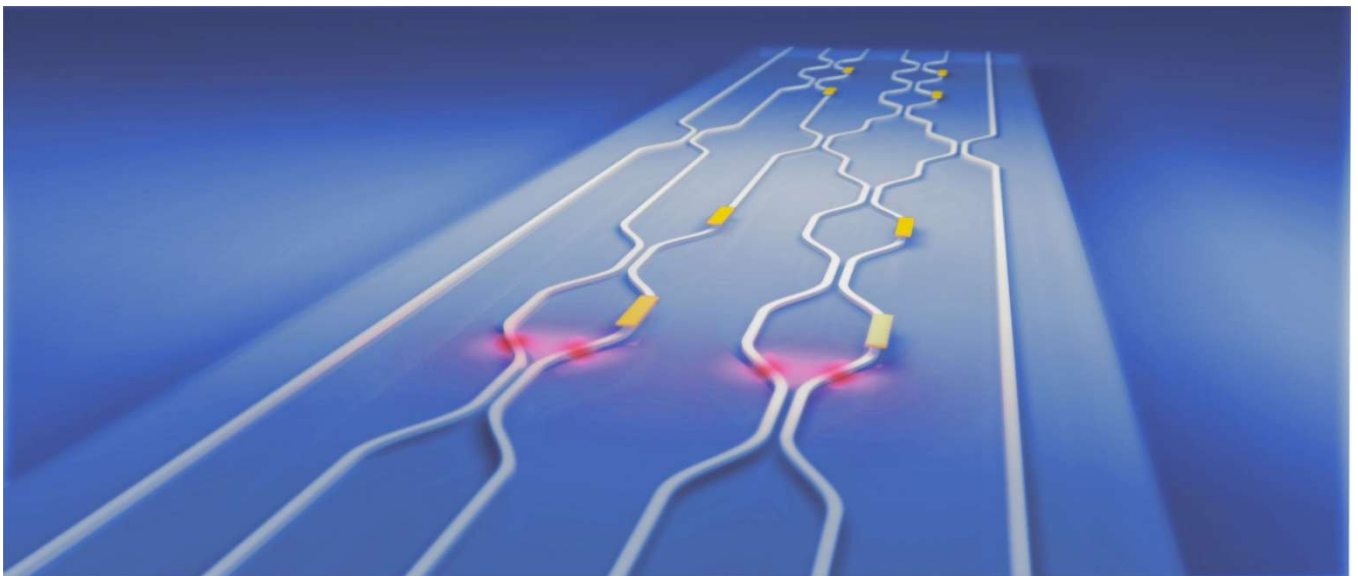


PHOTOCON 2026

The Photonic Conference Of Politecnico Di Milano



POLITECNICO
MILANO 1863



27 May 2026
Conference Proceedings

OVERVIEW



What PhotoCon is and what its goals are.

Photocon 2026 is the first edition of a new Photonic Conference organized by Politecnico Di Milano's students and professors. Everyone who has a passion for Photonics or anything that revolves around this world is highly invited to participate to this event. The goal is to get together to share the knowledge and find out something new about Photonics.

TPC BOARD



Members of the steering committee.



Andrea Ivano Melloni

FULL PROFESSOR
-
GENERAL CHAIR



Andres Ivan Martinez Rojas

RESEARCH FELLOW
-
PROGRAM CHAIR



Alessandro Ettore

MSC STUDENT IN TELECOMMUNICATION
ENGINEERING
-
PROGRAM COMMITTEE
-
ETTORE@PHOTOCON2026.COM



Luca Grossi

MSC STUDENT IN TELECOMMUNICATION
ENGINEERING
-
PROGRAM COMMITTEE
-
GROSSI@PHOTOCON2026.COM



Marion Henriot

MSC STUDENT IN TELECOMMUNICATION
ENGINEERING
-
PROGRAM COMMITTEE
-
HENRIOT@PHOTOCON2026.COM

PRESENTATION



When and where the papers' presentation will take place

Teams will present their research on 27 May 2026 at 12:30 in the Conference Room of Building 20A. Each group will have a total of 12 minutes to showcase their paper, questions included.

PROGRAM



Conference program and time allocated for each activity

12:40 Welcome

12:45 - 13:00 : Plenary by Prof. Francesco Morichetti on Chips JU pilot line projects in photonics

Chair: Alessandro Ettore

13:00 - 13:12 : Simulation Study Of A Graphene-On-Silicon Microring Resonator Photodetector (L. Polverari, R. Jafari, M. Cargnelutti)

13:12 - 13:24 : Basic Principles And Fabrication Of Distributed Feedback Lasers (A. Comana, M. Ricciotti)

13:24 - 13:36 : Photodetector Basics And Application In DQPSK Receivers (G. Lori, P. Ricci)

13:36 - 13:45 : BREAK

Chair: Marion Henriot

13:45 - 14:00 : Invited talk: Lorenzo Zerboni on 3D printed microstructures for photonics

14:00 - 14:12 : From Modulators to Biosensing: Silicon Micro-Ring Resonators For Bio-Chemistry Applications (M. Malagrino', R. Brizzi)

14:12 - 14:24 : Optical Satellite Communications (A. Sau, D. Misani)

14:24 - 14:36 : Silicon Photonic Micro-Ring Resonator Biosensors: Principles, Performance, and Biomedical Applications (K. Khodami)

Awards & Cheers

The best paper will be awarded the final prize and then we'll celebrate together the end of the conference!

Simulation Study Of A Graphene-On-Silicon Microring Resonator Photodetector

Livia Polverari
DEIB
Politecnico di Milano
livia.polverari@mail.polimi.it

Razia Jafari
DEIB
Politecnico di Milano
razia.jafari@mail.polimi.it

Marta Cargnelutti
DEIB
Politecnico di Milano
marta.cargnelutti@mail.polimi.it

Abstract

Graphene photodetectors provide broadband operation and ultrafast carrier response but suffer from weak optical absorption and limited responsivity. This work presents a MATLAB-based simulation study of graphene and germanium photodetectors integrated on a silicon microring resonator platform. Optical transmission characteristics, enhancement factor, responsivity, and noise-equivalent power are analyzed and compared. The results show that resonant cavity enhancement significantly improves detector sensitivity and wavelength selectivity while highlighting the distinct operating characteristics of graphene and germanium photodetectors for compact and high-performance photonic integrated systems.

I. INTRODUCTION

Integrated silicon photonics has become an important technology for high-speed optical communication and photonic integrated systems. Graphene has attracted significant attention for photodetection because of its broadband optical response, ultrafast carrier dynamics, and compatibility with complementary metal-oxide-semiconductor technology. However, the atomic thickness of graphene results in weak interaction with guided optical modes and consequently limits optical absorption and detector responsivity.

Microring resonators offer an effective approach for increasing light confinement and enhancing light-matter interaction within compact dimensions. Under suitable coupling conditions, optical absorption inside graphene can be significantly increased. In this work, MATLAB simulations are employed to investigate the behavior of a graphene-on-silicon microring photodetector and analyze the effect of different device parameters on detector performance.

II. STRUCTURE AND OPERATING PRINCIPLE

The proposed detector consists of a single-layer graphene channel integrated on a silicon microring resonator fabricated on a silicon-on-insulator platform. The graphene layer is encapsulated using hexagonal boron nitride (hBN) to improve carrier mobility and reduce environmental effects. Source and drain metal contacts are connected to the graphene region for electrical signal extraction, while split-gate electrodes independently control the carrier concentration and form the p-n junction necessary for photo-thermoelectric operation. Fig. 1 illustrates the device structure.

The operating principle combines optical resonant enhancement and the photo-thermoelectric effect. Input light propagating through the bus waveguide couples into the microring resonator and circulates inside the cavity at resonance wavelengths.

$$m\lambda = n_{eff}L \quad (1)$$

where m is the resonance order, n_{eff} is the effective refractive index, and L denotes the optical path length. Constructive interference occurs when the cavity satisfies the resonance condition, increasing the optical field intensity within the resonator and enhancing light-matter interaction. Maximum optical absorption occurs under critical coupling conditions:

$$\xi = 1 - \kappa \quad (2)$$

where ξ denotes the round-trip transmission coefficient and κ represents the coupling coefficient. The round-trip propagation loss inside the resonator can be expressed as

$$\xi = e^{-W\alpha_{SLG}} e^{-2\pi R\alpha_{WG}} \quad (3)$$

where W is the graphene coverage length, α_{SLG} is the graphene attenuation coefficient, R denotes the ring radius, and α_{WG} represents the waveguide attenuation coefficient.

The photoresponse mechanism relies on the photo-thermoelectric effect. Absorbed optical energy heats carriers inside graphene, generating hot electrons and a temperature gradient across the p-n junction region:

$$V_{PTE} = \int S(x) \nabla T_e(x) dx \quad (4)$$

where S denotes the Seebeck coefficient and T_e represents electron temperature. The wavelength-dependent transmitted optical power of the resonator is given by

$$P_{trans} = P_{in} \frac{(1 - \kappa) + \xi - 2\sqrt{(1 - \kappa)\xi} \cos(\theta)}{1 + (1 - \kappa)\xi - 2\sqrt{(1 - \kappa)\xi} \cos(\theta)} \quad (5)$$

where P_{in} is the input optical power and θ represents the round-trip phase shift.

The enhancement factor $EF(\lambda)$ characterizes the increase in light-matter interaction inside the microring resonator due to resonant cavity confinement. The higher intra-cavity energy density within the resonator enhances the optical field and increases the interaction between the guided optical mode and graphene.

The detector performance is further characterized by responsivity, which represents the efficiency of converting optical power into electrical output. For graphene photo-thermoelectric photodetectors, voltage responsivity is defined as

$$R_V = \frac{V_{PTE}}{P_{in}} = \frac{\Delta S \cdot \Delta T_e(\lambda)}{P_{in}} \quad (6)$$

where R_V denotes voltage responsivity, V_{PTE} is the generated photo-thermoelectric voltage, and P_{in} represents the incident optical power.

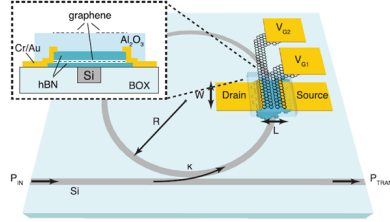


Fig. 1: Schematic structure of the graphene-on-silicon microring resonator photodetector.

III. SIMULATIONS

A. Simulation set-up

In order to demonstrate the benefits and performance improvements of the proposed device, a numerical model is implemented in MATLAB. The simulation is based on the Transfer Matrix Method (TMM) applied to the intra-cavity graphene-on-silicon microring resonator photodetector. The first technology presented here uses material properties, dimensions, and parameters taken from [1], ensuring a physically consistent model. All extracted parameters are reported in Table I. As indicated by the footnotes, the group index n_g and effective index n_{eff} are derived from the experimentally measured FSR. This self-consistent extraction ensures that the simulated resonance wavelength matches the experimental value of 1553.55 nm.

TABLE I: Simulation and Experimental Physical Parameters of the Graphene-on-Ring Photodetector

Parameter Details		
Description	Symbol	Value
Ring Radius	R_{ring}	40 μm
Resonance Wavelength	$\lambda_{res}^{a,b}$	1553.55 nm
Free Spectral Range	FSR^a	1.45 nm
Group Index	$n_g^{a,b}$	4.274
Effective Index	$n_{eff}^{a,b}$	2.874
Waveguide Propagation Loss	α_{WG}^a	1.4 dB/cm
Power Coupling Coefficient	$(\kappa^2)^a$	0.10
Graphene Absorption Coeff.	α_{SLG}^a	0.07 dB/ μm
Optimal Graphene Window	W_{opt}^a	6 μm
Peak Voltage Responsivity	$R_{PTE,peak}^a$	90 V/W
Seebeck Coeff. Difference	ΔS	200 $\mu\text{V/K}$
Ambient Temperature	T_0	294 K

^aFrom [1] experimental data.

^b $n_g = \lambda_{res}^2 / (FSR \cdot L)$; $n_{eff} = n_g + \lambda dn/d\lambda$, correction ≈ -1.40 from [1].

B. Responsivity and Enhancement factor

One key figure of merit of the device is the spectral selectivity of the responsivity. As described in the previous section, in (6), the responsivity of the device is function of the wavelength. If we first consider the case of a simple isolated graphene photodetector, without the ring, although ΔT_e depends in principle on the quantum efficiency and therefore on wavelength, graphene's absorption coefficient α_{SLG} is nearly wavelength-independent, making this dependence negligible in practice. As a result, $R_{V,0}$ is approximately constant across the telecom band, as shown by the blue line in Fig. 2, providing no wavelength selectivity.

On the other hand, when the graphene is integrated inside a silicon microring resonator, the circulating optical field is resonantly enhanced by the intracavity enhancement factor $EF(\lambda)$, increasing the absorbed power at resonance by EF_{peak} times. The responsivity obtained with the ring is therefore:

$$R_{V,\text{ring}}(\lambda) = R_{V,0} \cdot EF(\lambda) \quad (7)$$

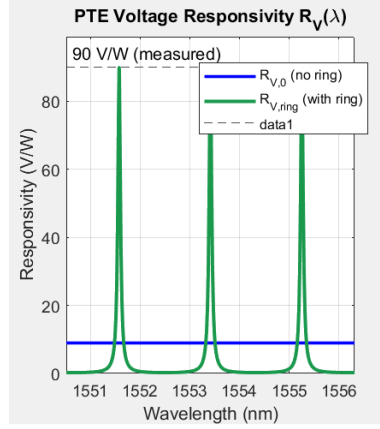


Fig. 2: Voltage responsivity R_V vs. wavelength. Blue: $R_{V,0} \approx 9 \text{ V/W}$ without ring (flat, broadband). Green: $R_{V,\text{ring}}$ peaking at 90 V/W at each resonance ($EF_{\text{peak}} = 10\times$). Dashed: measured value from [1].

As shown in "Fig. 2", $R_{V,\text{ring}}$ reaches 90 V/W at each resonance (a $10\times$ improvement over $R_{V,0} \approx 9 \text{ V/W}$) while remaining near zero off-resonance.

Fig. 3 shows the through-port transmission $T(\lambda)$ and the enhancement factor $EF(\lambda)$ at $W = 6 \mu\text{m}$. The dip at the at λ_{res} reaches -40 dB , confirming a near-perfect critical coupling, while $EF_{\text{peak}} = 10\times$ drives a proportionally larger PTE voltage.

