Sensors & Transducers, Vol. 274, Issue 3, October 2026, pp. 12-18

www.sensorsportal.com

Sensors & Transducers

Published by IFSA Publishing, S. L., 2026
http://www.sensorsportal.com

Silicon Photonics: Basics and Applications

[1] H. J. EICHLER, [2, *] B. SZYSZKA, [2] M. BURLA and [3] O. LUX

[1] Technische Universität Berlin, Institut für Physik und Astronomie, 10623 Berlin, Germany
[2] Technische Universität Berlin, Institut für Hochfrequenz- und Halbleiter-Systemtechnologien, 10587 Berlin, Germany
[3] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, 82234 Oberpfaffenhofen, Germany
[2] Tel.: +49 30 314-27382
E-mail: bernd.szyszka@tu-berlin.de

Received: 8 Sept. 2026 /Revised:19 Oct. 2026 /Accepted: 26 Oct. 2026 /Published: 30 Oct. 2026

Abstract: Silicon photonics denotes optical systems in which photonic components are integrated and fabricated in a manner analogous to electronic integrated circuits. Photons, or light waves, propagate through waveguides often etched into thin silicon CMOS layers. Their effective refractive index can be controlled by nanoscale structures, such as holes, enabling both linear and curved waveguiding. Strong optical pumping can induce stimulated Raman scattering, leading to high-gain amplification and, under suitable conditions, to Raman laser action. Light modulation in silicon is also possible by leveraging several physical phenomena, namely plasma-dispersion effect (the change in silicon's refraction index due to carriers, either by their injection in PIN junctions, or depletion in p-n junctions), or electro-absorption effect. Light coupled out of the waveguides can be detected by conventional photodetectors integrated on the silicon photonic chip. Electronic circuits for the generation, processing, and detection of photonic signals can likewise be integrated on the same chip. Thus, photonic devices can serve as transmitters and receivers, or as combined transceivers, in optical fiber communication systems. Silicon photonic chips are expected to help meet the continuously increasing data-rate and bandwidth demands of the global Internet. Longitudinally structured photonic waveguides can serve as optical filters, while numerous applications, including autonomous driving and medical sensing, are being investigated for large-scale deployment. This review summarizes fundamental concepts of silicon photonics and revisits selected experimental results previously reported by the former Optical Institute, now the Institute of Physics and Astronomy, at Technische Universität Berlin, placing them into the context of recent applications.

Keywords: NLO of silicon, Raman laser, Silicon photonics, CMOS platform, Glass fiber, Data processing and transfer, Sensing, Quantum computing.

1. Introduction

Silicon Photonics denotes optical waveguide systems built in a manner analogous to electronic transistor circuits. Photonic devices for the generation, amplification, modulation, switching, deflection, processing, and detection of light can be constructed on a complementary metal–oxide–semiconductor (CMOS) platform [1, 2]. Thus, silicon photonic chips are expected to help meet the increasing data-rate and bandwidth demands of the global Internet [3].

Numerous applications, including fiber-optic communications, autonomous driving, and medical sensing, are being investigated for large-scale deployment. Due to their CMOS compatibility, the integration of optical and electrical signal processing on a single platform enables ultra-high data-rate transmission in data centers and even on-chip communication.

Scope and contribution of this review is to explain updated applications for communications, lidar systems, gyroscopes, healthcare, AI/datacenter and quantum-photonics applications versus the findings

previously published on experiments at Technische Universität Berlin [4].

2. Optical Communication Systems

Today, digital data transmission has become an essential and integral part of modern society. Optical communication systems, in which light is used as the transmission medium, generally consist of a transmitter that encodes a message into an optical signal, an optical fiber that carries the signal to its destination, and a receiver that retrieves the information from the received optical signal, as shown in Fig. 1.

Optical fibers are typically made of glass, with silicon dioxide (SiO_2) as their primary material. For bidirectional operation, the transmitter and receiver can be integrated into a single device called a transceiver.

