

A review for a multidisciplinary approach to integrate and micro-scale sensors, energy and antennas for self-powered smart contact lenses

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Abstract. This review examines the multidisciplinary challenges involved in developing self-powered smart contact lenses that integrate sensing, energy harvesting, and wireless communication within a highly constrained, biocompatible platform. It highlights recent advances enabling lenses to evolve from vision-correction devices into noninvasive health monitoring tools, augmented vision, and real time physiological analysis. Particular attention is given to autonomous energy solutions, including tear-fluid electrochemical reactions and biomechanical harvesting from eye blinking, which offer promising alternatives to conventional batteries. The study also analyzes compact loop antenna designs compatible with lens geometries, operating in the 900 MHz–1.1 GHz range, and evaluates their performance, limitations, and integration constraints. Key considerations such as material biocompatibility, signal integrity, thermal effects, and specific absorption rate compliance are discussed in the context of safe and reliable operation. The paper further emphasizes the importance of combining expertise of optics, electronics, materials sciences and system engineering to achieve functional prototypes. Overall, this work provides a comprehensive framework for optimizing the integration of microscale components, contributing to the advancement of energy-autonomous smart contact lenses for biomedical and wearable applications.

Keywords: Smart contact lenses / eye blink energy / tear salinity / micro batteries / bio-compatibility / loop-antenna / multidisciplinary optimization / 1 GHz / 900 MHz-1.1 GHz

1 Introduction

Since first Contact lenses were introduced by Adolph G. E. Fick [1] in 1888, their main purpose is correction of refractive errors. Compared with eyeglasses, they provide unobstructed peripheral vision, reduced optical distortion, and greater comfort during physical activity, leading to widespread adoption. Emerging technologies are now expected to further expand their functions, potentially transforming the concept of contact lenses. In recent years, advances in microelectronics, materials science, and wearable technologies have extended contact lenses beyond vision correction. So-called smart contact lenses integrate miniaturized sensors, communication systems, and electronic components into the lens substrate. They are being

explored for applications such as non-invasive biosensing, augmented vision, drug delivery, and physiological monitoring [2–6], with functions going from augmented reality up to real time health tracking. Recent literature highlights strong interest in these devices. Smart contact lenses (SCLs) can be considered as emerging with tools for noninvasive glucose monitoring, intraocular pressure and other bio markers, with potential to improve diseases like glaucoma management [7]. They also enable continuous multi bio marker sensing in tear fluid, although challenges in stability, fabrication, regulation remain [8]. Additional studies report progress in real world implementation challenges, intra ocular pressure monitoring, glucose sensing, ocular drug detection, treatment for color blindness, emphasizing electro spun fibers for controlled release and [9–11]. Kim et al. further review developments in smart lenses for drug detection and therapy, highlighting noninvasive functionalities and future prospects [12].

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A major challenge is integrating reliable power and wireless communication within the extremely limited, biocompatible volume of a contact lens. Conventional batteries are impractical due to safety and size constraints, leading to exploration of microscale energy harvesting. Approaches include electrochemical generation using tear fluid and biomechanical harvesting from blinking. Other proposals exploit eyelid motion and tear ions as energy sources [13]. Yun et al. developed tear-based bio chargeable batteries using enzymatic glucose reactions for safe energy generation [14], while Li et al. proposed a power-free lens using electrochromic color changes for non-invasive glucose monitoring without external electronics [15]. Another key element is the wireless communication interface for the transmission of data to external devices such as smartphones or wearables. This requires miniaturized antennas operating efficiently within soft, constrained geometries while ensuring RF safety compliance. Building on works in optical systems and lens fabrication [16,17] and preliminary studies [18,19], this article examines the integration of energy harvesting systems and GHz-range antennas in smart contact lenses. Particular attention is given to compact loop antenna designs compatible with standard lens dimensions and operating in the 900 MHz-1.1 GHz band.

