideband lobes produced by the amplitude modulation, effectively acting as a frequency-selective element within the OEO. In this configuration, the microwave frequency produced is dictated by the wavelength gap between the laser and the ring resonance. Consequently, seamless tuning of the microwave frequency is achievable by simply adjusting the wavelength of the laser source. A proof-of-concept demonstration validates this approach, showcasing experimental microwave frequency generation spanning from 5.9 GHz to 18.2 GHz.

Chen J et.al-2018[23]**:** In this paper the proposed OEO utilizing SiO_2 OWRR demonstrates a transition in oscillation mode spacing from 40.32 MHz to 2.137 GHz. This results in a 20 dB improvement in its SMSR, while the phase noise at 2.137 GHz decreases from -87.9dBc/Hz to -100.54dBc/Hz at a 10 kHz offset frequency. Additionally, the compact size of the SiO2 OWRR renders it more manageable than a long fibre-optic delay line, facilitating potential integration of the OEO onto a photonic chip. Consequently, this integration promises effective reductions in the OEO's size, weight, and power consumption, thereby advancing its miniaturization and commercial viability.

Chew et.al-2017[24]**:** integrated silicon-on-insulator-based micro ring resonator, utilized to construct a microwave photonic bandpass filter (MPBF). This MPBF effectively attenuates the side modes of the optoelectronic oscillator (OEO) by over 30 dB, thereby generating a peak RF signal that translates the detected optical changes into corresponding shifts in the oscillating frequency. Illustrated through an application example, this optical sensor system is deployed for temperature detection, showcasing experimental findings of a highly sensitive optical temperature sensor boasting a sensitivity of 7.7 GHz/°C. Additionally, the proposed sensing system exhibits a measurement resolution of 0.02 °C, representing a tenfold enhancement over the modest resolution of 0.23 °C offered by conventional MPBF systems lacking the OEO loop. This enhancement renders the system well-suited for a broad array of high-resolution sensing applications.

Saleh K et.al-2012[25]**:** Theoretical and experimental investigations have been conducted with the goal of mitigating the phase noise in a passive fibre ring resonator-based optoelectronic oscillator (OEO). A phase noise level of -128dBc/Hz at a 10 kHz offset frequency has been achieved in a 100m long passive-cavity OEO configuration. Remarkably, this result is comparable to that obtained in a 330m active-cavity coupled OEO. Further enhancements are conceivable if the noise from the laser and RF amplifiers can be minimized.

Pillet G et.al-2014[26]**:** optical frequencies can be independently and electrically tuned across a bandwidth exceeding 1 GHz. The fibre-ring resonator utilized in the setup spans 25 meters in length, boasting a quality factor close to 5.10^8. To stabilize one laser line, a PDH servo-controller locks it onto a resonance of the resonator. Meanwhile, the heterodyne beat note, which remains tunable through adjustment of the frequency of the other laser line, is locked utilizing an optical frequency-locked loop based on the same resonator. Consequently, the beat note is stabilized on the closest multiple of the resonator's free spectral range. At a frequency of 10 GHz, phase noise measurements revealed levels below -85dBc/Hz at a 10 kHz offset frequency.

Do P.T. et.al-2018[27]**:** This paper presents a 16 GHz-FSR silicon add-drop ring into an OEO system as a microwave photonic bandpass filter. With numerous optoelectronic components within the OEO loop, like the modulator and photodetector, now being standard features of silicon photonics tools, and with other elements such as the RF amplifier and filter easily manufacturable in CMOS lines, our study highlights the promise of fully integrated OEO systems on a single chip. This advancement not only underscores cost efficiency but also scalability, paving the way for expanded applications across various fields.

2.5 Research Objectives

After doing the deep literature survey on the past works related to OEO with WGM resonator, OEO with RTD-PD Laser diode and OEO with Micro Ring Resonator I found the following area of improvement and worked through that. Following are the objectives of the research work carried out for this thesis

1. Improve the Quality factor (Q) of Ring Resonator by increasing the width of ring wave guide and calculate the free spectral range (FSR) and Full width half maximum (FWHM) for different designs of silicon based micro ring resonator.

2. Obtain Stopband Rejection Ratio (SRR) of the microwave photonic filter and obtain good Sidemode Suppression Ratio (SMSR) to generate high purity of RF signal by using silicon micro ring resonator in the optoelectronic oscillator.

Chapter 3

DESIGN OF RING RESONATOR AND PERFORMANCE CHARACTERISTICS

3.1 Introduction

In recent years, the field of silicon photonics has seen rapid advancements in performance and capabilities, making it one of the most promising platforms for photonic integration. This technology combines the advantages of nanoscale electronics with broadband photonics. The design typically involves a looped waveguide paired with a straight waveguide, creating resonance when the optical path length of the silicon ring resonator matches an integer multiple of the wavelength. Silicon ring resonators in particular, are fascinating optical components with a wide range of applications, including communication, switching, healthcare, environmental monitoring, sensing, and medical diagnostics. For instance, they are used in optical parametric oscillators, which are light sources similar to lasers and are employed in laser spectroscopy and various other scientific applications.

The performance of a silicon ring resonator is evaluated using several parameters, including quality factor, full width half maximum, and free spectral range (FSR). These parameters are influenced by physical attributes such as the coupling ratio and the dimensions of the structure. To enhance these characteristics, simulated with different waveguide designs and materials. A high-quality factor signifies lower energy loss per cycle relative to the energy stored, meaning the resonances decrease more slowly. Both the coupling ratio and intrinsic optical loss significantly affect the quality factor. Consequently, the design and material composition of the ring resonator are crucial in determining its quality factor.