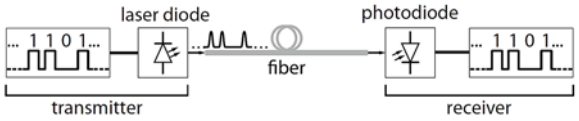


Fig. 1. Optical communication via glass fibers. Multiple data channels are coupled into one fiber [5].

Semiconductor laser transmitters are key components of broadband communication systems. With the ever-increasing demand for bandwidth, speed, and efficiency, diode-laser technology is continuously evolving to provide optical communication systems with higher transmission speeds, lower production costs, smaller dimensions, and lower power consumption.

3. Optical Waveguides

Silicon photonics developed during the final decades of the last century, although it was not initially based on silicon waveguides. Various linear, nonlinear, and electro-optic effects and applications had already been demonstrated in bulk silicon [5–8].

In recent years, the strongest drive of silicon photonics development has been the need for high-speed data transmission in glass fibers [10]. For this purpose, a laser beam in the 1330 nm wavelength range (O-band) or in the 1550 nm range (C-band) is coupled into a silicon waveguide that provides low-loss transmission [11]. A section of the waveguide serves as an electro-optic modulator, encoding the data onto the laser beam. While silicon is centrosymmetric and displays no ordinary Pockels effect, electro-optic modulation is possible in silicon by leveraging other physical phenomena, such as plasma-dispersion effect – that is, the change in silicon's refraction index due to carriers, either by their injection in PIN junctions, or depletion in p-n junctions – or electro-absorption effect, that allows the realization of electro absorption modulators (EAMs). Recent progress of EAMs has shown devices capable of 3 dB bandwidths in excess of 100 GHz, high energy efficiency in the 10s fJ/bit range, sub-100 micrometer lengths and CMOS compatible fabrication [12]. Furthermore, integration of nonlinear materials e.g. within waveguide trenches, has also allowed the realization of efficient and high-speed electro-optic modulators in silicon based on Pockels effect at commercial level [13]. The waveguide, including the modulator section, is integrated with an electronic driver circuit on a small silicon chip and forms an optical transmitter [14, 15]. The modulated laser beam is then coupled into the glass fiber, which guides the data stream over large distances.

At the fiber endface, the data stream is detected by a photo detector, referred to as the receiver. For bidirectional transmission over a fiber, the transmitter and receiver can be combined into a single photonic device, the transceiver. Optical waveguides used for the construction of transceivers and other silicon photonic devices are shown in Fig. 2.

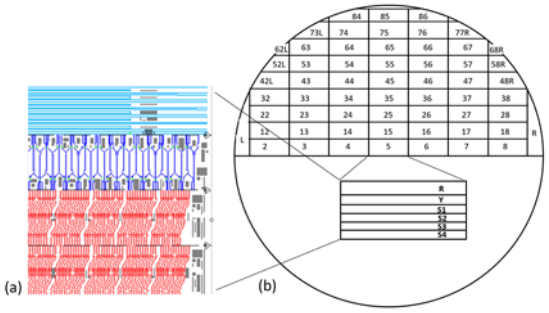


Fig. 2. Example for the production of photonic chips on Si wafers. 20 cm wafer with 100 chips (b), 800 devices per chips with size of 11 × 25 mm^2 (a). Designed at TU Berlin, manufactured at IHP Frankfurt (Oder). (a) shows some details of the photonic layout with Raman waveguides R, coupling devices Y and other components S1 to S4.

Waveguides are etched into, for example, 200 nm thick silicon layers on oxidized CMOS silicon chips and covered by a structured mask. Rectangular silicon photonic waveguides may have cross-sectional dimensions of approximately 200 × 500 nm. Mostly linear waveguides are shown. Light is coupled into a waveguide by focusing the divergent beam emerging from an optical fiber onto the waveguide endface. A circular waveguide may serve as an optical ring resonator, as depicted in Fig. 3. Light is coupled into the ring by the evanescent field of a nearby linear waveguide.