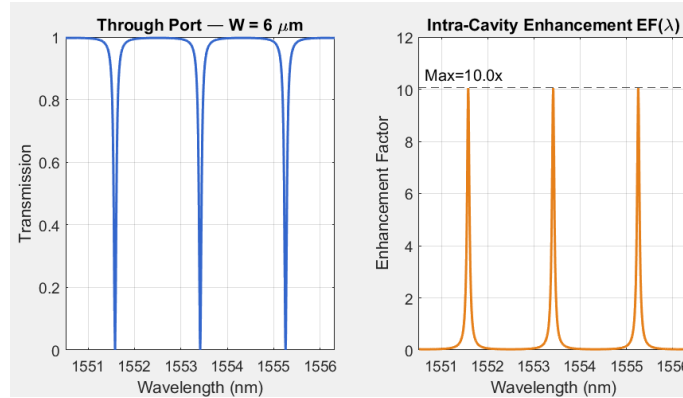


Fig. 3: Left: through-port $T(\lambda)$ at $W = 6 \mu\text{m}$, showing -40 dB extinction at critical coupling. Right: $EF(\lambda)$ peaking at $10\times$ at the same resonance wavelengths.

C. Noise Equivalent Power of Graphene PTE Detector

For the graphene PTE detector operating at zero bias, the dominant noise mechanism is Johnson thermal noise from the single layer graphene channel resistance $R_G \approx 800 \Omega$ [1]:

$$v_{\text{noise}} = \sqrt{4k_B T R_G} \quad (8)$$

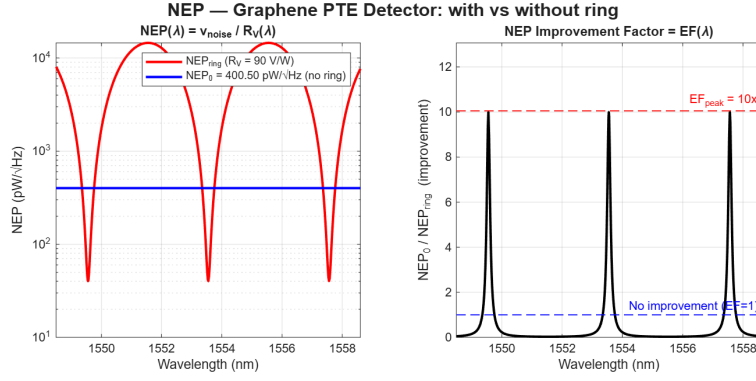


Fig. 4: NEP of the graphene PTE detector. Left: $NEP(\lambda)$ in $\text{pW}/\sqrt{\text{Hz}}$, showing sharp minima at each resonance wavelength with periodicity equal to the FSR of 1.450 nm. Right: NEP improvement factor, confirming $NEP_0/NEP_{ring} = EF(\lambda) = 10\times$ at resonance.

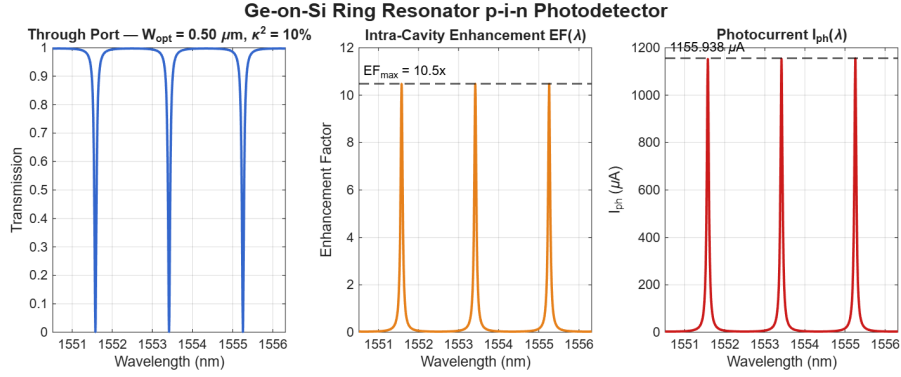


Fig. 5: Spectral response of the Ge-on-Si ring resonator p-i-n photodetector. Left: through port transmission with $W_{opt} = 0.50 \mu\text{m}$. Center: enhancement factor $EF_{max} = 10.5\times$. Right: photocurrent $I_{ph}(\lambda)$ with peak value of $1155.938 \mu\text{A}$ at $P_{in} = 1 \text{ mW}$.

Since Johnson noise is independent of optical input power and of the ring enhancement factor, any improvement in responsivity due to the cavity translates directly into an equivalent NEP improvement.

Without the ring, the flat baseline responsivity $R_0 = 9.0 \text{ V/W}$ yields a wavelength-independent NEP floor of $NEP_0 = 400.50 \text{ pW}/\sqrt{\text{Hz}}$. With the ring, the NEP acquires a strong wavelength dependence:

$$NEP_{ring}(\lambda) = \frac{NEP_0}{EF(\lambda)} \quad (9)$$

At $\lambda_{res} = 1553.55 \text{ nm}$, where $EF_{max} = 10\times$, the NEP drops to $\approx 40 \text{ pW}/\sqrt{\text{Hz}}$, a tenfold improvement achieved purely through optical field enhancement, with no modification of the detector material or bias conditions.

D. Noise Equivalent Power of Ge p-i-n Detector

The Ge p-i-n detector produces a photocurrent. The noise is dominated by shot noise from the dark current and Johnson noise from the load resistance $R_{load} = 50 \Omega$:

$$i_{noise} = \sqrt{2qI_{dark} + \frac{4k_B T}{R_{load}}} \quad (10)$$

with NEP defined as:

$$NEP_{Ge}(\lambda) = \frac{i_{noise}}{R_{Ge}(\lambda)} \quad (11)$$

where $R_{Ge}(\lambda) = EQE_{Ge} \cdot q\lambda/hc$ is the current responsivity computed using the absorption model with $\alpha_{Ge} = 0.8 \text{ dB}/\mu\text{m}$. Critical coupling is reached at $W_{opt} = 0.50 \mu\text{m}$, significantly shorter than the $6 \mu\text{m}$ of graphene, reflecting the higher absorption coefficient of germanium on the Silicon-On-Insulator waveguide.

Without the ring, the Ge detector NEP floor is $NEP_0^{Ge} = 163609.588 \text{ fW}/\sqrt{\text{Hz}}$. With the ring, the same $10.5\times$ improvement applies, reducing the NEP to $\approx 15582 \text{ fW}/\sqrt{\text{Hz}}$ at resonance.

E. Graphene vs Germanium — Direct Comparison

Table II summarizes the main performance metrics and device characteristics for both detector architectures implemented on the same SOI ring platform.

TABLE II: Comparison of Graphene PTE and Ge p-i-n Ring Detectors

Parameter	Graphene PTE	Ge p-i-n
Output quantity	Voltage [V/W]	Current [A/W]
Peak responsivity	90 V/W	0.1102 A/W
Noise mechanism	Johnson voltage	Shot + Johnson
NEP_0 (no ring)	400.50 pW/ $\sqrt{\text{Hz}}$	163609 fW/ $\sqrt{\text{Hz}}$
NEP_{min} (ring)	≈ 40 pW/ $\sqrt{\text{Hz}}$	≈ 15582 fW/ $\sqrt{\text{Hz}}$
NEP improvement	10 $\times$	10.5 $\times$
Bias required	Zero bias	Reverse ~ 1 V
Dark current	Zero	0.12 nA
W_{opt}	6 μm	0.50 μm
Cutoff wavelength	None (broadband)	1880 nm
TIA required	No	Yes

The most significant practical distinction lies in the readout architecture. Converting to consistent units, $NEP_0^{Ge} = 163609$ fW/ $\sqrt{\text{Hz}} = 163.6$ pW/ $\sqrt{\text{Hz}}$, comparable to the graphene baseline of 400.50 pW/ $\sqrt{\text{Hz}}$. Despite the fundamentally different noise mechanisms, both detectors exhibit similar absolute sensitivity at 1550 nm, with the ring providing the same relative improvement of approximately 10 $\times$ in both cases. The Ge detector requires a transimpedance amplifier (TIA) to convert photocurrent to voltage, introducing additional power consumption and circuit complexity [1]. The graphene PTE detector directly generates a voltage, which is particularly advantageous for energy-constrained applications such as on-chip optical interconnects in data centers.

As shown in Fig. 3 and Fig. 5, both devices exhibit comparable spectral profiles and identical FSR, differing only in the output quantity: voltage responsivity $R[\text{V/W}]$ for graphene versus photocurrent $I_{ph} [\mu\text{A}]$ for Ge.

The wavelength selectivity of the NEP improvement has direct implications for WDM systems. Each detector responds with maximum sensitivity only at its ring resonance wavelength, providing intrinsic channel selectivity without external optical filters. With an FSR of 1.450 nm, multiple ring detectors in cascade, each tuned to a different resonance by slightly varying the ring radius, can implement a complete WDM demultiplexer on a single SOI chip, compatible with C-band channel spacing standards.

IV. CONCLUSIONS

In this work, we presented a Transfer Matrix Method simulation of a microring resonator-enhanced photodetector on a silicon-on-insulator platform, based on the device architecture reported in [1]. Two detection materials were systematically investigated on the same ring geometry ($R = 40 \mu\text{m}$, $\kappa^2 = 10\%$, FSR = 1.450 nm): single-layer graphene exploiting the photo-thermoelectric effect, and germanium operating as a conventional p-i-n photodiode.

For the graphene PTE detector, critical coupling at $W_{opt} = 6 \mu\text{m}$ yields $EF_{max} = 10\times$ at $\lambda_{res} = 1553.55$ nm, a peak responsivity of 90 V/W, and a tenfold NEP improvement. For the Ge p-i-n detector, $W_{opt} = 0.50 \mu\text{m}$ and $EF_{max} = 10.5\times$ provide a comparable NEP improvement, confirming that cavity enhancement is material-independent.

The two architectures present complementary strengths: graphene offers zero-bias operation, zero dark current, direct voltage output without TIA, and broadband spectral coverage; germanium offers higher fabrication maturity and CMOS compatibility. In both cases, the ring resonator provides intrinsic wavelength selectivity enabling WDM channel demultiplexing on chip without external optical filters, representing a compelling architecture for next-generation data center optical interconnects operating in the C-band.

REFERENCES

- [1] S. Schuler, J. E. Muench, A. Ruocco, O. Balci, D. van Thourhout, V. Sorianello, M. Romagnoli, K. Watanabe, T. Taniguchi, I. Goykhman, A. C. Ferrari, and T. Mueller, "High-responsivity graphene photodetectors integrated on silicon microring resonators," *Nat. Commun.*, vol. 12, June 2021.
- [2] L. Alloatti and R. J. Ram, "Resonance-enhanced waveguide-coupled silicon-germanium detector," *Appl. Phys. Lett.*, vol. 108, no. 7, Feb. 2016.
- [3] A. Chatterjee, S. Yadav, S. K. Sikdar, and S. K. Selvaraja, "Compact ring resonator enhanced silicon metal-semiconductor-metal photodetector in SiN-on-SOI platform," *Opt. Express*, vol. 28, no. 22, Oct. 2020.
- [4] J. F. Liu, D. Ahn, C. Y. Hong, D. Pan, S. Jongthammanurak, M. Beals, L. C. Kimerling, J. Michel, A. T. Pomerene, D. Carothers, C. Hill, M. Jaso, K. Y. Tu, Y. K. Chen, S. Patel, M. Rasras, D. M. Gill, and A. E. White, "Waveguide-integrated Ge p-i-n photodetectors," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 1, Jan.-Feb. 2007.
- [5] J. E. Muench, M. Ruocco, M. A. Giambra, O. Balci, D. van Thourhout, V. Sorianello, M. Romagnoli, I. Goykhman, A. C. Ferrari, and T. Mueller, "Waveguide-integrated plasmonic enhanced graphene photodetectors," *Nano Letters*, vol. 19, no. 11, pp. 7632–7644, 2019.

Basic Principles And Fabrication Of Distributed Feedback Lasers

Andrea Comana
DEIB
Politecnico di Milano
andrea.comana@mail.polimi.it

Matteo Ricciotti
DEIB
Politecnico di Milano
matteo.ricciotti@mail.polimi.it

Abstract—This paper is a theoretical explanation of the basic working principles of lasers, a particular attention is posed to the peculiar characteristics of DFB lasers and their fabrication. (*Abstract*)

Keywords—laser, single mode lasers, DFB laser, Bragg gratings, nanoimprinting (*key words*)

I. INTRODUCTION

In many scientific and technological fields, coherent and monochromatic light sources are fundamental. In particular, the realization of easy tunable lasers with a very narrow bandwidth, is a key aspect in the modern WDM optical communication systems. In the following, the basic physical working principles of lasers will be discussed (a wide explanation can be found in [1]), then particular attention will be posed in the description of Distributed Feedback Lasers (which represent a solution to most of the critical aspects cited above) and their fabrication through the nanoimprinting technique.

II. BASIC PRINCIPLES OF LASERS

A. Stimulated Emission

As explained in [2], the fundamental physical principle at the basis of coherent emission and optical amplification is the stimulated emission of photons, in fact LASER means Light Amplification by Stimulated Emission of Radiation.

Considering, as in [2], an atom with two energy levels E_1 and E_2 , where $E_1 < E_2$, if an electron at level E_2 interacts with an incoming photon of energy $E = h\nu = E_2 - E_1$, the electron decays from level E_2 to E_1 causing the emission of a photon with same: energy, frequency, polarization and phase of the incoming one (as illustrated in Fig. 1). In brief, starting from one photon, two perfect coherent photons have been obtained. The material where stimulated emission occurs, it's called active medium.

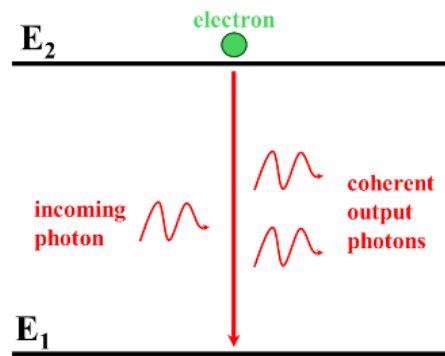


Fig 1. Stimulated emission

B. Pumping and Population Inversion

According to [2], in normal equilibrium conditions, most of the electrons would be at E_1 and few at E_2 . To make possible the stimulated emission, it's essential to promote some electrons from E_1 to E_2 through a process called pumping. However, to ensure that the stimulated emission would be the dominant phenomena, it's fundamental that E_2 is more populated than E_1 , this condition is called population inversion.

C. Laser Levels

With only two energy levels it's impossible to achieve population inversion, because pumping and stimulated emission are in competition, therefore, as explained in [2], a working laser needs at least three energy levels to separate the two processes, see Fig. 2. A four-level laser can provide higher efficiency because the population inversion condition can be obtained pumping a very few number of electrons as illustrated in Fig. 3.