3.2 Design of Silicon Micro Ring Resonator

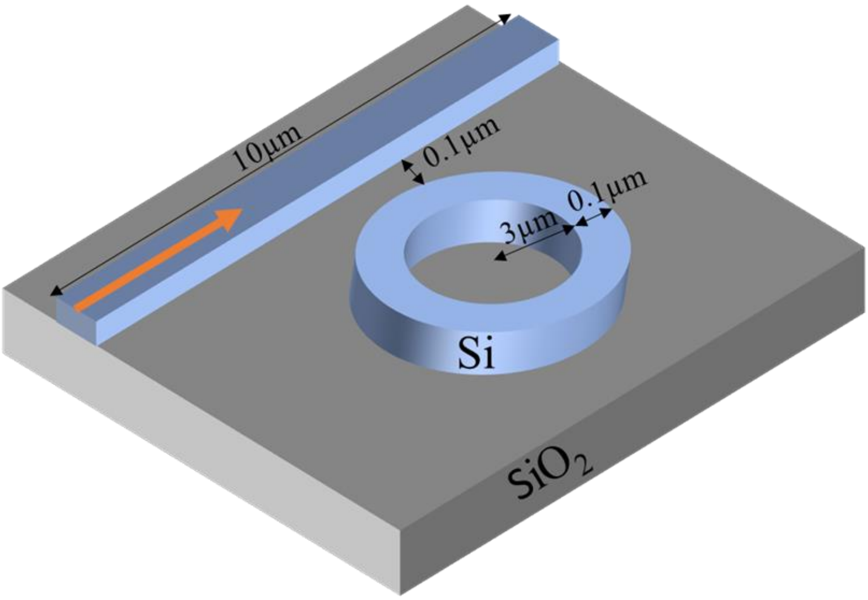


Figure 3. 1 Design of ring resonator with radius 3 µm and width 0.1 µm in 3D view

Figure 3.1 shows the design of silicon ring resonator with radius 3 µm, waveguide width is 0.1 µm and gap between waveguides is 0.1 µm. The coupling can be achieved through a small gap that allows evanescent coupling, where the light from the straight waveguide partially transfers into the ring and vice versa. Light from an input waveguide enters the ring resonator through evanescent coupling. When the optical path length of the ring is an integer multiple of the wavelength of the light, constructive interference occurs, and the light resonates within the ring. This condition is given by

$$L = m\lambda$$

Where L is the circumference of the ring, λ is the wavelength of light and m is an integer mode number.

At resonance, light constructively interferes within the ring, leading to a build-up of the optical field. Non-resonant wavelengths, which do not satisfy the resonance condition, are minimally coupled into the ring and primarily pass through the straight waveguide. The light within the ring can couple back into the straight waveguide at the coupling points. Because only resonant wavelengths build up in the ring, the output from the straight waveguide will have filtered out these specific wavelengths. This makes the ring resonator an effective filter for particular wavelengths. The key parameters are Free Spectral Range, Full Width Half Maximum and Quality Factor(Q). Free Spectral Range (FSR) is the wavelength separation between successive resonant peaks, defined as:

$$FSR = \frac{\lambda 2}{ngL}$$

The Full Width Half Maximum (FWHM) of a ring resonator is a measure of the bandwidth or spectral width of its resonance peak at half of its maximum intensity. It is an important parameter for assessing the performance and quality of the resonator. The quality factor or Q-factor, of a ring resonator is a dimensionless parameter that measures the efficiency of the resonator in terms of energy loss relative to the energy stored within it. A higher Q-factor indicates lower energy loss and sharper resonance peaks, making the resonator more efficient.

$$Q = \frac{\lambda 0}{\mathrm{FWHM}}$$

Where $\lambda 0$ is the resonant wavelength, FWHM is the full width at half maximum of the resonance peak.

3.3 Performance characteristics of Ring Resonator

This design proposed with radius of 3µm and ring waveguide width is 0.1µm and the gap between ring wave guide and straight waveguide is 0.1µm and total span of the ring resonator is taken as 10µm, with these dimensions the waveguides ring waveguide and straight waveguide are of the material Si placed on SiO_2 substrate and plotted the transmission spectrum of the light when laser source of 1550nm sent at the input and calculated parameters Free Spectral Range(FSR), Full Width Half Maximum(FWHM) and Quality factor(Q).

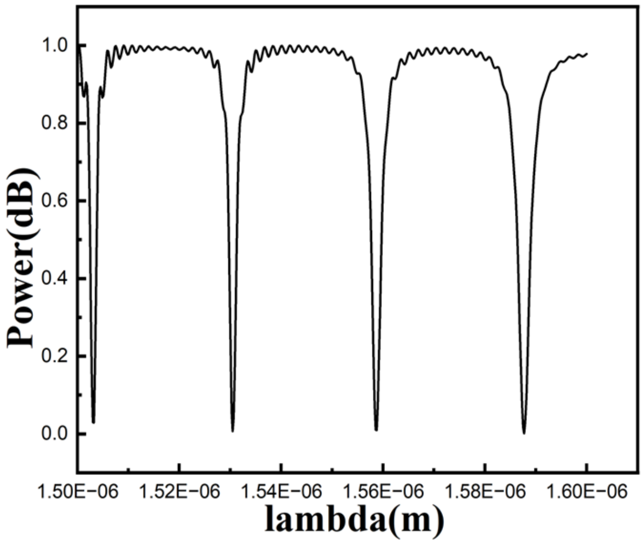


Figure 3. 2 Transmission spectrum of silicon ring resonator of FSR 30 nm, FWHM 1.5 nm and Q factor is 1300

Figure 3.2 shows that transmission spectrum and the obtained parameters are effective index(n_{eff}) is 2.3, group index(n_g) is 4.7, free spectral range is 30nm, Full width half maximum is 1.5nm. The quality factor(Q) is obtained is 1300.This is a very low-quality factor so resonant peak is not sharp so we need to further improve the quality factor of the ring resonator.