Glass fibres for data transmission are mainly operated at wavelengths of 1.3 and 1.6 µm. Therefore, many SiPho developments are carried out at these wavelengths. InGaAsP laser diodes are available, but their integration onto silicon wafers remains

challenging. It is therefore desirable to develop silicon-based light sources instead [16–18]. The weak electroluminescence of silicon can be enhanced and spectrally shifted using silicon quantum dots. Laser action has been demonstrated under optical pumping with a femtosecond (fs) laser. Electrical excitation of diodes at the desired wavelength [17] has yet to be demonstrated. SiGe photodiodes are used for optical detection. Typical mode profiles in Si waveguides of different dimensions are shown in Fig. 4. Recent efforts are focused on heterogeneous or hybrid integration of III-V materials on silicon to realize light sources. A number of high-quality reviews have been reported on the topic for the interested reader [19, 20].

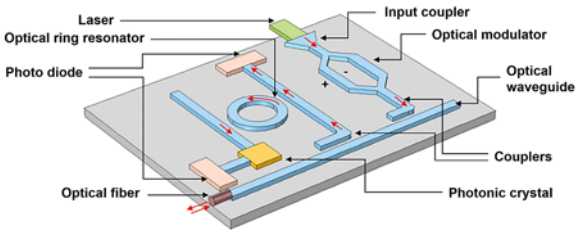


Fig. 3. Scheme of photonic devices and integrated photonic circuits (see text). Source: Comsol Multiphysics Software.

4. Wavelength Filters

The wavelength filter shown in Fig. 5 is produced by etching holes with a diameter a into a linear waveguide. This modifies the effective refractive index of the waveguide in the region containing the holes. The resulting structure acts as a wavelength-selective filter or Fabry–Pérot resonator. As shown in previous work by our group [3] Fig. 5(b), the transmission spectra for different cavity lengths l_c exhibit distinct resonance wavelengths. The resonance condition is determined by the optical path length of the cavity, with high transmission occurring when the cavity length corresponds to an integer multiple of half the effective wavelength in the cavity. Increasing the cavity length therefore shifts the resonance wavelengths. The total length of the filter is below 5 µm. The resonance wavelengths are determined by the cavity length and the effective refractive index of the waveguide. The latter is dominated by the high refractive index of silicon.

A Mach–Zehnder interferometer provides another approach to wavelength-selective filtering and is also widely used for optical modulation. The optical signal is split into two waveguide arms and subsequently recombined. Their wavelength-dependent interference allows the device to function as a wavelength filter. By electrically controlling the phase in the arms, it can also be used as an electro-optic modulator.

5. Optical Modulators

A Fabry-Pérot filter can also be tuned by injecting electron–hole pairs into the cavity region of the waveguide. This changes the effective refractive index of silicon, as has previously been demonstrated in previous work by our group in bulk silicon [8]. Instead of optical excitation, electrical carrier injection into a p-i-n junction can therefore be used to construct fast electro-optic modulators integrated into transceivers for optical data transmission and other photonic devices.