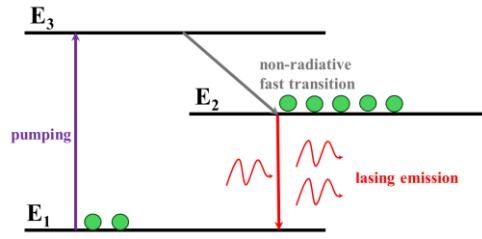


Fig 2. Three-level laser

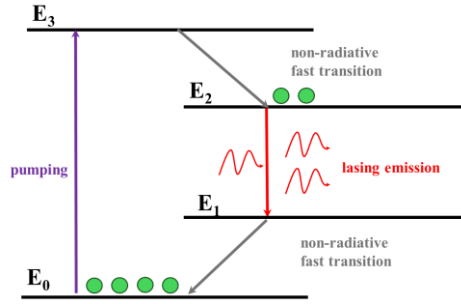


Fig 3. Four-level laser

D. Laser Cavity and Modes

In [2] is explained that, for a lasing emission is required a huge number of coherent photons and this is achieved by putting the active medium inside an optical resonator which provides positive feedback and filtering. One of the simplest resonators is the so-called Fabry-Perot, which consists in a cavity with two mirrors at the ends. The frequencies that can survive inside it, given by (1) and reported in [3], defines the cavity modes. In (1) n and L are respectively the refractive index and the length of the cavity while m is an integer.

$$v_m = m \cdot \frac{c}{2nL} \quad (1)$$

As explained by [3], the output spectrum is the superposition of these modes with the optical gain spectrum of the laser as qualitatively shown in Fig. 4.

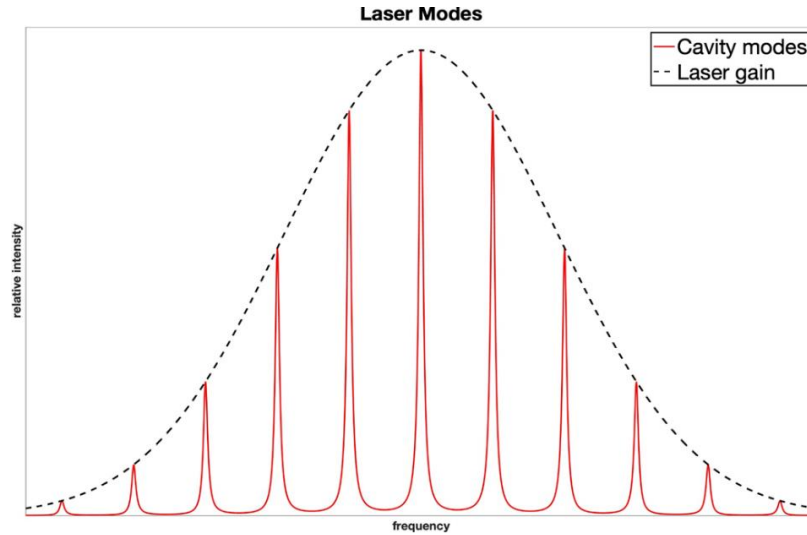


Fig 4. Qualitative output spectrum of a Fabry-Perot cavity laser

III. CHARACTERISTIC ASPECTS OF DISTRIBUTED FEEDBACK LASERS

A. Key Aspects and Structure

As explained by [5], in many applications is desirable to have a laser with a spectrum as narrow as possible, ideally a single frequency laser. In practice this is impossible to achieve but, with some improvements, it's possible to design a single mode laser with high modal purity. A practical implementation is the DFB laser, which is a laser diode, where the cavity is constituted by a Bragg grating.

While in a simple Fabry-Perot laser diode the discontinuity semiconductor-air provides the necessary optical feedback, as illustrated in Fig. 5 and explained in [4], in a DFB laser the feedback is distributed. As says [5], waves travelling from left to right

are partially and periodically reflected by the Bragg grating and these are amplified by the active medium constituting waves that travel from right to left as illustrated in Fig. 6.

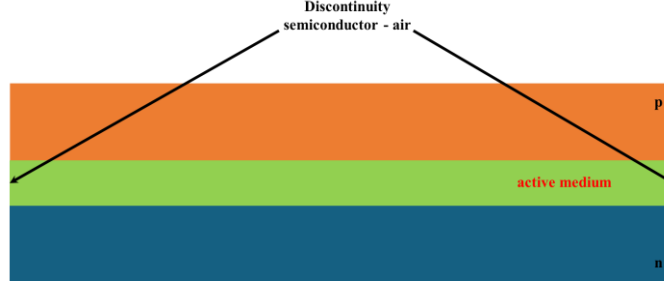


Fig 5. Approximate structure of a laser diode



Fig 6. Waves travelling in a DFB laser

B. Spectrum

These opposite travelling waves can create a standing wave only if they are coherently coupled. As reported in [5], the allowed DFB modes are given by (2) where: λ_B is the Bragg wavelength given by (3), n is the effective refractive index given by (4), d_1 and d_2 are the thickness of the n_1 and n_2 regions, Λ is the grating period, q and m are integers.

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL} (m + 1) \quad (2)$$

$$q \frac{\lambda_B}{n} = 2\Lambda \quad (3)$$

$$n = \frac{n_1 d_1 + n_2 d_2}{\Lambda} \quad (4)$$

In theory this is not a single mode laser because there are two modes placed around λ_B . However as said in [5], in practice the corrugation length L is so much larger than Λ so that the two modes are identical. Reference [5] reports that typical telecom DFB laser diodes have a spectral width less than 0.1 nm at 1550 nm.

C. Tunability

Reference [5] points out one defect of DFB lasers, that is the peak wavelength dependance on temperature. This is because Λ and n change with temperature. So, a precise control of temperature is needed to avoid peak wavelength shifting.

However, as stated in [5], this undesired effect can be exploited to realize finely tunable lasers by finely controlling the temperature.

IV. DFB LASER FABRICATION THROUGH NANOIMPRINTING

A. Advantages of Soft UV Nanoimprint Lithography

As reported in [6], nanoimprint lithography (NIL) is a next-generation technology for patterning narrow linewidths on a substrate at low cost and high throughput. Its resolution is not constrained by the wavelength of light, and a single template can be employed to precisely reproduce the same pattern across multiple wafers. Moreover, soft, flexible NIL stamps offer several advantages compared to the rigid ones, for example, they can adapt to the substrate surface, allowing uniform imprinting over an entire wafer, also in presence of dust particles, with an extremely high resolution (≈ 2 nm), in a single imprint step.

B. Practical Aspects of UV-NIL

Reference [6] says that, for GaAs and InP substrates (whose diameter for optoelectronics applications is typically 2" or 3"), if a flexible stamp is used, it can be detached from the wafer with very low mechanical force, reducing the risk of defects or damage and the whole wafer can be patterned with a single imprint step.

In [6] is shown how the effective hardness of the stamp and the viscosity of the resist can affect the thickness of the imprinted layer, in particular, an effectively harder stamp can take advantage of the reduced viscosity of the resist, as the stamp is less prone to deformation. So [6] tried to increase the effective hardness of the stamp.

Again [6], highlights the economic reasons favoring the use of soft stamps in diode laser fabrication, such as that, the throughput of full-wafer NIL is 10–20 wafers an hour. In [6] is stated that, this type of stamp will play a key role in the imprinting of surface reliefs on 2" and 3" wafers, in particular, if simultaneous micro- and nano-patterning is required.

In conclusion, [6] believes that soft UV-NIL is a promising nano-patterning approach, which is suitable for accurate pattern generation on fragile full-wafer GaAs and InP substrates.

REFERENCES

- [1] S. O. Kasap, Optoelectronics and Photonics: Principles and Practices. Second edition, Pearson Education Limited, 2013, ISBN 9780273774174, pp. 281–380
- [2] S. O. Kasap, Optoelectronics and Photonics: Principles and Practices. Second edition, Pearson Education Limited, 2013, ISBN 9780273774174, pp. 281–286
- [3] S. O. Kasap, Optoelectronics and Photonics: Principles and Practices. Second edition, Pearson Education Limited, 2013, ISBN 9780273774174, pp. 306–310
- [4] S. O. Kasap, Optoelectronics and Photonics: Principles and Practices. Second edition, Pearson Education Limited, 2013, ISBN 9780273774174, pp. 327–331
- [5] S. O. Kasap, Optoelectronics and Photonics: Principles and Practices. Second edition, Pearson Education Limited, 2013, ISBN 9780273774174, pp. 354–358
- [6] Jukka Viheriälä, Juha Tommila, Tomi Leinonen, Mihail Dumitrescu, Lauri Toikkanen, Tapio Niemi, Markus Pessa, Applications of UV-nanoimprint soft stamps in fabrication of single-frequency diode lasers, Microelectronic Engineering, Volume 86, Issue 3, 2009, Pages 321-324, ISSN 0167-9317, <https://doi.org/10.1016/j.mee.2008.10.010>. (<https://www.sciencedirect.com/science/article/pii/S016793170800467X>). [Online]. Available: https://www.academia.edu/62386959/Applications_of_UV_nanoimprint_soft_stamps_in_fabrication_of_single_frequency_diode_lasers

Photodetector Basics And Application In DQPSK Receivers

Giancarlo Lori

Politecnico di Milano - Electronic Engineering
giancarlo1.lori@mail.polimi.it

Paolo Amedeo Basso Ricci

Politecnico di Milano - Electronics Engineering
paoloamedeo.basso@mail.polimi.it

Abstract

Photodiodes are fundamental optoelectronic devices widely used for the detection and conversion of optical signals into electrical currents. This paper presents a comprehensive overview of the physical principles governing photodiode operation, introducing its main features. Building on these fundamentals, the paper explores the practical implementation of photodiodes in a Differential Quadrature Phase Shift Keying (DQPSK) optical receiver.

I. SEMICONDUCTOR PHOTODIODES

A. Main idea

Photodiodes are reverse-biased PIN junctions featuring an active area that can be either front or side illuminated, with the latter being more common in optical applications. Upon illumination, incident light generates electron-hole pairs thanks to the photoelectric effect. If generated within the depletion region, these carriers produce a photocurrent proportional to the incident optical power. On the other hand, if generated in the neutral regions, they are simply screened by the population of free carriers and do not contribute to the current.

B. Stationary operation

Under stationary illumination, the device operates in reverse bias, maximizing the width of the depletion region W_d , and therefore the probability of carrier pair generation within it. The built-in electric field sweeps the photo-generated electrons and holes toward the n-type and p-type contacts, respectively, giving rise to a net photocurrent I_P . The response is linear with incident power over several decades, making PIN photodiodes well suited for analog optical links.

II. MAIN PARAMETERS

A. Photon Detection Efficiency: η_D

It is the parameter which express the probability of a photon to generate a free electron-hole pair in the depletion layer. We can describe it as the product of the probabilities of not being reflected at the surface and of being absorbed by the depletion layer

$$\eta_D = (1 - R_f)(1 - e^{-\frac{\Gamma W_d}{L_a}}) \quad (1)$$

where R_f is the reflectivity coefficient of the substrate, Γ is the optical confinement factor, L_a is the absorption length and W_d is the physical length of the depletion layer.

B. Radiant Sensitivity: S_D

It's the parameter which expresses the quantity of current generated by the optical power. Since with the energy of one photon we have some probability to generate a current of one electron-hole pair, it can be easily computed as

$$S_D = \frac{\eta_D \cdot q}{hc/\lambda} = \eta_D \cdot \frac{\lambda[\mu m]}{1.24} \quad (2)$$

In real world this S_D is not perfectly linear with λ : there is a band in which it's linear, outside of which it drops towards zero.

C. Dark-Current

A reverse biased diode will never have zero current, except for a nihil bias voltage. So there will be a so called *Dark Current* circulating in our component even with no light. This current is responsible for a shot noise component of the device. The physical origin of this current can be traced back to the phenomena of carrier generation within the depletion region.

D. Current expression

Based on the previous parameters, we can easily compute the photocurrent generated by the device as

$$I_P = S_D * P_{opt} \quad (3)$$

It goes accordingly that to be properly sensed, I_P must be higher than I_{dark} , so we need $P_{opt} > \frac{I_{dark}}{S_D}$.

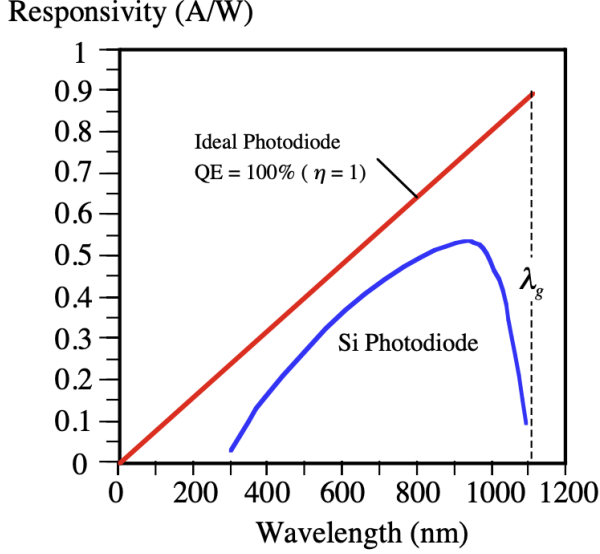


Fig. 1. Radiant sensitivity S_D vs wavelength λ in an ideal and a real Si-Photodiode

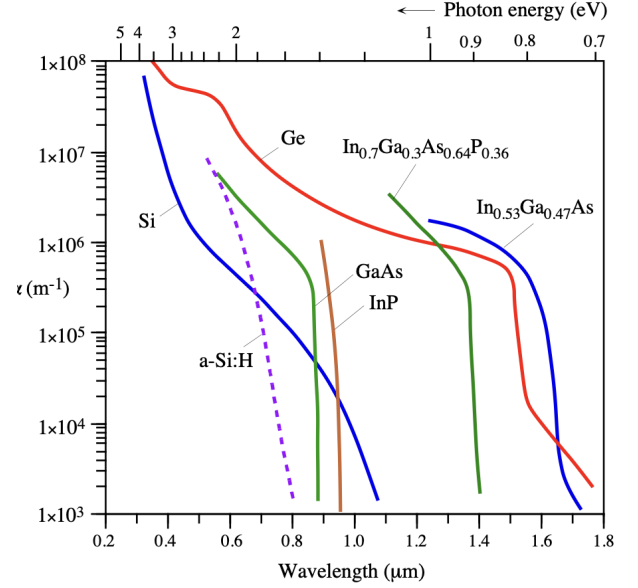


Fig. 2. Absorption coefficient Γ vs wavelength λ for various semiconductors

III. DYNAMIC RESPONSE

The frequency response of a photodiode is limited by two concurrent mechanisms:

A. Transit-time limit.

Carriers photo-generated within the depletion layer must drift to the contacts under the action of the electric field. The associated 3-dB bandwidth is approximately:

$$f_{tr} \approx \frac{0.45 v_s}{W_d} \quad (4)$$

where v_s is the carrier saturation velocity ($\approx 10^7$ cm/s in silicon). A wider depletion region improves η_D but degrades f_{tr} , creating a fundamental trade-off. This approximation was done considering the current at the contacts passing abruptly from a constant value to zero, creating a rectangular response. In the frequency domain this becomes a sinc, which is put equal to the -3dB bandwidth

$$\left| \frac{\sin(\pi f_{tr} \tau)}{\pi f_{tr} \tau} \right| = \frac{1}{\sqrt{2}}$$

We solve analytically finding

$$\pi f_{tr} \tau \approx 1.39$$

B. RC limit.

The junction capacitance $C_j = \epsilon_r \epsilon_0 A / W_d$ (where A is the device active area) forms a low-pass RC filter with the load resistance R_L :

$$f_{RC} = \frac{1}{2\pi R_L C_j} \quad (5)$$

C. Bandwidth estimation

The overall 3-dB bandwidth is obtained by combining both limits:

$$\frac{1}{f_{3dB}^2} \approx \frac{1}{f_{tr}^2} + \frac{1}{f_{RC}^2} \quad (6)$$

IV. EQUIVALENT CIRCUIT

A. Small-Signal Model

The small-signal equivalent circuit of a PIN photodiode consists of a current source I_P in parallel with the junction capacitance C_j , the shunt resistance R_{sh} (modelling the finite reverse-biased leakage), and a series resistance R_s accounting for contact and bulk resistances. The model is shown schematically in Fig. 3.