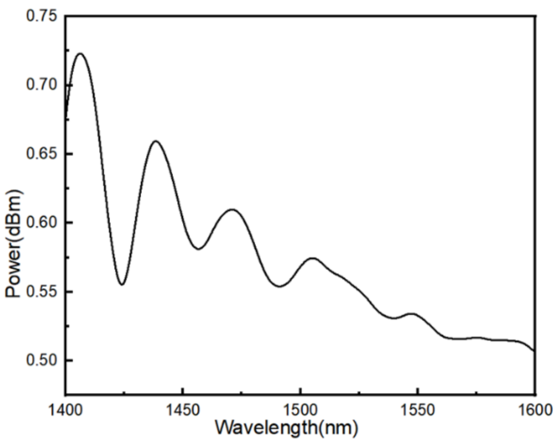


Figure 3. 3 Transmission spectrum of ring resonator with waveguide 0.18 µm width and input is 1550 nm

Figure 3.3 shows the transmission spectrum of design of ring resonator radius is 6.8 µm and the gap between the ring waveguide and straight waveguide is 0.78 µm and the width of the ring waveguide is 0.18 µm and the total span of the ring resonator is taken as 20 µm. At standard wavelength 1550nm if we simulate this design, we are getting full width half maximum is more and it is less resonance is occurring so that we can get lower Q quality factors which is not desirable.

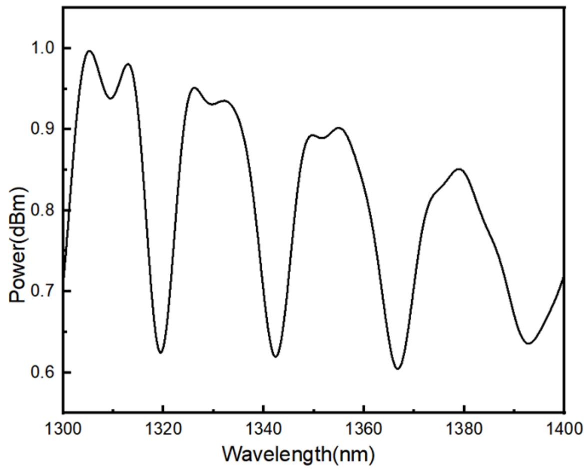


Figure 3. 4 Power spectrum of ring resonator 0.18 µm width and input is 1320 nm

Figure 3.4 shows the design is simulated with same specifications and parameters of the ring resonators and applied lower wavelength to the input with respect to standard wavelength so good resonance is occurring at lower wavelength like 1320nm so that it can give good Q quality factor because full width half maximum is lower.

3.4 Results and Discussion

In the design of the ring resonator width of the ring waveguide is varied to improve the quality factor so we will get a good resonance and sharp peak of the signal. That resonant sharp peak tells less full width half maximum and high-quality factor and from that we can say that there is a less loss of power so that maximum power is transmitted to the output port of the ring resonator. The high-quality factor ring resonator can be designed by varying the width of the ring wave guide and width of the straight waveguide. This is also possible by varying the gap between straight waveguide and ring waveguide. The different designs are discussed below nicely and obtained the results.

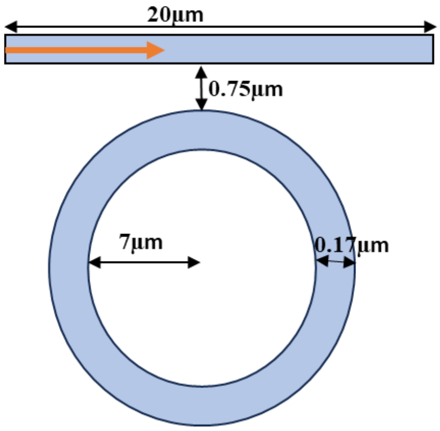
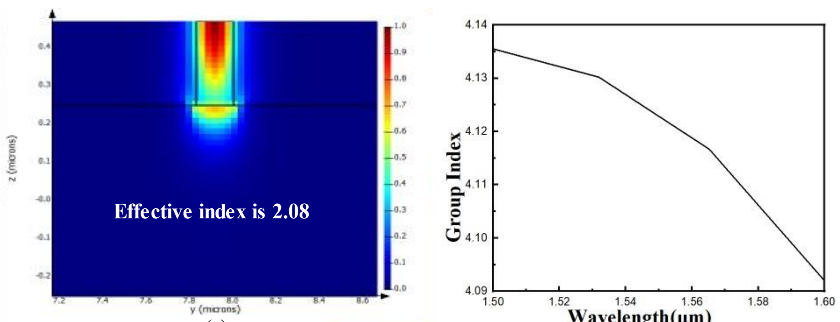


Figure 3. 5 Design of ring resonator with radius 7 µm and 0.17 µm of waveguide width in 2D view

This design of Figure 3.5 shows a radius increased to 7µm and the width of the ring waveguide is 0.17µm and the gap between straight waveguide and ring waveguide is 0.75µm and the span of the ring resonator is 20µm and the 1550nm laser source is applied at the input port and plotted mode profile, effective index, power loss and group index as below



(a) (b)

Figure 3. 6 (a)mode profile with effective index 2.08 (b)group index obtained is 4.13 with radius 7 µm and waveguide width 0.17 µm of silicon micro ring resonator

Figure 3.6(a) shows the mode profile of silicon ring resonator and from this plot we can get the parameter effective index 2.08. From figure 3.6(b) the obtained group index is 4.13 on applying 1550nm laser source to the input of ring resonator.

The transmission spectrum at the output port is plotted calculated the parameters.