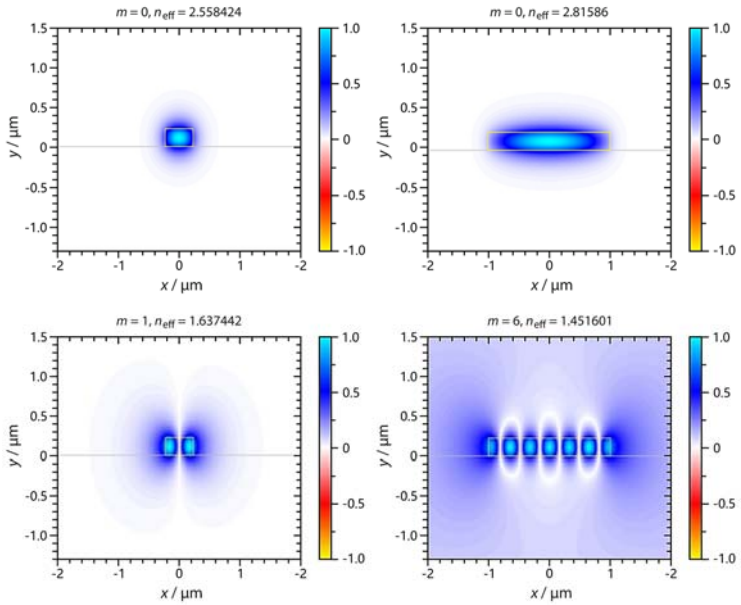


Fig. 4. Transverse mode profiles (normalized electric field) of Si waveguides with a thickness of 0.22 µm and widths of 0.45 µm (left panels) and 2 µm (right panels), partially embedded in silicon oxide. The profiles were calculated using FullWAVE software from RSoft (TU Berlin, 2013). Higher-order transverse modes, TE$_{mn}$, with additional field maxima in the transverse directions can also exist for larger waveguide thicknesses. Adopted from [5].

The basic configuration of such an optical modulator is shown in Fig. 6. Electrons and holes are injected into a waveguide embedded in a p-i-n junction. Applying a DC or AC voltage modulates the carrier concentration and, consequently, the effective refractive index of the waveguide. Fabry-Pérot modulators can be very compact and efficient compared with Mach-Zehnder modulators, while Mach-Zehnder modulators generally offer greater stability against temperature variations.

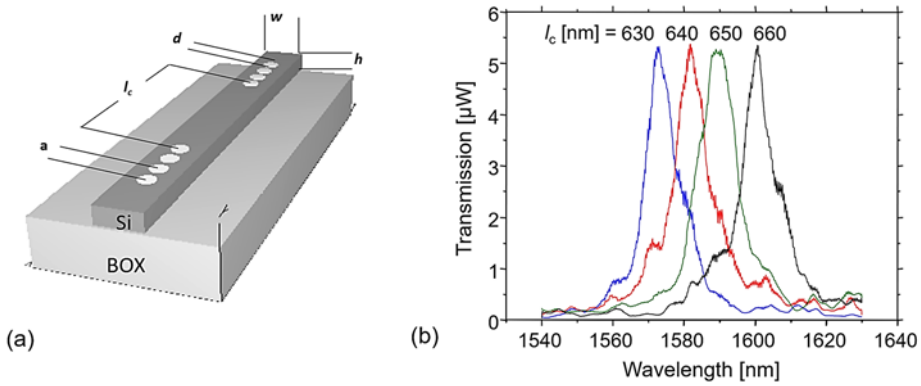


Fig. 5. Fabry-Perot micoresonators (a) or 1D photonic crystals in SOI waveguides. Design parameters: Wavelength ~1550 nm, 220 nm Si waveguide thickness on 2 μm buried oxide (BOX). Photonic crystal microcavities: Cavity length l_c ~ mirror separation (1st order cavity with l_c = 630 nm). Constants: Waveguide width: w ~500 nm, Lattice constant: a = 420 nm. Variables: Number of holes, cavity length l_c, hole diameter d = 200 … 270 nm, (b) resulting transmission spectra for 1st order single cavities (4+4 holes) with different l_c. Adopted from [3].