B. Noise Model

Two primary noise contributions must be accounted for in the equivalent circuit. The *shot noise* current has a power spectral density:

$$S_{i,shot} = 2q(I_P + I_{dark}) \quad (7)$$

The *thermal noise* (Johnson-Nyquist) from the shunt resistance R_{sh} contributes:

$$S_{i,th} = \frac{4k_B T}{R_{sh}} \quad (8)$$

In high-speed receivers, the transimpedance amplifier (TIA) input noise also plays a significant role and is usually the dominant term at low optical powers. The current produced will then be processed by the TIA and converted into voltage through ADC in the following steps.

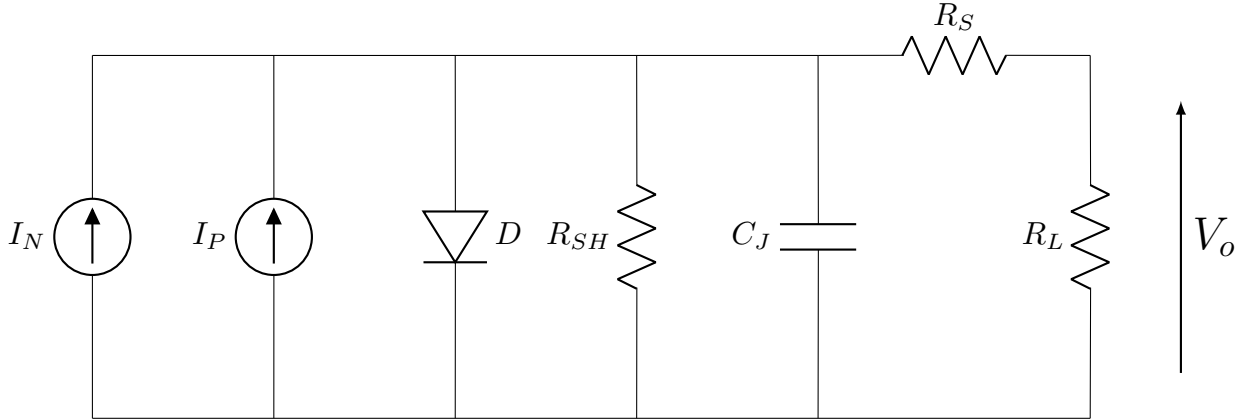


Fig. 3. Small-signal equivalent circuit of a PIN photodiode.

V. DQPSK RECEIVER APPLICATION

A. DQPSK Modulation Format

Differential Quadrature Phase Shift Keying (DQPSK) encodes two bits per symbol by differentially encoding the phase of the optical carrier in four possible states ($0, \pi/2, \pi, 3\pi/2$). Compared to QPSK, DQPSK doubles the spectral efficiency and relaxes the required optical signal-to-noise ratio (OSNR) by approximately 3 dB. These properties make it attractive for dense WDM systems operating at 40 Gbaud (symbols/second), which means reaching up to 80Gbps thanks to the two bits transported by each symbol.

B. Receiver Architecture

A DQPSK receiver demodulates the received signal thanks to two parallel Umbalanced Mach-Zehnder filters, each providing a one-symbol delay and a differential phase shift of $\pm\pi/4$, respectively. The structure is illustrated in Fig. 4.

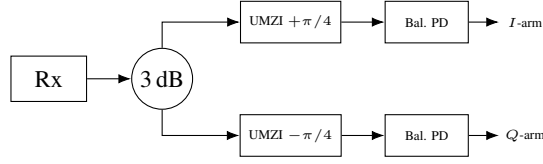


Fig. 4. Block diagram of a DQPSK optical receiver.

C. Balanced Photodetection

Each filter drives a pair of photodiodes connected in a balanced configuration. The two output ports of the Mach-Zehnder carry complementary signals; their photocurrents are:

$$I_{\pm} = \frac{S_D P_{\text{in}}}{2} (1 \pm \cos(\Delta\theta - \phi_{\text{ref}})) \quad (9)$$

where $\Delta\theta$ is the differential phase between adjacent symbols and $\phi_{\text{ref}} = \pm\pi/4$. The balanced detector computes $I_+ - I_-$, thus obtaining:

$$I_{\text{diff}} = S_D P_{\text{in}} \cos(\Delta\theta - \phi_{\text{ref}}) \quad (10)$$

This subtraction doubles the signal swing while suppressing common-mode noise (in particular intensity noise and dc dark current), improving the receiver sensitivity by up to 3 dB relative to single-ended detection [3].

D. System Requirements

Usually, the photodiodes employed in a 40 Gbaud DQPSK receiver must satisfy stringent specifications. The required 3-dB bandwidth must exceed 30 GHz (roughly $0.75 \times B$), with a junction capacitance below 100 fF to limit the RC contribution. The radiant sensitivity S_D should be maximised at the transmission wavelength (typically 1530–1565 nm), calling for InGaAs absorbers on InP substrates, which provide a responsivity of 0.8–1.0 A/W in that range [4]. Dark current must be kept below a few nanoamperes to avoid excessive shot noise that would degrade the OSNR.

E. Performance Metrics

The primary value of the evaluated DQPSK receiver is the required Optical Signal-to-Noise Ratio (OSNR), typically defined within a standard 0.1 nm reference bandwidth, to achieve a target Bit Error Rate (BER). Under ideal shot-noise-limited operation with balanced configuration, the theoretical E_b/N_0 required to reach a baseline BER of 10^{-3} is approximately 7.5 dB. Where E_b is the Energy per bit and N_0 is the noise spectral density, this enables removing the dependance on the transmission velocity and extension of the bandwidth, normalizing to the single bit.

$$SNR = \frac{S}{N} = \frac{E_b \cdot R_b}{N_0 \cdot B}$$

From which we obtain:

$$\frac{E_b}{N_0} = SNR \cdot \frac{B}{R_b}$$

Where R_b is the Bit-Rate and B/R_b represents the spectral efficiency of the system.

In practical implementations, hardware non-idealities introduce a significant OSNR penalty. Specifically, at low input optical powers, the photodiode dark current and thermal noise injected by the subsequent transimpedance amplifier (TIA) dominate, severely degrading the SNR. Furthermore, the finite extinction ratio of the Mach-Zehnder Interferometers causes signal leakage, inducing phase crosstalk between the in-phase (I) and quadrature (Q) tributary channels. Consequently, minimizing the dark current ($< a \text{ few nA}$) and optimizing the TIA noise spectral density are strict design constraints to approach the fundamental shot-noise limit and preserve receiver sensitivity.

VI. CONCLUSION

In conclusion, PIN photodiodes represent critical components in modern high-speed optical communication systems. Their physical design inherently involves a fundamental trade-off between photon detection efficiency and dynamic bandwidth, primarily governed by the depletion region width which dictates both transit-time and RC limits. The implementation of balanced photodetector pairs within a 40 Gbaud DQPSK receiver architecture proves highly effective in maximizing performance. This balanced configuration significantly improves receiver sensitivity, allowing the system to approach the shot-noise limit. Finally, the continuous co-integration of these detectors onto silicon photonic platforms will be essential for developing the compact, low-loss, and high-efficiency receivers required by future needs.

REFERENCES

- [1] J. -S. Choe, W.-S. Han, C. J. Youn, D. J. Kim, J.-H. Kim, D.-Y. Kim, Y.-H. Kwon, "Fabrication and characterization of waveguide photodetector array for coherent optical communication application," *2014 12th International Conference on Optical Internet 2014 (COIN)*, Jeju, Korea (South), 2014, pp. 1-2.
- [2] Y. Kwon, J. Choe, J. Kim, K. Kim, K. Choi, B. Choi, and H. Yun, "Fabrication of 40 Gb/s front-end optical receivers using spot-size converter integrated waveguide photodiodes," *ETRI J.* vol. 27, pp. 484-490, 2005.
- [3] A. Hakansson, M. Aamer, N. Sotiropoulos, A. Brimont, P. Sanchis, J.-M. Fedeli, D. Marris-Morini, E. Cassan, L. Vivien, K. Gilbert, P. Grosse, J. M. Hartmann, D. Vermeulen, G. Roelkens, "Compact silicon differential receiver with integrated zero biased balanced detection," *The 9th International Conference on Group IV Photonics (GFP)*, San Diego, CA, USA, 2012, pp. 165-167.
- [4] . Faralli *et al.*, "25 Gbaud DQPSK receiver integrated on the hybrid silicon platform," *8th IEEE International Conference on Group IV Photonics*, London, UK, 2011, pp. 326-328.
- [5] M. S. Hai, M. N. Sakib and O. Liboiron-Ladouceur, "A compact silicon-on-insulator optical hybrid for low loss integration with balanced photodetectors," *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*, London, 2013, pp. 1-3.
- [6] G. Unterborsch, M. Kroh, J. Honecker, A.G. Steffan, G. Tsianos, H.-G. Bach, J. Kreissl, R. Krunkel, G. G. Mekonnen, W. Rehbein, D. Schmidt, J. Bruns, T. Mitze, K. Voigt, L. Zimmermann, "Hybrid flip-chip integration of a 40 Gb/s DPSK receiver comprising a balanced photodetector on a DLI-SOI board," *2008 34th European Conference on Optical Communication*, Brussels, Belgium, 2008, pp. 1-2.

From Modulators to Biosensing: Silicon Micro-Ring Resonators For Bio-Chemistry Applications

1st Matteo Malagrino
DEIB
Politecnico di Milano
matteo.malagrino@mail.polimi.it

2nd Riccardo Brizzi
DEIB
Politecnico di Milano
riccardo.brizzi@mail.polimi.it

Abstract

Photonic devices are gaining significant traction in the sensor market due to their ability to detect minute variations in physical parameters with high sensitivity and minimal invasiveness. This work focuses on the experimental characterization of Silicon Micro-Ring Resonators (MRRs) and discusses their utility for biochemical applications. The MRR enables effective molecular detection by exploiting localized changes in the refractive index within the evanescent field when target particles are captured by specific chemical acceptors. The device performance relies on a sophisticated surface functionalization process that integrates photonics, materials science, and biochemistry.

Keywords: Photonic; Silicon Micro-Ring Resonators; Biosensors; Label-Free Molecular Biosensing; Micro-Ring Modulators

I. INTRODUCTION

The optical biosensing has emerged as a transformative technology for healthcare, environmental monitoring, and food safety. Compared to traditional analytical methods, such as Enzyme-Linked Immunosorbent Assay (ELISA), photonic sensors offer the advantage of label-free detection, high sensitivity, and the potential for extreme miniaturization. Traditional biochemical assays often require complex labeling steps using fluorescent or radioactive markers, which can be time-consuming, costly, and may alter the natural state of the analyte. To overcome these limitations, Micro-Ring Resonators (MRRs) have been widely adopted as a robust platform for real-time, label-free molecular sensing. The sensing mechanism of an MRR relies on the interaction between the evanescent field of the circulating light and the surrounding medium. When target molecules bind to the resonator's surface, they induce a local change in the refractive index, resulting in a measurable shift in the resonance wavelength ($\Delta\lambda$). In this work, we present an in-depth analysis of a Silicon-on-Insulator (SOI) Micro-Ring Resonator designed for molecular biosensing. We explore the synergy between photonic design and surface chemistry, demonstrating how a tailored functionalization process enables the detection of specific analytes with high sensitivity. The results discussed herein highlight the potential of MRR-based PICs as a scalable and efficient solution for the next generation of Point-of-Care (PoC) diagnostic devices.

II. SILICON MICRORING RESONATORS

A. State of the Art

Over the past two decades, Silicon Micro-Ring Resonators (MRRs) have emerged as cornerstone components in integrated photonics, primarily due to their high quality factor (Q), compact footprint, and CMOS compatibility. The versatility of MRRs is evidenced by their dominance in three primary domains: optical modulation, spectral filtering, and sensing. In high-speed communication, MRRs are employed as electro-optic modulators. By integrating $p-i-n$ junctions or using carrier depletion in silicon-on-insulator (SOI) platforms, the refractive index of the ring can be rapidly tuned to shift the resonance peak. Furthermore, the inherent periodic nature of the resonance allows MRRs to function as high-order filters and de-multiplexers in Wavelength Division Multiplexing (WDM) systems, where cascaded configurations achieve box-like filter responses [1]. Perhaps the most transformative application, and the focus of this work, lies in refractive index (RI) sensing. The resonant wavelength (λ_{res}) is highly dependent on the effective index (n_{eff}) of the circulating mode, governed by the relation: $\lambda_{res} = \frac{n_{eff} \cdot L}{m}$, where L is the round-trip length and m is an integer. In the context of biosensing, MRRs offer a label-free platform capable of detecting minute concentrations of analytes. While traditional sensors rely on bulk refractive index changes, state-of-the-art biosensors utilize functionalized surfaces to capture specific biomolecules (e.g., proteins or DNA) directly within the evanescent field of the resonator [2]. Recent advancements have pushed the limits of detection (LoD) toward the single-molecule regime, positioning MRRs as the premier candidate for integrated Point-of-Care (PoC) diagnostic devices, where sensitivity and miniaturization are paramount [3], [4].

III. EXPERIMENTAL CHARACTERIZATION

In this work, we focus on the comparative analysis of the Silicon Micro-Ring (Si-MRR, in Fig. 1) by performing an experimental characterization to extract its key operational parameters. The experimental setup (Fig. 2) employed a continuous-wave (CW) tunable laser source with an output power set to 0 dBm. Given that Silicon-on-Insulator (SOI) waveguides exhibit high polarization sensitivity, a manual polarization controller was utilized to align the input light to the Transverse Electric (TE) mode. Optical coupling was achieved via single-mode fibers tilted at a 12° angle, targeting the input and through-port grating couplers of the MRR (Fig. 3). Fine alignment was maintained using high-precision 3-axis micro-positioners. The transmitted signal was monitored by an optical power meter, revealing an off-resonance baseline power of approximately -22 dBm. This total insertion loss (IL) includes the coupling losses from the two grating couplers—estimated at 6 dB per facet—while the remaining 10 dB is attributed to fiber propagation losses and multiple mating sleeves in the optical path. Following optical alignment, electrical probes were landed on the chip's metal pads to drive the integrated heaters and p-n junctions.