The objectives of this study are therefore threefold. First, we review potential energy sources that may enable autonomous operation of smart contact lenses, including tear-fluid electrochemical reactions and biomechanical energy from blinking. Second, we analyze the design constraints and theoretical performance of compact loop antennas suitable for integration into soft contact lenses. Third, we discuss the multidisciplinary challenges associated with combining sensing, power management, and wireless communication within a wearable ocular device. By outlining these technological elements, this review paper aims to contribute to the development of future smart contact lenses that could support both biomedical monitoring and novel tools for mobile eye-movement research. It should also be emphasized that this article is primarily a review, although Sections 5 and 6 incorporate some of our original contributions. The purpose of including these results is to demonstrate that a review-based approach, supported by the most recent advances in the field and complemented by our own work, provides compelling evidence for the feasibility of smart contact lenses. In particular, this approach highlights the potential integration of relatively simple sensors whose measurements can be processed and wirelessly transmitted to connected devices, such as smartwatches, using signals in the gigahertz frequency range. This work obviously requires a multidisciplinary approach.

2 Smart contact lenses: functional principles

Smart contact lenses combine embedded sensors, communication modules, and power-management electronics within a soft, transparent material that is placed directly on the corneal surface. Their potential applications include.

2.1 Noninvasive health monitoring

SLCs have been proposed for non-invasive monitoring of biomarkers such as glucose and intraocular pressure using tear-fluid sensing technologies, it could be blood glucose or intraocular pressure without breaking the skin or entering the body. Instead of using needles or surgical tools, these methods rely on sensors, light-based technologies, or wearable devices to gather data through the skin or eyes. Researchers are currently developing smart contact lenses capable of monitoring intraocular pressure in patients with glaucoma. This rapidly expanding field seeks to improve health monitoring by making it more practical, safer, and comfortable for users.

2.2 Applications for augmented vision

Enhanced vision technologies such as night vision and instant text translation are examples of augmented vision systems, which improve human visual perception by adding or enhancing visual information. Night vision systems amplify low-light conditions to allow visibility in darkness, while real-time translation tools employ augmented reality to overlay translated text onto signs or menus through smart glasses or smartphone cameras. These technologies broaden the ability of the human eye to perceive and interpret information instantly.

2.3 Assistive visual technologies for individuals with visual impairments

Smart contact lenses integrating antennas and sensors could enable continuous monitoring of ocular motion, including saccades, micro-saccades, and blink dynamics, providing new tools for eye-movement research outside laboratory environments. Our type of device could potentially be used to detect unwanted eye movement patterns. Imagine sending a signal to trigger an alarm if a driver falls asleep on the highway. Real-time medical diagnosis of unexpected eye movements is also within the scope of possible applications. There is also the possibility of continuous monitoring of eye behavior.

Assistive technologies for people with partial or complete vision impairment are designed to improve environmental awareness, information accessibility, and the ability to carry out everyday activities. Their primary purpose is to enhance autonomy and quality of life through better accessibility solutions. Moreover, smart contact lenses (SCLs) may compensate for the accommodative function of the eye lens by replacing the convergence power normally controlled by the ciliary muscle. The ciliary muscle, a smooth ocular muscle located within the ciliary body, adjusts the convergent power of the lens to enable visual accommodation.

Thiele et al. demonstrated the first 3D-printed hybrid refractive/diffractive achromatic and apochromatic micro-lenses fabricated through multi-material direct laser writing, substantially decreasing chromatic aberrations in the visible spectrum by combining diffractive surfaces with photo-resists of varying dispersions [20]. The same