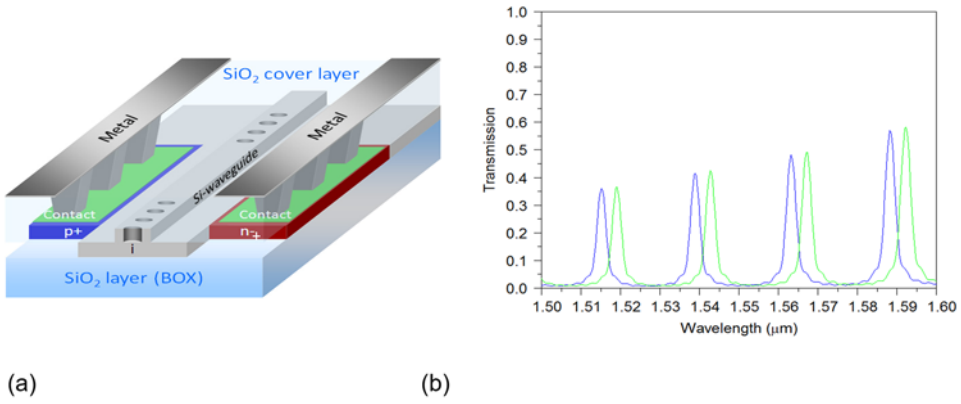


Fig. 6. Fabry-Perot modulator with p-i-n diode (a) enables tuning of the optical index by means of free carrier plasma dispersion effect. The resulting transmittance spectra for different settings of the diode are shown in (b). The FP cavity length amounts to about 4 times of half the wavelength so that 4 transmission peaks appear. Intensity modulation is achieved by changing the index of refraction of the cavity by Δn ~5 x 10^{-3}. Adopted from [2].

6. Application Scenarios and Key Projects

Richard A. Soref is considered one of the pioneers of silicon photonics in the United States. In 1985, he published his paper entitled “Single-crystal silicon: a new material for 1.3 and 1.6 μm integrated-optical components.” in *Electronics Letters* [21]. Since then, major international companies have contributed to the development of silicon photonics, including:

– Cisco Systems, San Jose, California, USA;
– Hamamatsu Photonics, Japan;
– IBM Corporation, USA;
– Intel Corporation, USA;
– STMicroelectronics, Switzerland/France.

The Berlin-based silicon photonics company Sicoya was established by a team that began working on silicon photonics in 2007. The company develops and manufactures silicon photonic transceiver devices and is involved in the European Union-funded STARLight project, which aims to develop technologies for the mass production of silicon photonic devices on 300 mm wafers. Significant research and development activities in silicon photonics are also ongoing in Spain and the United Kingdom. NVIDIA has invested in the laser companies Coherent and Lumentum for research and development related to silicon photonics and optical interconnects for large data centers. Industry publications such as *Laser Focus World* and *Electro*

Optics regularly report on these developments. Fig. 7 provides an overview of the main application areas of silicon photonics.

Silicon photonics is becoming a key technology in modern communication, sensing, and computing systems because it enables high-speed data transmission with low power consumption. A major application is in optical fiber transceivers for data centers and telecommunication networks, where silicon photonic transceivers enable fast and energy-efficient data transfer. This is particularly important for AI and data-center interconnects, which require high-speed server-to-server communication to process large amounts of data.

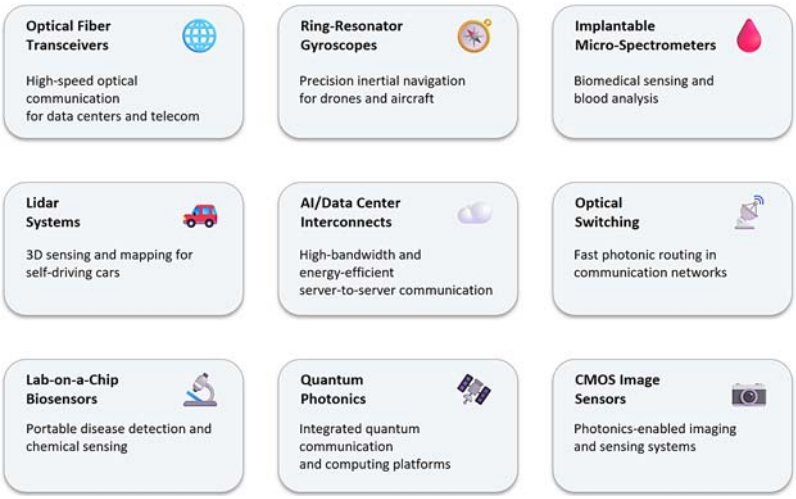


Fig. 7. Overview on the key application areas of SiPho technologies. The image is the author's own work (see text).

In transportation technology, silicon photonics is increasingly used in Lidar systems for autonomous vehicles. These systems generate accurate three-dimensional maps for navigation and obstacle detection. Optical switching technologies can further improve communication networks by enabling faster photonic signal routing and supporting the increasing demand for Internet traffic.

Recent work from Taiwan has demonstrated the development of on-chip gyroscopes using silicon photonics [22, 23]. Further improvements in precision are the subject of ongoing research [24].