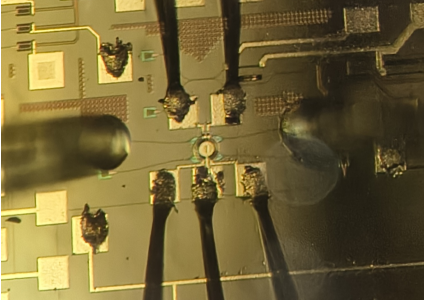


Fig. 1: Microscope detail of the probes on the chip.

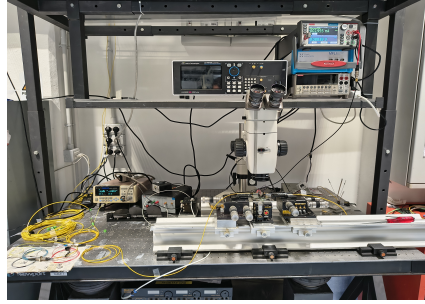


Fig. 2: Overall view of the experimental setup.

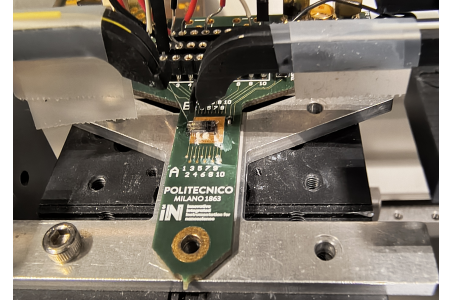


Fig. 3: Detailed view of the Silicon Micro-ring.

A. Spectral Characterization and Data Extraction

The analysis of the transmission spectrum enables the extraction of the resonator's fundamental figures of merit. The *Free Spectral Range* (FSR) and the quality factor Q characterize the resonance periodicity and selectivity, respectively, where $\Delta\lambda_{FWHM}$ denotes the optical bandwidth (BW_{nm}). Furthermore, the modulation depth is quantified by the *Extinction Ratio* (ER). In this work, resonance tuning and environmental compensation are achieved through the thermo-optic effect. The application of a bias voltage V to the integrated micro-heater induces local Joule heating, resulting in a resonance redshift $\Delta\lambda$. From this shift, the induced optical phase change ($\Delta\phi$) and the effective refractive index variation (Δn_{eff}) are derived, assuming a group index $n_g \approx 4.2$. The system is supposed to operate at a baseline temperature slightly above ambient to allow efficient bi-directional control. The results are summarized below, pairing the optical spectrum with its corresponding physical parameters.

$$\begin{aligned} FSR &= \frac{c}{n_g \cdot L_r} \\ Q &= \frac{\lambda_{res}}{BW_{nm}} \\ BW_{GHz} &= \frac{c}{\lambda_{res}^2} BW_{nm} \\ ER_{dB} &= P_{base} - P_{min} \\ \Delta\phi &= 2\pi \frac{\Delta\lambda}{FSR} \\ \Delta n_{eff} &= \frac{\Delta\lambda}{\lambda_{0V}} n_g \end{aligned}$$

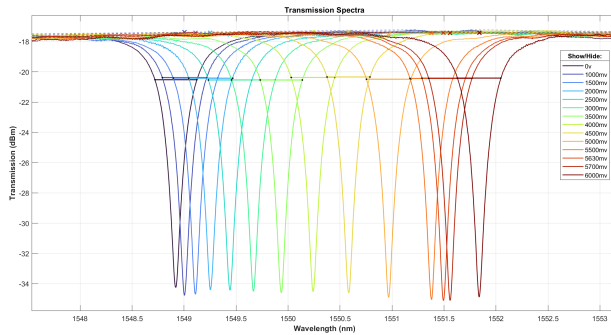


Fig. 4: Transmission of a MRR at various voltage levels.

V (V)	FSR (nm)	BW (nm)	$\Delta\phi$ (rad)	Δn_{eff} ($\times 10^{-3}$)	ER (dB)	Q ($\times 10^3$)
0.00	5.131	0.427	0.000	0.00	17.43	3.68
1.00	5.132	0.427	0.099	0.20	17.39	3.68
2.00	5.132	0.428	0.407	0.90	17.37	3.67
3.00	5.133	0.427	0.914	2.00	17.38	3.68
4.00	5.115	0.403	1.624	3.60	16.57	4.30
5.00	5.117	0.417	2.515	5.60	16.90	3.77
5.63	5.118	0.417	3.162	7.00	16.83	3.78
5.70	5.120	0.416	3.239	7.20	16.75	3.79
6.00	5.119	0.415	3.583	7.90	16.75	3.79

TABLE I: Extracted Parameters. ($V_\pi = 5.61$)

B. Geometry Recovery and Dispersion Analysis

The device geometry was validated by back-calculating the cavity length ($L \approx 111.48 \mu\text{m}$) and radius ($R \approx 17.74 \mu\text{m}$) from the experimental FSR at 0 V ($n_g = 4.2$). These results show excellent agreement with the design specifications.

Chromatic dispersion was quantified by evaluating the group index at the spectral extremities, yielding $n_g = 4.1973$ at 1523.7 nm and $n_g = 4.1924$ at 1575.0 nm. The experimental dispersion slope, calculated as $dn_g/d\lambda = \Delta n_g/\Delta\lambda \approx -9.51 \times 10^{-5} \text{ nm}^{-1}$, implies a negligible n_g variation (0.0004%) for a typical 0.18 nm sensing shift. This confirms the robustness of the first-order linear model for PoC applications, as second-order effects remain well below the experimental noise floor.

C. Modulation Efficiency and V_π

The modulation efficiency is quantified by the half-wave voltage V_π , representing the bias required for a π phase shift. For the thermo-optic heater, we extracted $V_\pi \approx 5.61 \text{ V}$, enabling a resonance sweep across more than half the FSR. As shown in Table I, the tuning is non-disruptive: the Q-factor ($\approx 3700 \div 3800$) and Extinction Ratio ($> 16.5 \text{ dB}$) remain stable across the entire voltage range, confirming the integrity of the optical cavity during tuning.

IV. MICRORING RESONATORS AS BIOSENSORS

The transition from an electro-optic modulator to a biosensor relies on the fundamental sensitivity of the guided optical mode to its surrounding environment. While in a modulator the refractive index is perturbed via electrical means (thermal or plasma dispersion), in a biosensor, the perturbation is induced by the presence of biological matter within the reach of the optical field.

A. The Physical Principle: Evanescent Field Interaction and Surface Functionalization

The core physical principle of waveguide-based biosensing is the interaction between the evanescent field and the surrounding medium. When a Transverse Electric (TE) mode propagates through a silicon-on-insulator (SOI) waveguide, the electromagnetic field is not entirely confined within the silicon core ($n_{Si} \approx 3.48$). A fraction of the optical power, known as the evanescent tail (Fig. 5), extends exponentially into the top cladding for approximately 100 to 200 nm: $E(z) = E_0 \cdot \exp(-z/\delta)$, where δ is the penetration depth. In a biosensing configuration, the traditional oxide cladding is locally etched away, and the sensor is exposed to a biological matrix (the complex fluid carrying the molecules of interest, such as blood serum, saliva, or a purified buffer solution). To transition a bare silicon surface from a non-specific transducer to a selective biosensor, a process called bio-functionalization is required. This chemical preparation typically utilizes silane chemistry to attach specific capture agents—such as antibodies, DNA, or proteins—which act as molecular “baits”. In this lock-and-key mechanism, these receptors selectively bind only the target analyte, allowing non-target molecules in complex biological matrices to flow past without inducing false-positive shifts [3]. When biological molecules bind to the waveguide surface (Fig. 6), they displace the water-based buffer ($n \approx 1.33$) with denser organic matter (e.g. $n \approx 1.45$). This localized increase in the refractive index modifies the overall effective refractive index (n_{eff}) of the guided mode.

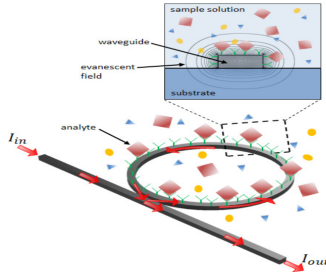


Fig. 5: Illustration of a micro ring resonator with a biochemical layer to attract molecules [5].

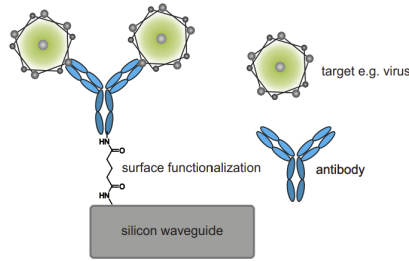


Fig. 6: Surface functionalization demonstrating lock-and-key mechanism [5].

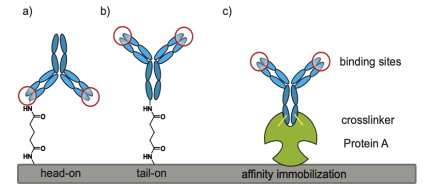


Fig. 7: Head-on (a), tail-on (b) and oriented (c) immobilization with the affinity Protein A [5].

B. Spectral Transduction: The Resonance Shift

The microring acts as an optical transducer, converting this microscopic refractive index change into a macroscopic, measurable optical signal. As target molecules accumulate on the surface, the increase in n_{eff} forces the resonance wavelength (λ_{res}) to increase proportionally to maintain the equation's balance. This results in a red-shift (a displacement toward longer wavelengths) of the transmission notch (Fig. 8): $\Delta\lambda_{res} = \frac{\Delta n_{eff} \cdot \lambda_{res}}{n_g}$ where n_g is the group index extracted during our experimental characterization. By continuously monitoring the position of this spectral dip, the system can track the binding process over time, generating a *binding curve*.

V. EXPERIMENTAL VALIDATION: PERFORMANCE LIMITS AND DEVICE VIABILITY

To assess the practical utility of the characterized Silicon Microring Resonator (Si-MRR), we developed a predictive sensing model anchored directly to our laboratory results. Unlike standard theoretical studies that rely on idealized Lorentzian curves, this analysis utilizes the actual transmission spectrum at 0 V as a baseline. By mathematically perturbing the experimental data, we demonstrate the sensor's performance in a realistic Point-of-Care (PoC) diagnostic scenario, highlighting where the device excels and identifying its physical operational boundaries.

A. Analytical Performance Metrics and Figure of Merit

Based on the waveguide cross-section (500×220 nm) and the experimentally extracted group index ($n_g \approx 4.2$), we evaluate the following critical parameters:

- **Bulk Sensitivity (S_b):** It quantifies how much the resonance shifts per unit of refractive index change (RIU). It is essential to convert the measured $\Delta\lambda$ (e.g., 0.18 nm) into a concentration value (e.g., mg/dL of glucose).
- **FWHM ($\Delta\lambda_{3dB}$):** Defines the "sharpness" of the notch. In sensing, a narrow FWHM is crucial to distinguish the signal from experimental noise and to track even sub-picometer shifts.
- **Figure of Merit (FOM):** It represents the overall efficiency of the sensor. High sensitivity (S_b) is useless if the peak is too wide (high FWHM); the FOM allows us to compare our device with other state-of-the-art resonators.
- **iLoD / sLoD:** These define the physical and practical limits of the system. They tell us the minimum amount of analyte the sensor can "see" before the signal becomes indistinguishable from noise.

TABLE II: Calculated Biosensing Metrics

Metric	Analytical Formula	Value
S_b	$\frac{\lambda_{res}}{n_g} \cdot f_{clad}$	80 nm/RIU
FWHM	$\Delta\lambda_{3dB}$	0.427 nm
FOM	$\frac{S_b}{FWHM}$	187.35 RIU ⁻¹
iLoD	$\frac{FWHM}{S_b}$	$5.34 \cdot 10^{-3}$ RIU
sLoD	$\frac{FWHM}{10 \cdot S_b}$	$5.34 \cdot 10^{-4}$ RIU

The obtained sLoD ($\approx 5.34 \times 10^{-4}$ RIU) is a key result: it proves that our device can resolve refractive index variations typical of clinical glucose fluctuations ($> 10^{-4}$ RIU), confirming its viability for Point-of-Care diagnostics.

B. Clinical Case Study: Macroscopic Glucose Monitoring

We simulated the device's response to physiological glucose concentrations, comparing a healthy fasting state (≈ 90 mg/dL) against a diabetic post-prandial state (≈ 250 mg/dL). Glucose in aqueous solution induces a refractive index variation of $\approx 1.4 \times 10^{-5}$ RIU per mg/dL. A concentration increase of 160 mg/dL produces a measured spectral shift of 0.18 nm. Since this shift (0.18 nm) is significantly larger than the calculated system resolution (0.0427 nm), the device can distinguish these clinical states. This numerical evidence confirms that the characterized Si-MRR is *highly suitable* for robust Point-of-Care (PoC) glucose diagnostics.

C. Active Thermal Stabilization and Operational Bias

A major challenge for silicon-based PoC diagnostics is thermal drift (≈ 80 pm/°C). To neutralize environmental noise, we leverage the integrated micro-heaters characterized in Section III.

1) *Thermal Control Logic: The Necessity of a Voltage Bias:* To achieve bidirectional thermal control, the micro-heater must be operated at a non-zero Voltage Bias (V_{bias}). This configuration is fundamental for two reasons:

- **Bidirectional Compensation:** By maintaining a baseline bias (e.g., 2.0 V), a feedback loop can counteract ambient cooling by increasing power, or ambient heating by decreasing the bias.
- **Sensitivity Enhancement:** Operating at a bias moves the working point to a region with a higher $d\lambda/dV$ slope, ensuring faster and more precise corrections.

2) *Practical Example: Compensating a 0.5 °C Drift:* Using our experimental data ($V_\pi \approx 5.61$ V, $FSR \approx 5.13$ nm), we simulated the response to a typical environmental drift of +0.5 °C:

- 1) **Ambient Drift:** A +0.5 °C increase induces a red-shift of approximately +0.040 nm.
- 2) **Locked State:** The sensor is initially stabilized at $V_{bias} = 2.00$ V.
- 3) **Active Restoration:** To counteract the ambient heat, the control loop reduces the heater voltage to 1.87 V. This reduction in local power dissipation perfectly offsets the external thermal gain.