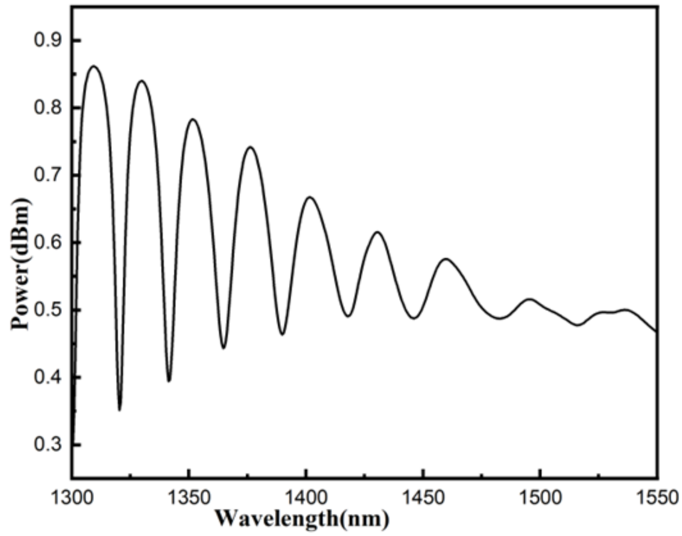


Figure 3. 7 Transmission spectrum of silicon ring resonator of free spectral range is 25 nm, FWHM is 1 nm and Q factor is 1500

Figure 3.7 shows transmission spectrum of silicon ring resonator. In this design free spectral range (FSR) is 25nm which is wavelength separation between two different resonant peaks and full width half maximum (FWHM) at 3dB frequency is 1nm and the Quality factor(Q) achieved is 1500. The quality factor in this design is improved from 1300 to 1500 which is also low-quality factor another design is proposed to improve the quality factor.

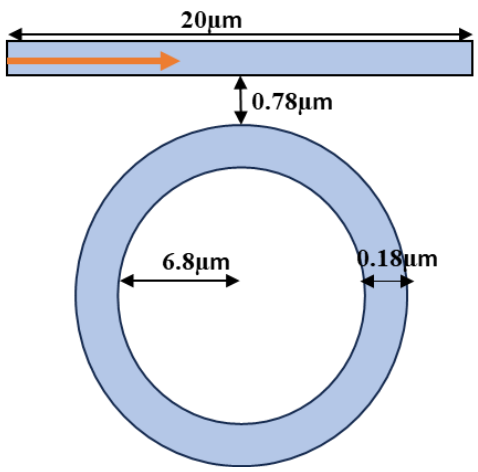


Figure 3. 8 Design of silico ring resonator with radius 6.8 µm and waveguide width 0.18 µm in 2D view

Figure 3.8 shows the design of silicon micro ring resonator which has a radius increased to 6.8µm and the width of the ring waveguide is 0.18µm and the gap between straight waveguide and ring waveguide is 0.78µm and the span of the ring resonator is 20µm and the 1550nm laser source is applied at the input port and plotted mode profile, effective index, power loss and group index as below

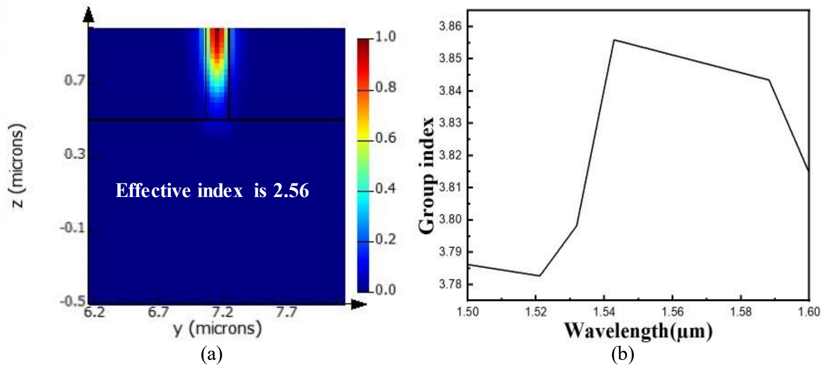


Figure 3. 9 (a)mode profile with effective index 2.08 (b) group index obtained is 3.86 with radius 6.8 µm and waveguide width 0.18 µm of silicon micro ring resonator

Figure 3.9(a) shows mode profile of silicon ring resonator, from this graph the obtained parameters are effective index is 2.56. Figure 3.9(b) plot of group index with respect wavelength and the obtained group index is 3.86 on applying the 1550nm laser source as input to ring resonator. The transmission spectrum at the output port and calculated the parameters.

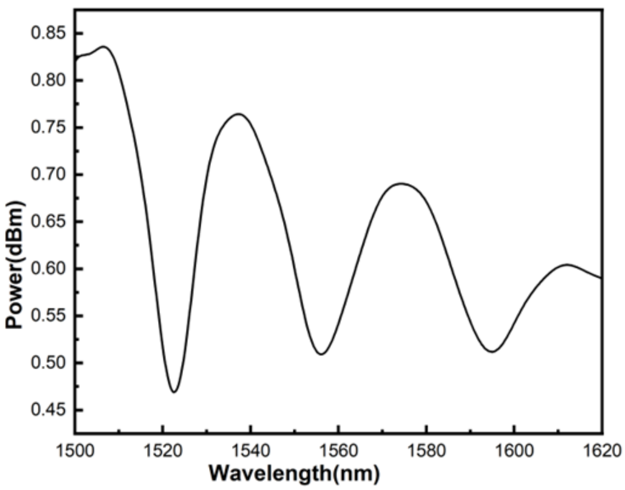


Figure 3. 10 transmission spectrum of silicon ring resonator of free spectral range is 38 nm, FWHM is 0.5 nm and Q factor is 3120

Figure 3.10 shows the transmission spectrum of silicon micro ring resonator. The extracted parameters from this design are free spectral range (FSR) is 38nm and full width half maximum (FWHM) is 0.5nm and thereby we got the quality factor(Q) is 3120 which tells how sharp the resonant peak and low loss of the signal.