Biomedical and healthcare applications represent another important field. Implantable micro-spectrometers can perform real-time blood analysis and health monitoring, while lab-on-a-chip biosensors provide portable and rapid disease detection for medical and environmental applications.

Silicon photonics also supports advanced scientific technologies such as ring-resonator gyroscopes for precise aircraft and drone navigation, quantum photonics for secure communication and quantum computing, and CMOS image sensors for enhanced imaging and sensing performance. Together, these applications demonstrate the growing impact of silicon photonics across science and technology.

7. Raman Lasers and Frequency Converters

Silicon is an indirect-bandgap semiconductor and therefore poorly suited for conventional laser emission. However, its pronounced third-order optical nonlinearity enables optical amplification, laser operation, and frequency conversion through stimulated Raman scattering (SRS) and four-wave mixing (FWM). Strong optical confinement in silicon-on-insulator (SOI) waveguides further enhances these nonlinear interactions.

Raman scattering originates from the interaction of light with optical phonons of the silicon crystal lattice. At sufficiently high pump intensities, stimulated Raman scattering provides optical gain at a frequency shifted by approximately 15.6 THz (520 cm^{-1}) towards longer wavelengths. For example, pumping at 1550 nm generates Stokes radiation near 1686 nm. By introducing optical feedback through suitable resonator structures, Raman laser operation becomes possible without requiring a direct electronic bandgap.

At Technische Universität Berlin, we initially investigated nonlinear optical effects in bulk crystalline silicon and demonstrated stimulated Raman scattering and Raman laser operation, including experiments at low temperatures [7, 8]. Subsequently, we designed and characterized integrated silicon photonic waveguide structures fabricated at the IHP CMOS foundry in Frankfurt (Oder), Germany.

An important limitation at telecommunication wavelengths is two-photon absorption (TPA), which generates electron–hole pairs and consequently causes additional free-carrier absorption (FCA). These losses can be reduced through carrier extraction using p-i-n junctions or by operating at longer infrared wavelengths.

Besides Raman scattering, silicon's Kerr nonlinearity enables four-wave mixing, in which interacting optical waves generate new frequency components. This process is particularly attractive for wavelength conversion in optical communication systems and, under suitable dispersion conditions, for generating optical frequency combs and ultrashort pulses. Such nonlinear functionalities extend silicon photonics beyond conventional signal transmission towards integrated spectroscopy, optical sensing, and advanced communication technologies.

8. Conclusions

Silicon photonics (SiPho) uses light (photons) in addition to electrical signals (electrons) to process and transmit data in compact communication and sensing systems. It combines optical waveguides, modulators, filters, and photodetectors on a silicon substrate and can be integrated with electronic components. SiPho transceivers in glass-fiber networks help overcome the bandwidth limitations of copper-based interconnects in applications such as data centres, telecommunications, sensing, and quantum computing, while offering high data rates and low power consumption. Cost-effective mass production is enabled by established semiconductor manufacturing platforms, such as CMOS technology. Novel thin-film concepts for the fabrication of direct-bandgap silicon devices by embedding nc-Si in an oxide matrix are being investigated, potentially opening the way to silicon-based laser diodes [17].

Acknowledgements

The authors would like to thank Dr. Christoph Theiss of Sicoya GmbH for his explanations of the structure and objectives of the STARLight project, as well as Prof. Jürgen Eichler of the Academy for Laser Safety in Berlin and Prof. Martin Reghely and Prof. Sigurd Schrader of the Technical University of Applied Sciences Wildau for providing information on their past and ongoing work in silicon photonics. M. Burla acknowledges support by European Research Council Starting Grant ELEPHANT 948624.

References

[1]. S. Meister, H. J. Eichler, Photonic integrated circuits for optical communication, *Optik & Photonik*, Vol. 7, Issue 2, 2012, pp. 59-62.

[2]. S. Meister, A. Al-Saadi, B. A. Franke, S. Mahdi, et al., Photonic crystal microcavities in SOI waveguides produced in a CMOS environment, *Proceedings of SPIE*, Vol. 7606, 2010, 760616.