The detection of such a drift (0.040 nm) is made possible by the device's sharp resonance ($FWHM = 0.427$ nm) and high extinction ratio. By employing a Lorentzian tracking algorithm, the system can resolve shifts as small as 1/10 of the FWHM, effectively translating the statistical data of the entire resonance curve into sub-picometer wavelength precision.

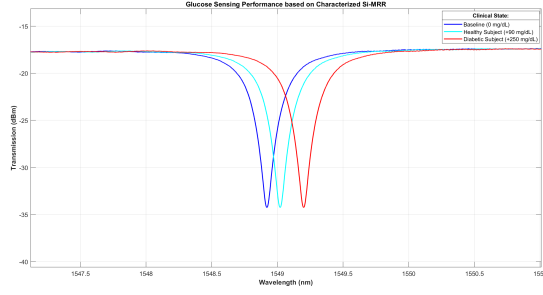


Fig. 8: Simulated biosensing response based on raw experimental data. The high ER ensures robust tracking between the healthy (light blue) and diabetic (red) states.

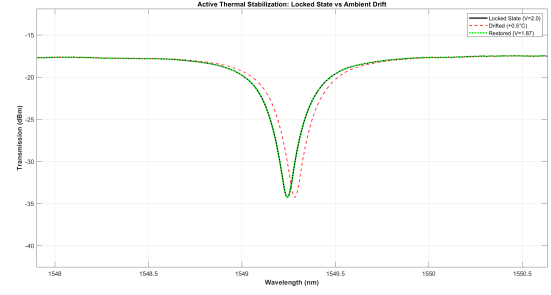


Fig. 9: Active thermal stabilization simulation. The drift induced by a $+0.5\text{ }^{\circ}\text{C}$ variation (dashed red) is restored to the baseline (dotted green) by modulating the heater voltage.

D. Discussion: Critical Advantages and Physical Limits

The practical viability of the device is assessed by comparing the simulated biological signals with the experimental electro-optic characterization:

Criticality: Without active control, a minimal environmental thermal drift would mask the clinical result. **Advantage:** The high heater efficiency allows the integrated resistors to act as a "thermal buffer", as demonstrated in the previous section.

- 1) **Dynamic Range vs. Sensitivity:** The large experimental FSR of 5.13 nm allows for a linear response up to concentrations as high as 4500 mg/dL , avoiding "spectral folding".
- 2) **Signal Integrity in Complex Media:** Our moderate Q-factor (≈ 3680) ensures that the 17.4 dB extinction ratio remains stable, enabling reliable detection in unpurified matrices.

VI. CONCLUSION

In this work, we experimentally characterized a Silicon Micro-Ring Resonator and validated its performance for biochemical sensing through a predictive numerical model. The device demonstrated a robust Quality Factor of ≈ 3680 and an Extinction Ratio of 17.4 dB , ensuring high signal integrity. The back-calculation of the geometry ($R \approx 17.74\text{ }\mu\text{m}$) and the extraction of the dispersion slope ($dn_g/d\lambda \approx -9.51 \times 10^{-5}\text{ nm}^{-1}$) confirmed the accuracy of the physical model. Furthermore, we demonstrated that integrated micro-heaters can effectively compensate for environmental thermal drifts, restoring the resonance with sub-picometer precision. These results position the Si-MRR as a reliable and scalable transducer for next-generation, thermally-stabilized Point-of-Care diagnostic platforms.

REFERENCES

- [1] W. Bogaerts *et al.*, "Silicon microring resonators," *Laser & Photonics Reviews*, vol. 6, no. 1, pp. 47–73, 2012.
- [2] F. Vollmer and S. Arnold, "Whispering-gallery-mode biosensors," *Nature Methods*, vol. 5, no. 7, pp. 591–596, 2008.
- [3] M.-C. Estevez, M. Alvarez, and L. M. Lechuga, "Integrated optical devices for lab-on-a-chip biosensing applications," *Laser & Photonics Reviews*, vol. 6, no. 4, pp. 463–487, 2012.
- [4] M. S. Luchansky and R. C. Bailey, "Rapid, multiparametric monitoring of biomarkers and therapeutic agents using silicon photonic microring resonator arrays," *Analytical Chemistry*, vol. 84, no. 2, pp. 793–821, 2012.
- [5] P. Steglich *et al.*, "Silicon Photonic Micro-Ring Resonators for Chemical and Biological Sensing: A Tutorial," in *IEEE Sensors Journal*, vol. 22, no. 11, pp. 10089–10105, 1 June 2022, doi: 10.1109/JSEN.2021.3119547.
- [6] Katrien De Vos, Irene Bartolozzi, Etienne Schacht, Peter Bienstman, and Roel Baets, "Silicon-on-Insulator microring resonator for sensitive and label-free biosensing," *Opt. Express* 15, 7610–7615 (2007)
- [7] M. S. Luchansky and R. C. Bailey, "High-Q Optical Sensors for Chemical and Biological Analysis," *Analytical Chemistry*, vol. 84, no. 3, pp. 793–821, 2012, doi: 10.1021/ac2029024.
- [8] S. Robinson and N. Dhanlaksmi, "Photonic Crystal Based Biosensor for the Detection of Glucose Concentration in Urine," *Photonic Sensors*, vol. 7, no. 1, pp. 11–19, 2017, doi: 10.1007/s13320-016-0347-3.
- [9] Diabete.com, "Glicemia: quali sono i valori normali? Valori di riferimento della glicemia o glucosio nel sangue," [Online]. Available: <https://www.diabete.com/valori-di-riferimento-della-glicemia/> [Accessed: 14-May-2026].

Optical Satellite Communications

Andrea Sau

Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
andrea.sau@mail.polimi.it

Darie Misani

Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
darie.misani@mail.polimi.it

Abstract

We aim to present the benefits and drawbacks in satellite to satellite and earth to satellite communication of optical systems (*Free Space Optics*) with respect to the most widely used RF; we'll explore the system structure and the challenges of it, and explain why this technology could take over RF in spatial communications.

I. OPTICAL VS RF COMMUNICATION

FSO technology is far less developed than the RF systems, but brings significant benefits along with limited drawbacks; to get a full comparison we can refer to the following table [1] :

TABLE I: FSO Vs RF

<i>Characteristic</i>	<i>FSO</i>	<i>RF</i>
Spectrum	Near infrared and visible light	Ka,Ku, mm-wave band
Bandwidth	in THz	in GHz
Wavelength	in nm	thousand of times larger than the optical one
Antenna size	smaller, $\approx \lambda$	Much bigger
Beam Spread	Much narrower	typically 1000 times more
Directivity	very high	very low
Power Consumption	More power recived for a given transmitted power	Less recived power for a given transmitted power
Security	High due to directivity	easy to intercept
Interference	Almost non due to very narrow beam width	severely degrade performance
Solar Radiation	Degrades performance	unaffected
Line-of-sight Obstruction	Severely impact performance	Severely impart only in the mm-wave band
Spectrum regulation	unlicensed	licensed

We see how FSO systems provides good performances compared to classic RF, having limited drawbacks. In our context this technology applies to a new generation of satellites that will take into account constraints for implementing FSO onboard. As the trend for the new generation of satellites is to prefer Low Earth Orbits (LEO), line-of-sight with eart base station(s) is a key factor in orbits design. Aiming is another technological challenge, again related to orbits.

With respect to RF, FSO suffers solar radiation interference, for this reason the wavelength selectivity of receiver, and so it's robustness and reliability over many aspects (thermal, EMC), has to be carefully considered, tending to an overall strict requirement.

A big advantage in Space-to-space (or inter satellite links, ISL) communication is that there is no atmosphere, thus a series of detrimental effects, such as fading and scintillation, on channel is erased; for earth-to-space (E2S) communications we still have to consider atmosphere propagation channel.

Keeping line of sight is among the most difficult tasks; this will be later discussed.

A big advantage to consider is that existing technological platform for fiber optic communications in C-Band is reused in this context, exploiting low cost of supply chain, big set of data and in general a quite mature industrial context; For intra-satellite this is no problem, but for earth-to-space studies demonstrated how C-Band is not the best choice in terms of attenuation and detrimental effects from fog,rain and atmospere in general, and far infrared in the $9\mu m$ region would be a better choice [15]. We present a solution that is valid for both IIS and E2S applications, so standard C-Band is considered.

II. SYSTEM DESIGN

So first of all we need to know the transparent window of the atmosphere, this depend of the satellite type, but as they all have to communicate back to earth, this means that the second and third window are our target.

Chosen the window of operation we need a very stable optical source; we need to ensure the lowest possible back-reflection and maximize the reliability of it, then we need to modulate the signal; the modulation format is very important as we get a lot of interference from the sun, and considering dual use (ISL and E2S) thus having atmosphere, very dense format like 16-QAM or higher are not feasible right now; a simpler modulation format has to be chosen, popular formats are DSPK and DQSPK.

In figure we reported a basic block diagram of the system, in reality we need optical beam stabilizer (OBS) as we need to control the angle of the beam, also we need to control the collimation and focal plane alignment in order to reduce insertion losses, on top we need of coarse a feedback control circuit to maintain every part in its optimal working point, a more detailed analysis can be seen in [8],[10], as we want to focus on modulator, demodulator and receiver.

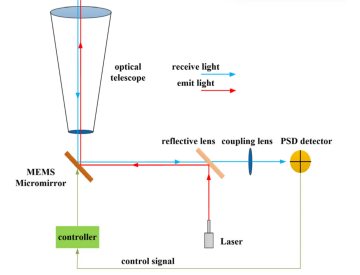


Fig. 1: Simple block diagram of the optical system

III. RECEIVER AND MODULATOR

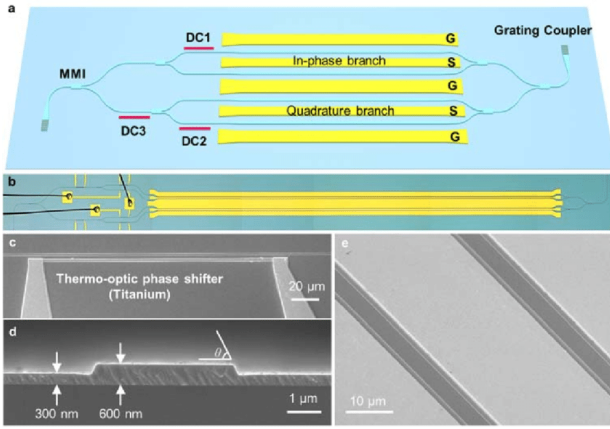


Fig. 2: [5] QPSK modulator

Among all possible modulation formats that have been used in FSO research projects, DPSK and DQPSK are good compromise of performance, reliability and implementation simplicity [4]. Such modulators are realized using phase modulator in combination with Mach-Zehnder interferometers. An emerging platform for realizing such modulators could be *Thin Film Lithium Niobate on Insulator* (LNOI) achieving better voltage-bandwidth performances [5]; this platform is not as consolidated as $LiNbO_3$ and is still in heavy development phase. This modulator achieves large bandwidths ($> 67GHz$) over all C-Band, yielding to $100Gbaud$ corresponding to $200Gbit/s$ and $400Gbit/s$ bitrates (DPSK and DQPSK) with $BER < 10^{-9}$. Overall length of device is $15mm$ and maximum driver voltages are $7.5V$ (for biasing) and 1.9 (max V_{π}). Measured $ER > 25dB$.

In figure (3a) is shown a simple demodulator for DPSK [6]; this design is compact as does not require optical local oscillator.

Turbulence is manifested in phase contributions that are not uniform over the section of beam; as the beam propagates, both it expands and accumulates different phase for different spatial position. Upon reaching a photodetector, the sum of all contributions gives noise thus degrading SNR. In figure (3b) is shown a prototype of turbulence-compensation POP realized in SiP (*Silicon Photonics*) technology. After collimation, beam is coupled inside chip with different gratings, then numerous Mach-Zehnders provide phase shift to each path in order to compensate turbulence. Such system has to be controlled in a closed loop with high-speed electronics (FPGAs are commonly used) and features many heater for control, resulting in heavy power consumption (and thermal dissipation), much greater than one of the receiver itself. Thermal budget has to be taken into account especially for space-borne systems where heat dissipation is limited to radiation.

Such turbulence compensation device could be integrated on the same substrate as the receiver, providing an embedded receiver and demodulator realized in SiP.

Variable attenuation is given by environmental conditions: rain, fog, clouds and solar radiation change randomly giving variable attenuation; this can be mitigated by algorithms on RX side [9] but the choice of DQPSK scheme is intrinsically resilient to such phenomena. If choosing to operate higher order modulation schemes (i.e. M-QAM), such algorithm would play an important role in keeping system performances reliable over atmospheric variations.

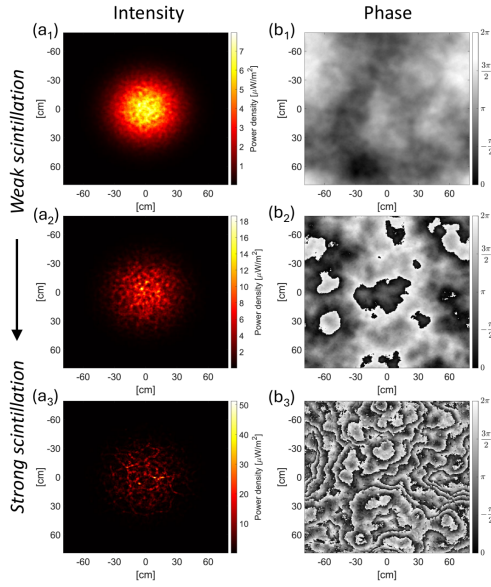
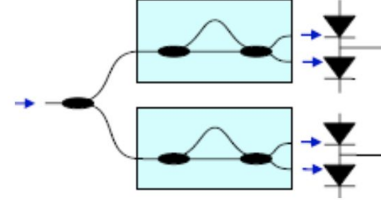
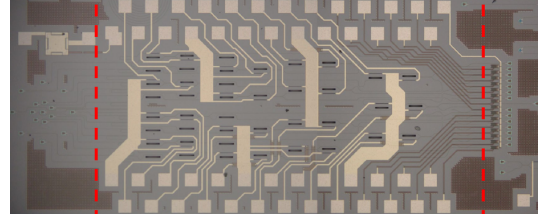


Fig. 3: [7] Turbulence and scintillation phenomena (Intensity and phase)



(a) [6] DPSK receiver



(b) [7] POP for turbulence compensation

IV. DIRECTION FOR IMPROVEMENTS AND FUTURE APPLICATION

As we have seen the technology is still in an unripe phase, but there is growing interest as this could be key technology enabling faster space communication; possible applications include *Deep Space Optical Communication (DSOC)*, [11] where NASA has shown an interest in FSO for earth-to-space communication systems and it's currently testing this technology. An effective large-scale deployment of ISL has been achieved by *SpaceX* with its *Starlink* constellation [14].