3.5 Summary

Among all the designs of silicon-based ring resonators with different widths of silicon ring wave guide and different radius of the ring resonators are discussed here. The silicon-based ring resonator with the ring wave guide width 0.18µm and radius of silicon ring resonator with 6.8µm and the gap between the silico ring waveguide and straight silicon waveguide is with 0.78µm is considered which gives highest quality factor(Q) of 3120 which has very less loss of the signal and sharp resonance peak of the signal. This silicon ring resonator acts as a micro wave photonic filter in the Optoelectronic Oscillator loop so this design of Silicon Ring Resonator will be used in the Optoelectronic Oscillator.

Chapter 4

OPTOELECTRONIC OSCILLATOR WITH RING RESONATOR

4.1 Introduction

A ring resonator-based optoelectronic oscillator (OEO) represents a sophisticated integration of photonics and electronics, harnessing the unique properties of optical resonators to generate high-frequency microwave signals with exceptional stability and low phase noise. Unlike traditional electronic oscillators, which depends on electronic components, a ring resonator-based OEO utilizes an optical feedback loop. This loop incorporates a ring resonator to provide high-quality optical filtering, which significantly enhances the performance of the oscillator. The inclusion of the ring resonator allows for the efficient modulation and stabilization of the optical signal, which is then converted into a microwave signal. OEOs used in applications requiring strong performance standards, such as in radar systems, communication networks, and various advanced sensing technologies.

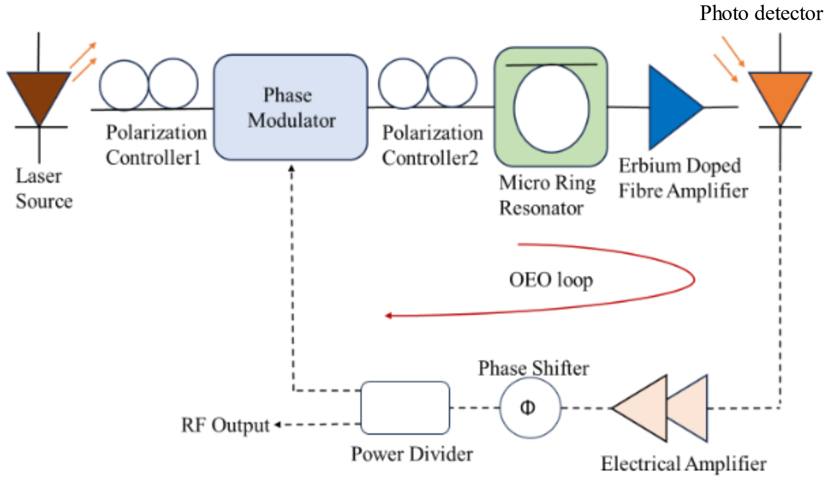


Figure 4. 1 Schematic diagram of micro ring resonator based OEO

4.2 Proposed Design of OEO with Ring Resonator

4.2.1 Design and Principle of Operation

The Optoelectronic Oscillator is a circuit which produces a repetitive Radio Frequency signal or modulated optical continuous wave signal thus optoelectronic oscillator works based on converting continuous light energy from a laser source to radio frequency or mm-wave signal.