[3]. A. Al-Saadi, H. J. Eichler, S. Meister, High speed silicon electro-optic modulator with p-i-n comb diode, *Optical and Quantum Electronics*, Vol. 44, Issue 3-5, 2012, pp. 125-131.

[4]. H. J. Eichler, B. Szyszka, O. Lux, Silicon nonlinear optics and photonics, *in Proceedings of the 9th International Conference on Optics, Photonics and Lasers (OPAL)*, 2026, pp. 9-12.

[5]. H. J. Eichler, J. Eichler, O. Lux, Lasers: Basics, Advances and Applications, *Springer*, Cham, 2018.

[6]. H. J. Eichler, B. Liu, M. Kayser, S. I. Khomenko, Er:YAG-laser at 2.94 μm Q-switched by a FTIR-shutter with silicon output coupler and polarizer, *Optical Materials*, Vol. 5, Issue 4, 1996, pp. 259-265.

[7]. O. Lux, H. Rhee, V. Lisinetskii, H. J. Eichler, Stimulated Raman scattering and Raman laser operation in silicon single crystals at low temperatures, *Laser Physics Letters*, Vol. 9, Issue 12, 2012, pp. 858-867.

[8]. H. Rhee, O. Lux, S. Meister, U. Woggon, et al., Operation of a Raman laser in bulk silicon, *Optics Letters*, Vol. 36, Issue 9, 2011, pp. 1644-1646.

[9]. H. J. Eichler, F. Massmann, Diffraction efficiency and decay times of free-carrier gratings in silicon, *Journal of Applied Physics*, Vol. 53, Issue 4, 1982, pp. 3237-3242.

[10]. S. Meister, H. J. Eichler, A. Al-Saadi, B. Franke, et al., Optical modulator, Patent US9195112B2, *United States*, 2015.

[11]. S. Mahdi, M. Grehn, A. Al-Saadi, M. Höfner, et al., Facet preparation of silicon nano-waveguides by cleaving the SOI chip, *Journal of Nonlinear Optical Physics & Materials*, Vol. 20, Issue 4, 2011, pp. 509-523.

[12]. D. Steckler, et al., Ultrafast electro-absorption modulators and fin-photodiodes in a SiGe photonics platform, in *Proceedings of the 52nd European Conference on Optical Communication (ECOC)*, 2026.

[13]. A. Schwarzenberger, et al., Silicon-organic hybrid (SOH) Mach-Zehnder modulators (MZM) for single-carrier IM/DD line rates of 500 Gbit/s and beyond, *Journal of Lightwave Technology*, Vol. 44, Issue 3, 2026, pp. 1030-1046.

[14]. S. Meister, H. Rhee, A. Al-Saadi, B. A. Franke, et al., Matching p-i-n-junctions and optical modes enables fast and ultra-small silicon modulators, *Optics Express*, Vol. 21, Issue 13, 2013, pp. 16210-16221.

[15]. S. Meister, H. Rhee, A. Al-Saadi, B. A. Franke, et al., High-speed Fabry-Pérot optical modulator in silicon with 3-μm diode, *Journal of Lightwave Technology*, Vol. 33, Issue 4, 2015, pp. 878-881.

[16]. D. C. Wang, C. Zhang, P. Zeng, W. J. Zhou, et al., An all-silicon laser based on silicon nanocrystals with high optical gains, *Science Bulletin*, Vol. 63, Issue 2, 2018, pp. 75-77.

[17]. S. M. A. Hosseini-Saber, R. Muydinov, N. Ahmadi, J. Ibaceta-Jaña, et al., Photoluminescence and stability of sputtered SiOx layers, *Physica Status Solidi A*, Vol. 218, Issue 20, 2021, 2100277.

[18]. F. Maier-Flaig, J. Rinck, M. Stephan, T. Bocksrocker, et al., Multicolor silicon light-emitting diodes (SiLEDs), *Nano Letters*, Vol. 13, Issue 2, 2013, pp. 475-480.