As for earth-to-satellite communications the challenges ahead are similar, one of the most critical point is to be able to pass through the atmosphere in a reliable way, so a lot of interest has been generated in receiver and in its sensors; an example of receiver to counteract the atmospheric interference was presented in the previous section [7]; another important breakthrough was the *Superconducting Nanowire Single Photon Detector* (fig 4), as it is the closest detector to an ideal SPAD.

This is a very recent development in the sensors scene, and has rapidly surpassed every other sensor in its optical region; by implementing this kind of devices in a receiver architecture that exalts its strong points and minimizes the atmosphere effect we could be close to a low power optical transmission in free space both in earth-to-earth and earth-to-space communication. Moreover the ideal scenario will be to go down to single photon communication, as this would guarantee the most secure transmission of data, but for all the reasons we cited before this is very unlikely, even if the evolution of detectors is aiming in this direction.

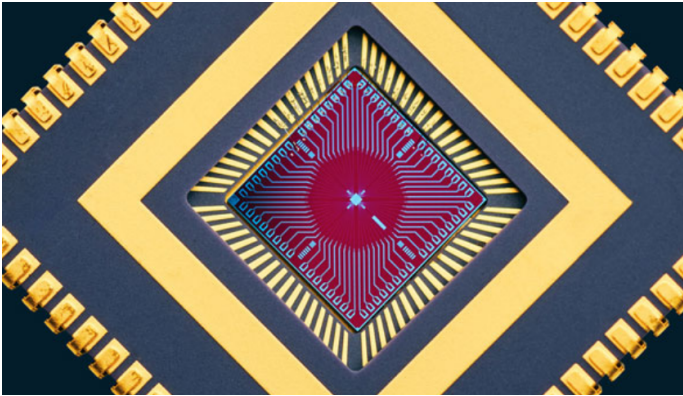


Fig. 4: tA 64-pixel SNSPD array

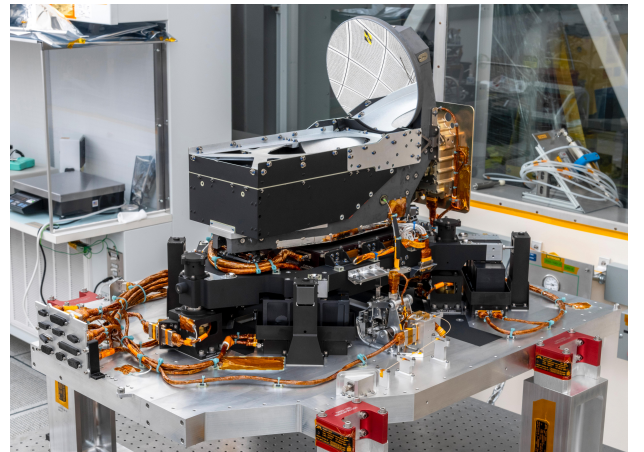


Fig. 5: NASA Prototype transceiver

V. CONCLUSION

FSO is overall a promising technology. Its intrinsic security, given by high directivity and non interceptability, combined with use of unregulated spectrum plays a big advantage with respect to RF communications. The quality of photonic components (modulator, demodulator) and mechanical systems (OBS) have to be really high, as well as the relative electronics control circuitry. Overall this technology will not become cheap in a short period, but presents strategic advantage to space applications, enabling low latency/high throughput between satellites and down to earth, that would otherwise require massive allocation of RF spectrum. Moreover new breakthrough in technology development could amplify the benefits; anyway we have to remember that RF systems have almost 80 years of development, while FSO is a much younger concept but still we can highlight how this technology is almost already surpassing the former over a lot of aspects.

REFERENCES

- [1] A. U. Chaudhry and H. Yanikomeroglu, "Free space optics for next-generation satellite networks," *IEEE Consumer Electronics Magazine*, vol. 10, no. 6, pp. 21–31, 2020.
- [2] H. Singh, N. Mittal, R. Miglani, H. Singh, G. S. Gaba, and M. Hedabou, "Design and analysis of high-speed free space optical (fso) communication system for supporting fifth generation (5g) data services in diverse geographical locations of india," *IEEE Photonics Journal*, vol. 13, no. 5, pp. 1–12, 2021.
- [3] B. K. Saw, G. Singh, and M. Tiwari, "Different modulation schemes employed in free space optical communication systems," in *Optical Technologies for Advancing Communication, Sensing, and Computing Systems*, S. W. Harun, Ed. London: IntechOpen, 2024, ch. 7. [Online]. Available: <https://doi.org/10.5772/intechopen.1007843>
- [4] A. Tou, S. Driz, and B. Fassi, "Designing reliable fso links: selection of optimal dual-polarization modulation schemes based on turbulence conditions," *Journal of Optics*, vol. 27, no. 8, p. 085702, aug 2025. [Online]. Available: <https://doi.org/10.1088/2040-8986/adf3c5>
- [5] M. Xu, M. He, H. Zhang, J. Jian, Y. Pan, X. Liu, L. Chen, X. Meng, H. Chen, Z. Li, X. Xiao, S. Yu, S. Yu, and X. Cai, "High-performance coherent optical modulators based on thin-film lithium niobate platform," *Nature Communications*, vol. 11, no. 1, Aug. 2020. [Online]. Available: <http://dx.doi.org/10.1038/s41467-020-17806-0>
- [6] P. Basso Ricci and G. Lori, "Dqpsk demodulation," *Advanced Tasks, Photonic Devices course, Politecnico di Milano*, 2026.
- [7] A. I. Martinez, G. Cavicchioli, S. Seyedinnavadeh, F. Zanetto, M. Sampietro, A. D'Acerno, F. Morichetti, and A. Melloni, "Self-adaptive integrated photonic receiver for turbulence compensation in free space optical links," 2024. [Online]. Available: <https://arxiv.org/abs/2406.05402>
- [8] A. Bekkali, H. Fujita, and M. Hattori, "New generation free-space optical communication systems with advanced optical beam stabilizer," *Journal of Lightwave Technology*, vol. 40, no. 5, pp. 1509–1518, 2022.
- [9] F. Rocco, "Adaptive modulation schemes for high-capacity free-space optics communications," *Master Degree thesis, Politecnico di Torino*, 2019. [Online]. Available: <https://webthesis.biblio.polito.it/id/eprint/12576>
- [10] C. Fuchs, F. Moll, J. Poliak, A. Reeves, and C. Schmidt, "Optical satellite links for telecommunications and time-transfer," in *2023 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, 2023, pp. 168–174.
- [11] Nasa, "Dsoc," <https://www.nasa.gov/mission/deep-space-optical-communications-dsoc/>.
- [12] W. Zhang, J. Huang, C. Zhang, L. You, C. Lv, L. Zhang, H. Li, Z. Wang, and X. Xie, "A 16-pixel interleaved superconducting nanowire single-photon detector array with a maximum count rate exceeding 1.5 ghz," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1–4, 2019.
- [13] A. J. Annunziata, D. F. Santavica, J. D. Chudow, L. Frunzio, M. J. Rooks, A. Frydman, and D. E. Prober, "Niobium superconducting nanowire single-photon detectors," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 327–331, 2009.
- [14] A. U. Chaudhry and H. Yanikomeroglu, "Laser inter-satellite links in a starlink constellation," 2021. [Online]. Available: <https://arxiv.org/abs/2103.00056>
- [15] M. Garlinska, A. Pregowska, I. Gutowska, M. Osial, and J. Szczepanski, "Experimental study of the free space optics communication system operating in the 8–12 μm spectral range," *Electronics*, vol. 10, no. 8, 2021. [Online]. Available: <https://www.mdpi.com/2079-9292/10/8/875>

Silicon Photonic Micro-Ring Resonator Biosensors: Principles, Performance, and Biomedical Applications

Kosar Khodami

Dept. of Electronics, Information and Bioengineering

Politecnico di Milano

kosar.khodami@mail.polimi.it

Abstract

Silicon photonic micro-ring resonators (MRRs) have emerged as one of the most promising platforms for label-free biosensing. This review covers their working principles, key performance metrics, and advanced sensitivity-enhancement configurations, including slot waveguides, subwavelength grating structures, and the Vernier effect in cascaded resonator systems. Reported bulk sensitivities range from 112 nm/RIU for a single ring resonator to 21,500 nm/RIU for Vernier-effect cascaded MRR-MZI systems. Biomedical applications in cancer cell and biomarker detection are reviewed alongside remaining fabrication and integration challenges.

I. INTRODUCTION

The convergence of silicon photonics and biosensing has produced a new generation of analytical devices capable of detecting molecular interactions in real time, without labels, and at the chip scale. Among the configurations available on silicon-on-insulator (SOI) – Mach–Zehnder interferometers (MZIs), photonic crystal (PhC) cavities, Bragg gratings, and micro-ring resonators – the MRR stands out for its compact footprint, high quality factor, and natural compatibility with dense multiplexed sensor arrays [1], [2]. A comprehensive review of silicon photonic biosensor performance metrics is given by Steglich et al. [6], who catalogue sensitivity and limit-of-detection (LoD) values across all major SOI resonator types.

The sensing mechanism relies on the evanescent field that extends beyond the waveguide core. When a target analyte binds to the functionalized ring surface, the local refractive index (RI) changes, shifting the resonant wavelength – the label-free sensor signal. The SOI platform exploits the high RI contrast between silicon ($n_{\text{Si}} = 3.48$) and silicon dioxide ($n_{\text{SiO}_2} = 1.44$), enabling sub-micron waveguides with strong optical confinement [1]. De Vos et al. [4] demonstrated one of the earliest SOI MRR biosensors, achieving a LoD of 1.6×10^{-6} RIU for protein detection in buffer, establishing SOI MRRs as a viable label-free sensing platform.

From the clinical perspective, early cancer detection is a critical unmet need. Cancer cells exhibit RIs of 1.39–1.402, measurably higher than the RI of normal cells (≈ 1.35) [2]. A chip-integrated array of 32 MRR sensors has been demonstrated for simultaneous quantification of eight cancer biomarkers from patient serum [3], highlighting the multiplexing advantage of this platform for oncology diagnostics.

This paper reviews the physical foundations of MRR sensing (Section II), sensitivity-enhancement strategies (Section III), biosensor architectures (Section IV), biomedical applications (Section V), and open challenges (Section VI).

II. OPERATING PRINCIPLE OF MRR BIOSENSORS

A. Resonance Condition

A micro-ring resonator consists of a circular waveguide loop evanescently coupled to a straight bus waveguide. Resonance occurs when the round-trip optical path length equals an integer multiple of the guided wavelength:

$$\lambda_m = \frac{2\pi r n_{\text{eff}}}{m}, \quad (1)$$

where r is the ring radius, n_{eff} is the effective mode index, and m is the resonance order [2]. At resonance, a sharp dip appears in the bus waveguide transmission spectrum. Any perturbation of n_{eff} due to analyte binding shifts λ_m and constitutes the sensing signal. De Vos et al. [4] provide a detailed experimental characterization of this resonance shift for streptavidin–biotin binding on functionalized SOI rings.

B. Evanescent Field Interaction

The guided mode extends partially into the cladding as an evanescent wave that decays exponentially with perpendicular distance d from the waveguide surface [1]:

$$E(d) = E_0 \exp\left(-\frac{d}{d_p}\right), \quad d_p = \frac{\lambda}{4\pi\sqrt{n_{\text{eff}}^2 - n_c^2}}, \quad (2)$$

where d_p is the penetration depth and n_c is the cladding RI. For a $220 \text{ nm} \times 500 \text{ nm}$ SOI waveguide at $\lambda = 1550 \text{ nm}$, the TM mode places more field power above and below the core than the TE mode, resulting in stronger bulk sensitivity at the cost of higher sidewall-scattering losses [1]. This TE/TM trade-off is a well-documented design choice for SOI biosensors reviewed in depth by Steglich et al. [6].

C. Sensitivity and Quality Factor

Two figures of merit dominate MRR sensor design. The bulk sensitivity S_{bulk} is the resonance wavelength shift per unit RI change:

$$S_{\text{bulk}} = \frac{\Delta\lambda}{\Delta n_{\text{fluid}}}, \quad (3)$$

and the surface sensitivity S_{surf} replaces Δn_{fluid} with the adlayer thickness $\Delta t_{\text{adlayer}}$ to characterize monolayer binding events [1]. The quality factor Q governs the sharpness of the resonance dip and hence the minimum detectable wavelength shift:

$$Q = \frac{\lambda_{\text{res}}}{\Delta\lambda_{\text{FWHM}}}, \quad (4)$$

where $\Delta\lambda_{\text{FWHM}}$ is the full-width at half-maximum [2]. Claes et al. [8] experimentally confirmed that high- Q cascaded SOI rings ($Q \sim 10^4$ – 10^5) achieve LoDs of 8.3×10^{-8} RIU, an order of magnitude below a single ring. The LoD in terms of minimum detectable surface mass density has also been characterized by Steglich et al. [6] for functionalized SOI rings exposed to bovine serum albumin (BSA).

III. PERFORMANCE ENHANCEMENT STRATEGIES

A. Slot Waveguide Integration

In a standard strip waveguide, only $\sim 20\%$ of the guided light interacts with the analyte; in a slot waveguide, two silicon rails separated by a narrow low-RI gap force $>70\%$ of the guided power into the slot region, in direct contact with the cladding medium [1]. This significantly increases both S_{bulk} and S_{surf} . Liu et al. [7] demonstrated a Si_3N_4 slot-waveguide MZI biosensor achieving $S_{\text{bulk}} = 1,300 \text{ nm/RIU}$ with a LoD of 5.4×10^{-6} RIU, a factor of ~ 3.5 improvement over the equivalent strip waveguide sensor. The same group showed that combining the slot geometry with grating couplers for efficient fiber-to-chip light injection allows robust packaging for microfluidic integration [7].

B. Subwavelength Grating Waveguide

Subwavelength grating (SWG) waveguides replace the homogeneous silicon core with a periodic array of alternating high-index (Si) and low-index (SiO_2 or air) blocks, with a period Λ well below the Bragg condition. The guided mode sees an effective medium whose RI is set by the duty cycle, bringing more optical power into the low-index sensing medium [1]. SWG ring resonators, SWG Bragg gratings – realized by interleaving two SWG waveguides with different duty cycles – and SWG racetrack resonators with extended coupling regions have all been implemented on SOI, each providing enhanced evanescent field overlap compared to conventional strip waveguides [1].

C. Vernier Effect in Cascaded Configurations

The most powerful enhancement exploits the Vernier effect by cascading two rings (or a ring and an MZI) with slightly different free spectral ranges (FSRs). If the sensing ring has FSR_1 and the reference ring has FSR_2 , the envelope of the combined spectrum shifts with a magnification factor:

$$M = \frac{\text{FSR}_1}{|\text{FSR}_1 - \text{FSR}_2|}. \quad (5)$$

Claes et al. [8] experimentally demonstrated cascaded SOI MRRs with FSRs of 10.09 nm and 10.66 nm , yielding $M \approx 17.7$ and a measured $S_{\text{bulk}} = 2,169 \text{ nm/RIU}$ – a 19-fold improvement over a single ring. Extending the concept to a cascaded MZI-ring configuration, Jiang et al. [5] reported $S_{\text{bulk}} = 21,500 \text{ nm/RIU}$, with the MZI providing $2,870 \text{ nm/RIU}$ as a standalone, giving a $7.5\times$ Vernier gain. These values, alongside other configurations, are compared in Table I and Fig. 1(b).