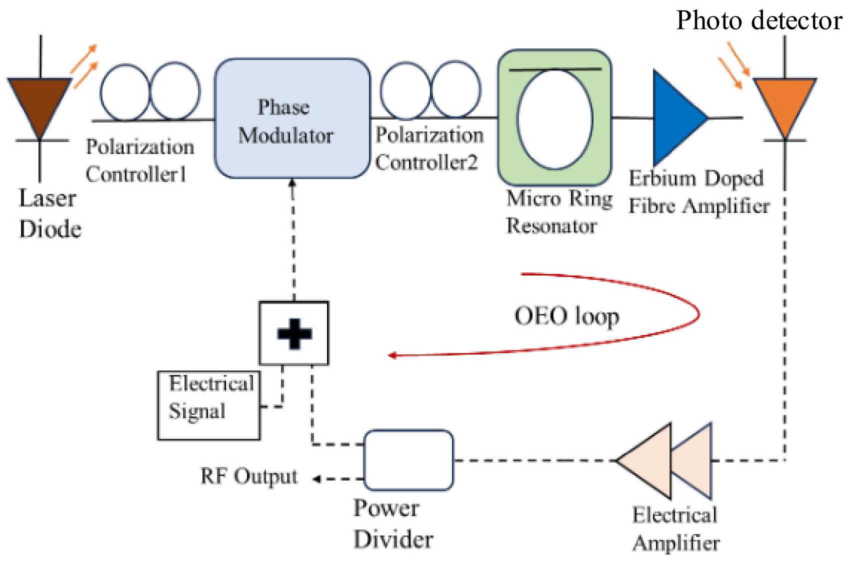


Figure 4. 2 Proposed design of Micro ring resonator based OEO

4.2.2 Analysis of Optoelectronic Oscillator

The principle of operation of a ring resonator-based optoelectronic oscillator (OEO) revolves around the utilization of an optical feedback loop, which incorporates a ring resonator to generate stable and high-purity microwave signals. The system begins with a continuous wave (CW) laser that serves as the optical source. This laser provides a stable light signal at a specific wavelength. The optical signal from the laser is fed into a modulator, typically an electro-optic modulator (EOM). An electrical signal, usually derived from the output of the OEO itself, modulates the light. This modulated optical signal carries the information of the desired microwave frequency. The modulated optical signal enters a ring resonator, which is a key component of the OEO. The ring resonator acts as an optical filter with a high-quality factor (Q-factor), allowing only specific wavelengths (or frequencies) of light to resonate within it. This selective resonance enhances the purity and stability of the optical signal. After passing through the ring resonator, the optical signal travel through an optical delay line. This delay line extends the effective length of the optical path, which improves the spectral purity and phase noise characteristics of the generated microwave signal. The filtered and delayed optical signal is then converted back into an electrical signal using a photodetector. The photodetector produces a microwave signal corresponding to the modulation frequency of the optical signal. The electrical microwave signal from the photodetector is amplified and fed back into the electro-optic modulator, completing the loop. This feedback loop is crucial for sustaining oscillations. A portion of the amplified microwave signal is extracted as the output of the OEO. This output can be used in various applications, such as radar systems, communications, and sensing technologies. Throughout this process, the ring resonator plays a pivotal role in ensuring that only the desired frequencies are amplified and fed back, thereby achieving a highly stable and low phase noise microwave signal. The combination of optical filtering, delay, and feedback results in an OEO with superior performance compared to traditional purely electronic oscillators. Optoelectronic oscillator (OEO) is an ideal signal source that can generate microwave signals with high spectral purity (the side-mode suppression ratio can reach > 60 dB) and low phase noise (currently, the lowest can reach −163dBc/Hz@10 kHz).

4.3 Microwave Photonic Filter (MPF)

In this design of optoelectronic oscillator, the electrical signal is added to optoelectronic oscillator loop and plotted the response of optoelectronic oscillator and microwave photonic filter (MPF) which is ring resonator acts as microwave photonic filter. calculated parameters like stopband rejection ratio (SRR) which is the ratio of passband amplitude of the signal to the stopband amplitude of the signal. In this design of optoelectronic oscillator ring resonator acts as bandpass microwave photonic filter. The parameter sidemode suppression ratio (SMSR) which is the ratio of resonant frequency peak amplitude to the immediate nearest side mode amplitude which we can get from the response of optoelectronic oscillator. The response of bandpass microwave photonic filter is plotted as

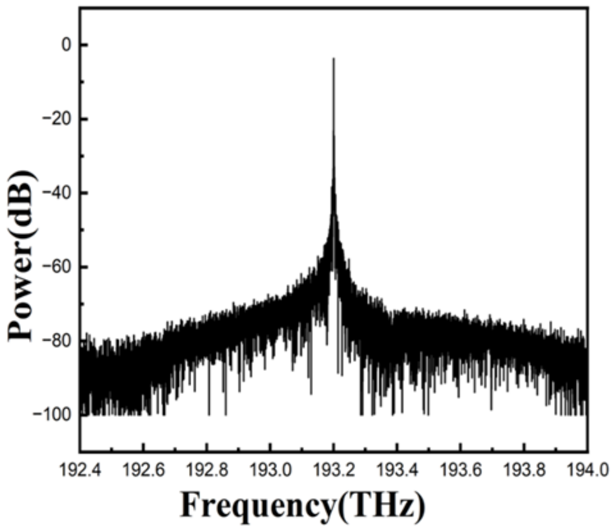


Figure 4. 3 response of microwave photonic filter

Here we can calculate the parameters, that the measured frequency response of microwave photonic filter (MPF) when input applied an optical carrier with a fixed wavelength of 1550nm. The 3dB bandwidth of microwave photonic filter at a centre frequency of 193.1THz is 100MHz. The amplitude ratio of passband to closest stopband is called stopband rejection ratio (SRR) and the measured SRR is 12dB. Now we can calculate the power of the signal and side mode suppression ratio (SMSR) which is the ratio of peak amplitude of resonant frequency to the closest side mode peak amplitude and we can also get at what time oscillations are starting. To get all these parameters like power, SMSR we need to plot the optoelectronic oscillator response. The standard laser source applied at the input is 1550nm and we get electrical signal spectrum from photodetector which is plotted through RF spectrum analyser is plotted as below.

4.4 Results and Discussion

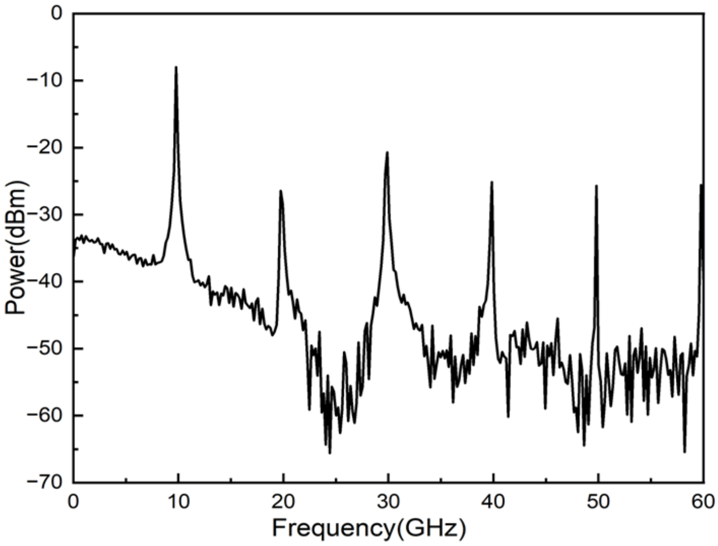


Figure 4. 4 The electrical spectrum OEO

This is the plot of the response of optoelectronic oscillator from this we can calculate the power of the signal and sidemode suppression ratio (SMSR). The calculated power of the generated optoelectronic signal is -6dBm and we calculated the side mode suppression ratio (SMSR) is 30dB.