[19]. Y. Han, H. Park, J. Bowers, K. M. Lau, Recent advances in light sources on silicon, *Advances in Optics and Photonics*, Vol. 14, Issue 3, 2022, pp. 404-454.

[20]. M. Tang, S. Chen, O. Almutairi, J. Wu, et al., Integration of III-V lasers on Si for Si photonics, *Progress in Quantum Electronics*, Vol. 66, 2019, pp. 1-18.

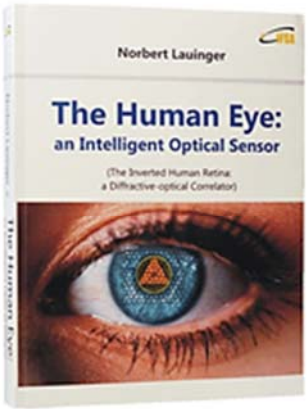
[21]. R. A. Soref, J. P. Lorenzo, Single-crystal silicon: A new material for 1.3 and 1.6 μm integrated-optical components, *Electronics Letters*, Vol. 21, Issue 21, 1985, pp. 953-954.
[22]. Y. C. Wang, Z. X. Liu, J. Q. Li, H. Y. Zhang, et al., Silicon photonics multi-function integrated optical circuit for miniaturized fiber optic gyroscope, *Journal of Lightwave Technology*, Vol. 41, Issue 19, 2023, pp. 6324-6332.
[23]. Y. J. Hung, T.-H. Kuo, M.-H. Tsai, S.-T. Yang, et al., Silicon photonics multi-function integrated optical circuit with hybrid (III-V) photodiode for miniaturized fiber optic gyroscope applications, *Journal of Lightwave Technology*, Vol. 44, Issue 7, 2026, pp. 2613-2621.
[24]. M. Voiculescu, M. Regehly, Optische Gyroskope auf dem Chip: Der Weg zur maximalen Empfindlichkeit, in *Proceedings of the 5th EcoPhotonics Symposium*, 2026 (in German).

Published by International Frequency Sensor Association (IFSA) Publishing, S. L., 2026 (http://www.sensorsportal.com).

Norbert Lauinger

IFSA

The Human Eye:
an Intelligent Optical Sensor
(The Inverted Human Retina: a Diffractive-optical Correlator)

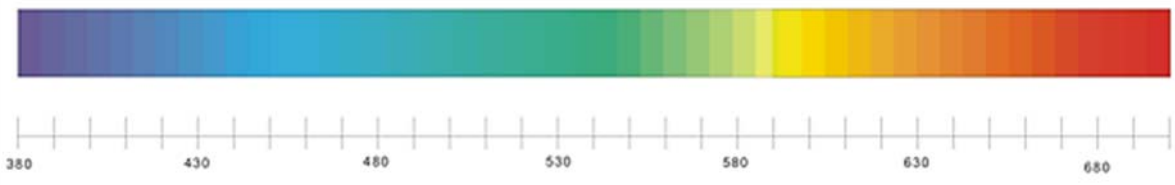


Hardcover: ISBN 978-84-617-2934-0
e-Book: ISBN 978-84-617-2955-5

The Human Eye: an intelligent optical sensor (The inverted retina: a diffractive - optical correlator) shows that the human eye from the prenatal structuring of the inverted retina hardware on up to the design of the central cortical visual pathway is not only different from but also radically more intelligent than a camera.

Many paradoxes in color vision (RGB peak positioning in the visible spectrum, overlapping of the RGB channels, relating local color to the whole scene, paradoxically colored shadows, Purkinje phenomenon etc.) are becoming intelligent solutions.

A fascinating book for all those wondering that the brightness of a scene is not cut in half and that the visible world doesn't collapse into a flat 2D-image when closing one eye. It should be a great of interest for students, scientists and engineers in eye-, vision- and brain-research, neuroscience, psychophysics, ophthalmology, psychology, optical sensor and diffractive optical engineering. Practical applications are the search for a retinal implant of the next generation and a helpful strategy against myopia in early childhood.



Order: http://www.sensorsportal.com/HTML/BOOKSTORE/Human_Eye.htm