TABLE I
PERFORMANCE COMPARISON OF MRR-BASED SENSOR CONFIGURATIONS

<i>Configuration</i>	<i>S_{bulk} (nm/RIU)</i>	<i>LoD (RIU)</i>	<i>Ref.</i>
Single MRR (SOI)	112	1.6×10^{-6}	[4]
MRR with MZI readout	2.5×10^3 ^a	1×10^{-8}	[1]
Cascaded MRR (Vernier)	2,169	8.3×10^{-8}	[8]
MZI-Ring (Vernier)	21,500	n.r.	[5]
Ring (disk) resonator	193	7.3×10^{-8}	[1]
Si ₃ N ₄ slot MZI	1,300	5.4×10^{-6}	[7]
Si ₃ N ₄ MRR (cancer)	568	n.r.	[10]

^aIn $\mu\text{m}/\text{RIU}$; n.r. = not reported.

IV. MRR BIOSENSOR ARCHITECTURES

A. Single-Ring and Add-Drop Configurations

The single-ring add-drop configuration uses a second bus waveguide to collect resonant power, improving signal-to-noise ratio. De Vos et al. [4] demonstrated SOI add-drop MRRs with $r = 5 \mu\text{m}$ and $Q \approx 20,000$, obtaining a LoD of 1.6×10^{-6} RIU and detecting interleukin-6 at concentrations down to 5 ng/mL without labeling. Steglich et al. [6] further showed that dual-polarization readout – tracking both TE and TM resonances of the same ring simultaneously – enables discrimination between bulk RI changes and surface adlayer formation, removing a key ambiguity in single-ring measurements.

B. Chip-Integrated Multiplexed Sensor Arrays

The compact footprint of MRRs allows hundreds of addressable sensors on a single chip. Washburn et al. [3] demonstrated a 32-sensor SOI array with two thermal reference rings for simultaneous quantification of eight cancer biomarkers – AFP, ALCAM, CA-15-3, CA-19-9, CA-125, CEA, osteopontin, and PSA – from 1 mL patient serum in under 60 minutes. Wavelength-division multiplexing (WDM) of the individual ring resonances allows single-laser swept readout, with active thermo-optic tuning aligning each ring to its WDM channel.

C. Suspended MRR Geometry

In suspended MRRs, the ring waveguide is released from the buried oxide to allow analyte contact on both top and bottom surfaces. Gaur et al. [9] applied this geometry to label-free detection of Herceptin (trastuzumab) for breast cancer therapy monitoring, demonstrating approximately double the surface sensitivity of a substrate-supported ring of identical dimensions. Microfluidic packaging for such chip-scale platforms was demonstrated by Adamopoulos et al. [12], who developed 3D-printed PDMS transfer-molded cartridges with $<150 \mu\text{m}$ channel spacing, achieving parallel analyte delivery to multiple ring sensors without cross-contamination in a CMOS back-end compatible process.

V. BIOMEDICAL APPLICATIONS: CANCER CELLS AND BIOMARKERS

A. RI Contrast Of Cancer Cells

The basis for MRR cancer sensing is the measurable RI difference between normal and malignant cells. As summarized by Sajan et al. [2], normal cells have $\text{RI} \approx 1.35$ while cancer cell lines range from HeLa ($\text{RI} = 1.390$) to Jurkat ($\text{RI} = 1.402$). This $\Delta n \approx 0.04$ RIU translates to a resonance shift of ~ 4.5 nm in a single MRR [4] and ~ 860 nm in a Vernier MZI-ring system [5] – both resolvable above the noise floor of a thermally stabilized platform [8].

B. Cascaded MRR for Gastric Cancer Detection

In the cascaded two-ring configuration illustrated in Fig. 1(a), one ring (Ring A) is hermetically sealed under a protective cladding and acts as a real-time thermal reference, while the second ring (Ring B) is exposed to the analyte through an open sensing window [2]. An FDTD simulation of this geometry shows a resonance shift of 0.38 nm in Ring B when switching from normal-cell buffer ($\text{RI} = 1.35$) to gastric cancer cell medium ($\text{RI} = 1.39$), as seen in the transmission spectra of Fig. 1(b). The two cell types yield distinct dips below and above $1.85 \mu\text{m}$, enabling unambiguous discrimination. Nejad et al. [11] further demonstrated a tunable PhC nanocavity nano-biosensor resolving RI differences as small as 10^{-5} RIU between cell lines, achieving 790 nm/RIU sensitivity for cervical cancer cells at 1550 nm.

C. Silicon Nitride Biosensors for Cancer Biomarkers

Kumaar and Sivasubramanian [10] designed a Si_3N_4 rib-slot waveguide MZI (970 nm wide, 400 nm thick) achieving $S_{\text{bulk}} = 568 \text{ nm/RIU}$ and device sensitivity of 2.07 RIU/RIU, operating on cancer cell blood samples as a bulk analyte solution. The slot-waveguide MZI results of Liu et al. [7] complement this work by confirming that Si_3N_4 slot geometries consistently outperform SOI strip waveguides for bulk analyte sensing, while maintaining compatibility with standard grating-coupler chip interfaces.

D. Multiplexed Cancer Biomarker Quantification

Washburn et al. [3] quantified eight cancer biomarkers simultaneously from patient serum using a chip-integrated SOI MRR array with antibody-functionalized surfaces, achieving clinically relevant LoDs for PSA, CEA, and CA-125 in a one-hour workflow without sample preprocessing. The microfluidic packaging solution developed by Adamopoulos et al. [12] directly supports such platforms by enabling automated multi-stream sample delivery to the chip with no cross-talk.

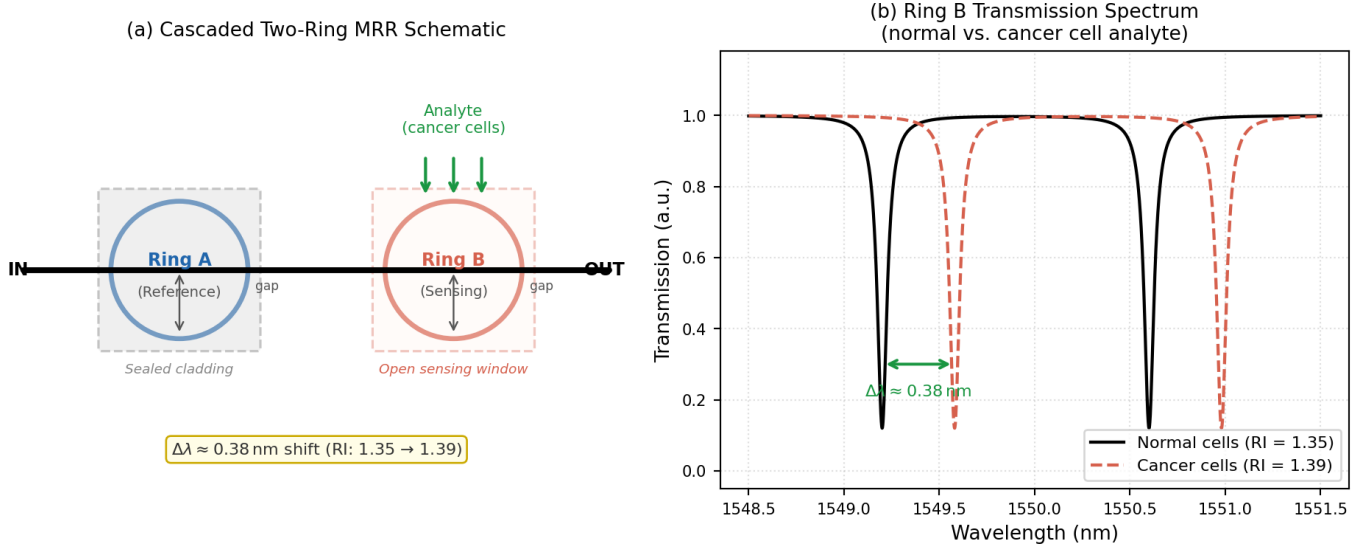


Fig. 1. (a) Schematic of the cascaded two-ring MRR biosensor. Ring A is sealed under a protective cladding and serves as a thermal reference; Ring B has an open sensing window exposed to the analyte. Both rings are evanescently coupled to the same bus waveguide. (b) Simulated transmission spectra of Ring B for normal-cell buffer (RI = 1.35) and gastric cancer cell analyte (RI = 1.39), showing the $\approx 0.38 \text{ nm}$ resonance shift reported in [2]. The shift is the primary sensor signal; thermal drift common to both rings is cancelled by the reference.

VI. CHALLENGES AND FUTURE DIRECTIONS

Despite impressive results, several barriers remain before MRR biosensors achieve routine clinical deployment.

Thermal stability: The silicon thermo-optic coefficient ($dn/dT \approx 1.8 \times 10^{-4} \text{ K}^{-1}$) causes resonance drift that can mask weak analyte signals [1]. Claes et al. [8] addressed this using the sealed reference ring of the cascaded system as a real-time drift compensator, reducing temperature-induced noise by an order of magnitude.

Surface biofunctionalization: Selective, high-density antibody immobilization on silicon surfaces is critical for specificity in blood matrices. Steglich et al. [6] review functionalization protocols for SOI MRRs, noting that amine-reactive cross-linking on thermal oxide surfaces offers the best coverage uniformity, while direct silanization of silicon sidewalls remains less reproducible.

On-chip light sourcing: Most platforms couple external tunable lasers via grating couplers, introducing insertion losses of 3–10 dB per facet [2]. Monolithic III-V-on-SOI laser integration is advancing, but foundry-compatible on-chip sources are not yet available at low cost.

Microfluidic packaging: Adamopoulos et al. [12] showed that 3D-printed PDMS cartridges can deliver multiple analyte streams to an SOI chip with no inter-channel cross-talk, but scaling this to wafer-level assembly remains an engineering challenge.

Looking ahead, suspended MRR geometries [9] and the SiON waveguide platform – whose RI is tunable between 1.44 and 2.00 by nitrogen content [2] – offer new design degrees of freedom. The slot-waveguide results of Liu et al. [7] also point toward environmental monitoring as a near-term application, where the sub-ppm sensitivity of Si_3N_4 slot MZIs is well matched to water quality sensing.

VII. CONCLUSION

Silicon photonic micro-ring resonators have matured into a well-characterized, chip-scale biosensing platform with demonstrated clinical relevance. The resonance condition $\lambda_m = 2\pi r n_{\text{eff}}/m$ provides a robust transduction mechanism whose sensitivity can be systematically enhanced – from 112 nm/RIU for a single SOI ring [4] to 21,500 nm/RIU for a Vernier-effect MZI-ring cascade [5] – through slot waveguide geometries [7], SWG structures, and FSR-engineering of cascaded resonators [8]. Multiplexed arrays of 32 rings have simultaneously quantified eight cancer biomarkers from patient serum [3], and suspended MRR geometries [9] extend sensitivity by exposing both ring surfaces to the analyte. The main remaining barriers – microfluidic packaging [12], on-chip light sourcing, and surface chemistry [6] – are all areas of active worldwide research, and their resolution will accelerate the translation of MRR biosensors into point-of-care clinical instruments.

REFERENCES

- [1] C. Dhote, A. Singh, and S. Kumar, “Silicon photonics sensors for biophotonic applications—A review,” *IEEE Sensors J.*, vol. 22, no. 19, pp. 18228–18239, Oct. 2022.
- [2] S. Cheeran Sajan, A. Singh, P. K. Sharma, and S. Kumar, “Silicon photonics biosensors for cancer cells detection—A review,” *IEEE Sensors J.*, vol. 23, no. 4, pp. 3366–3377, Feb. 2023.
- [3] A. L. Washburn, W. W. Shia, K. A. Lenkeit, S.-H. Lee, and R. C. Bailey, “Multiplexed cancer biomarker detection using chip-integrated silicon photonic sensor arrays,” *Analyst*, vol. 141, no. 18, pp. 5358–5365, 2016.
- [4] K. De Vos, I. Bartolozzi, E. Schacht, P. Bienstman, and R. Baets, “Silicon-on-insulator microring resonator for sensitive and label-free biosensing,” *Opt. Express*, vol. 15, no. 12, pp. 7610–7615, 2007.
- [5] X. Jiang, Y. Chen, F. Yu, L. Tang, M. Li, and J.-J. He, “High-sensitivity optical biosensor based on cascaded Mach-Zehnder interferometer and ring resonator using Vernier effect,” *Opt. Lett.*, vol. 39, no. 22, pp. 6363–6366, 2014.
- [6] P. Steglich, M. Hulsemann, B. Dietzel, and A. Mai, “Optical biosensors based on silicon-on-insulator ring resonators: A review,” *Molecules*, vol. 24, no. 3, p. 519, 2019.
- [7] Q. Liu, X. Tu, K. W. Kim, J. S. Kee, Y. Shin, K. Han, Y.-J. Yoon, G.-Q. Lo, and M. K. Park, “Highly sensitive Mach-Zehnder interferometer biosensor based on silicon nitride slot waveguide,” *Sens. Actuators B, Chem.*, vol. 188, pp. 681–688, Nov. 2013.
- [8] T. Claes, W. Bogaerts, and P. Bienstman, “Experimental characterization of a silicon photonic biosensor consisting of two cascaded ring resonators based on the Vernier-effect,” *Opt. Express*, vol. 18, no. 22, pp. 22747–22761, Oct. 2010.
- [9] G. Gaur, S. Hu, R. L. Mernaugh, I. I. Kravchenko, S. T. Retterer, and S. M. Weiss, “Label-free detection of Herceptin using suspended silicon microring resonators,” *Sens. Actuators B, Chem.*, vol. 275, pp. 394–401, Dec. 2018.
- [10] P. Kumaar and A. Sivasubramanian, “Design and bulk sensitivity analysis of a silicon nitride photonic biosensor for cancer cell detection,” *Int. J. Opt.*, vol. 2022, pp. 1–9, May 2022.
- [11] H. E. Nejad, A. Mir, and A. Farmani, “Supersensitive and tunable nano-biosensor for cancer detection,” *IEEE Sensors J.*, vol. 19, no. 13, pp. 4874–4881, Jul. 2019.
- [12] C. Adamopoulos, A. Gharia, A. Niknejad, V. Stojanovic, and M. Anwar, “Microfluidic packaging integration with electronic-photonic biosensors using 3D printed transfer molding,” *Biosensors*, vol. 10, no. 11, p. 177, Nov. 2020.