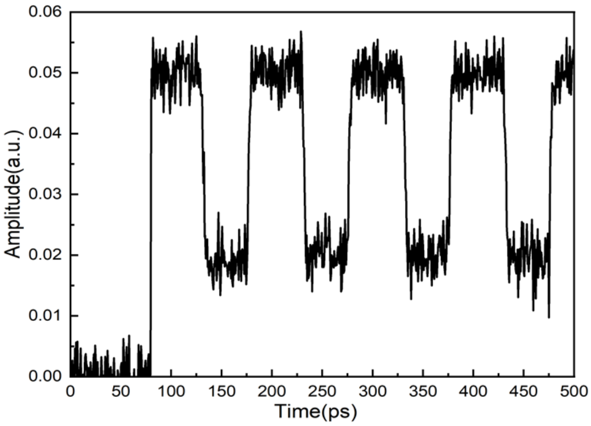


Figure 4. 5 Timing diagram oscillations of OEO

From this graph we can say that at what time the oscillations are starting. The resonant frequency signal oscillations are starting at nearly from 80ps. In this design simulation we got side mode suppression ratio is 30dB which is very less and the resonant peak of the signal is not sharp which tells that there is loss in RF signal generated through optoelectronic oscillator. So further we need to increase the power of the laser from zero dBm to some positive number and we also need to adjust responsivity of the photodetector and plot the response of optoelectronic oscillator. Now we have increased the power 1550nm laser source from zero dBm to 20dBm and also increased the responsivity of photodetector to 5 A/W and adjusted the frequency of modulator to desired frequency and ring resonator in this design acts bandpass microwave photonic filter and plotted the response of microwave photonic filter as below.

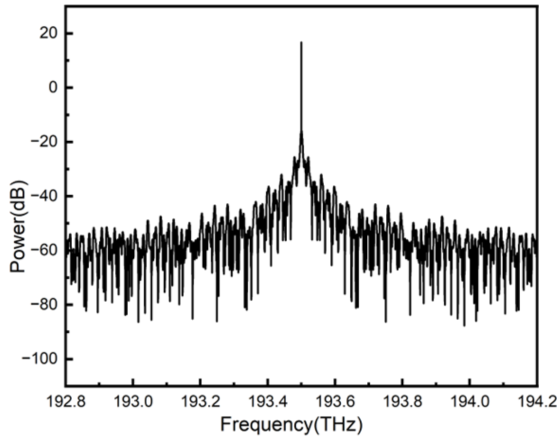


Figure 4. 6 The frequency response of bandpass MPF

From this we can extract the parameters such as stopband rejection ratio (SRR) and power of the signal. Therefore, the power of the signal estimated is 18dBm and the stopband rejection ratio (SRR) is 40dB. Now we can see the response of optoelectronic oscillator and we need to calculate SMSR. The response optoelectronic oscillator is plotted as

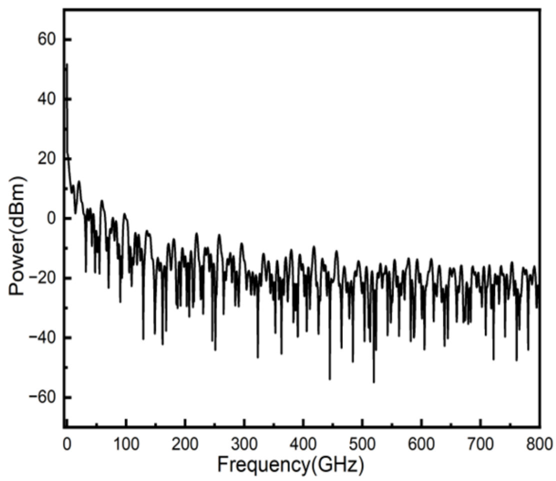


Figure 4. 7 Electrical spectrum of OEO

This graph shows the RF spectrum of optoelectronic oscillator here the resonant frequency is at zero GHz and its power is 50dBm and side mode suppression ratio (SMSR) is 40dB. To improve the parameters like side mode suppression, power and stopband rejection ratio we need to adjust the power of laser source and responsivity of the photodetector and plot the response of microwave photonic filter and optoelectronic oscillator to improve purity of signal. As high as side mode suppression ratio is there that much purity will be the signal. Now change the power of laser source to 20dBm and responsivity to 1 A/W and do simulation and plot the graphs. The response of microwave photonic filter is as below

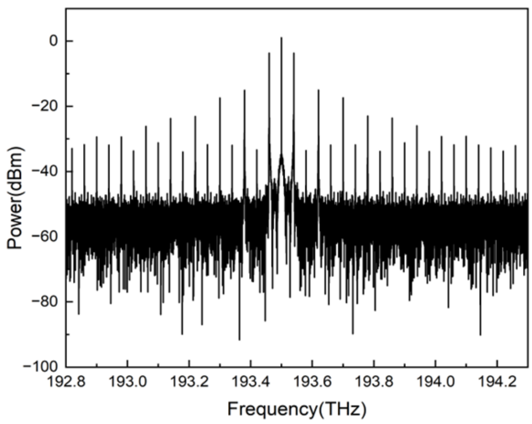


Figure 4. 8 Response MPF of proposed design

From this graph we can extract the parameters power of the signal and stopband rejection ratio (SRR). At centre frequency 193.5 THz the stopband rejection ratio of the signal is 50dB

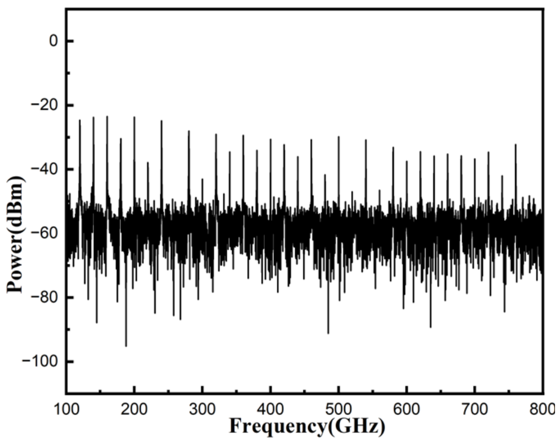


Figure 4. 9 The electrical spectrum of OEO at oscillating frequencies

This is the final optoelectronic oscillator response, from this the parameters can be calculated as the power of the signal is -15 dBm and the purity of signal can be measured by side mode suppression ratio which is calculated from the graph as SMSR is 45dB.

Now we introduce bandpass filter in the feedback loop of the optoelectronic oscillator to reduce the noise and also extract the side mode suppression ratio and power of the oscillating signal. The proposed design with bandpass filter as below

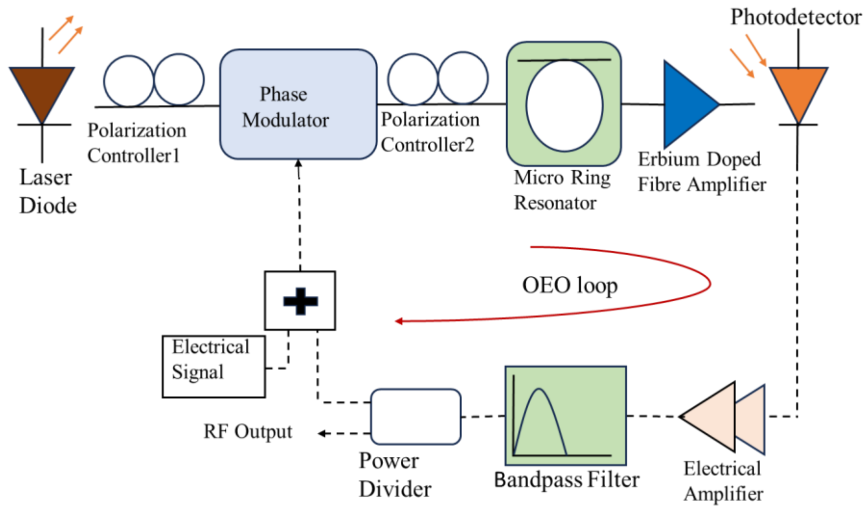


Figure 4. 10 Proposed design of Micro ring resonator based OEO with bandpass filter

In this we have inserted bandpass filter in the loop and simulated plotted the response of the optoelectronic oscillator and extract the required parameters like side mode suppression ratio and power of the oscillating signal at resonant frequency and it can be plotted as

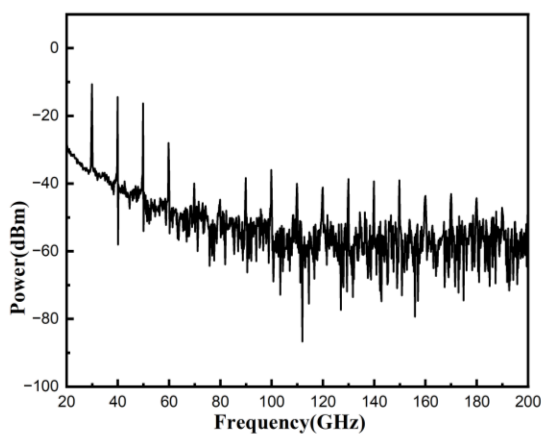


Figure 4. 11 Response of OEO with bandpass filter

The power of the signal at oscillating frequency of 30GHz is -10dBm and the side mode suppression ratio estimated from this graph is 49dB which is a very sharp RF signals are generated with less losses.

4.5 Summary

In this study ring resonator was introduced in path of optoelectronic oscillator to provide microwave photonic filter action and there to generate high purity signal of radio frequency signal. Which is possible with high quality factor of ring resonator. In this study of ring resonator high quality factor of 3120 is achieved and stopband rejection ratio of 12 dB is obtained and side mode suppression ratio 45dB is achieved and further by increasing the power of laser source to 20dBm we achieved optoelectronic oscillator response calculated SMSR is 49dB and by introducing bandpass filter in the feedback loop of optoelectronic oscillator the power of the signal obtained is -10dBm and amplitude of the noise signal is reduced. To get high purity signal we need to achieve more than 3120 quality factor of ring resonator and adjusting the frequency of modulator we can generate purity RF signal.

Chapter 5

CONCLUSION AND FUTURE SCOPE

In summary, the design of silicon ring resonator with a radius of 3 μm and the width of the waveguide 0.1 μm is designed to achieve quality factor of 1300 which is a very less quality factor. So further different designs of silicon ring resonator are studied. Now the radius of silicon-based ring resonator is 7 μm, the width of the waveguide is 0.17 μm and the gap between straight waveguide and ring waveguide is 0.75 μm in this design quality factor 1500, free spectral range is 25 nm and FWHM is 1 nm are obtained. To improve quality factor silicon ring resonator is now designed with 6.8 μm radius, 0.18 μm width and 0.78 μm is the gap between wave guides and achieved free spectral range is 38 nm, FWHM is 0.5 nm and quality factor obtained is 3120. Opto-Electronic Oscillator (OEO) utilizing a high-Q silicon Micro-Ring Resonator (MRR) and silicon di oxide substrate has been proposed and successfully demonstrated. The MRR exhibits a Full Width at Half Maximum (FWHM) of 1nm, resulting in a Q-factor of 3120. Integrating this into a phase-modulated link enables a 30 GHz Microwave Photonic Filter (MPF) with a 3-dB bandwidth of approximately 100MHz. This tunable MPF facilitates the creation of an OEO that operates with the 30 GHz frequency. The Side Mode Suppression Ratio (SMSR) of the 30GHz oscillation signal is 45dB.

The future scope of optoelectronic oscillators (OEOs) involves several key areas of advancement. One primary focus is to reduce the phase noise of the signal which can be possible up to -163 dB c/Hz with high SMSR greater than 60dB. Improving integration levels to create more compact and efficient devices. Enhanced integration can lead to better performance, reduced power consumption, and lower production costs. Additionally, efforts will be directed towards minimizing phase noise further, which is critical for applications requiring high signal purity and stability.

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