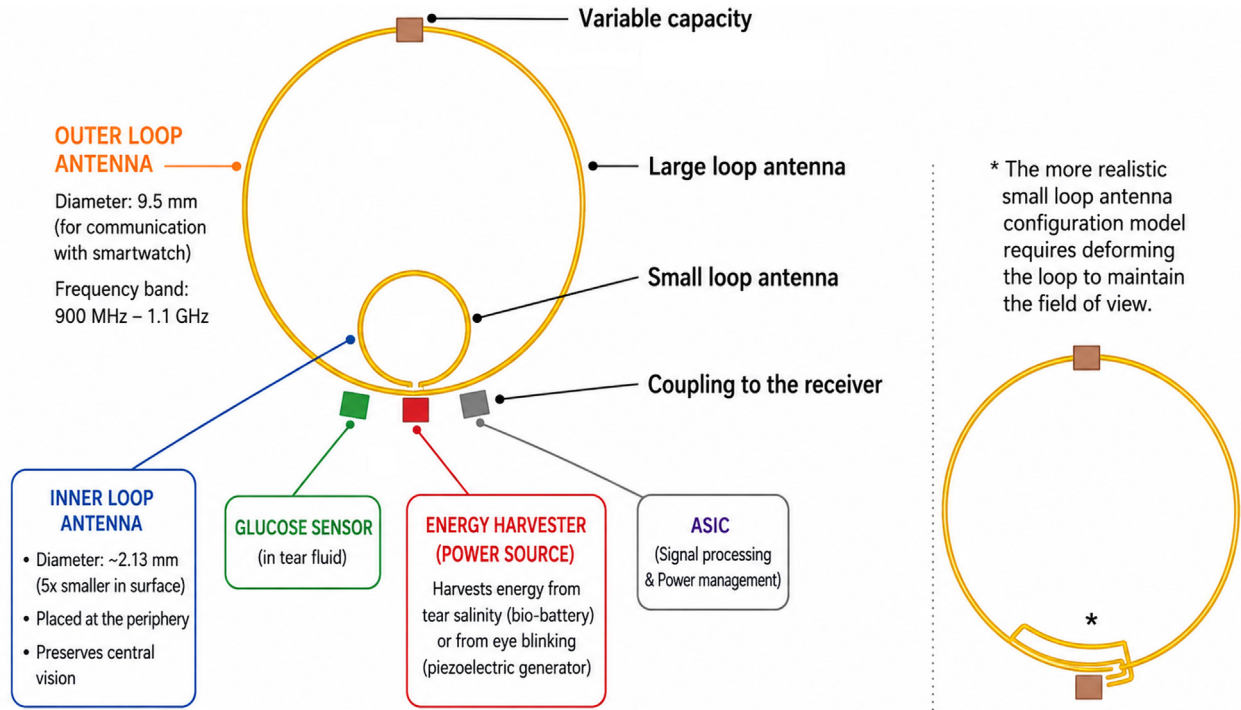


Fig. 1. We present the overall operating concept of a smart contact lens equipped with a double antenna with a realistic structure for the small loop inner one, sensors, and an application-specific integrated circuit (ASIC), enabling communication with external devices such as smartwatches, smartphones, or computers. From a technological view, integrating such components into the lens also makes it possible, when required, to correctly orient a progressive contact lens. Implementations are technologically achievable.

research team also produced a compact multi-lens foveated camera directly on a CMOS chip, inspired by eagle vision, by integrating lenses with different focal lengths to improve central image resolution [21].

Advanced functionalities may also be obtained through the use of materials such as Polydimethylsiloxane (PDMS) in 3D-printed optical lenses. PDMS is an elastomer known for its excellent optical, electrical, and mechanical characteristics, making it highly suitable for numerous engineering applications. Because of its biocompatibility, PDMS is extensively employed in biomedical applications. More recently, sophisticated 3D-printing techniques, particularly two-photon polymerization, have enabled the fabrication of highly precise microstructures and complex lens geometries [22]. This technological evolution is transforming the manufacturing of optical components for biomedical applications, especially in ophthalmology, where 3D-printed devices contribute to increasingly advanced and adaptive visual systems [23]. Building upon these advances, our work focuses on developing novel adaptive optical components for contact lenses using state-of-the-art microfabrication technologies.

2.4 Common considerations

The design process must achieve an optimal compromise between miniaturization, transparency, oxygen permeability and user comfort. The schematic integration of lens components is illustrated in Figure 1 (general operating principle), Figure 2 (integration of the power source), and Figure 3 (antenna integration and communication system).

Materials including flexible biocompatible polymers and nanoscale thin films, are essential for meeting these requirements. Recent review [24] studies have highlighted progress in materials science and sensor integration for ophthalmic applications.

SLCs are emerging as wearable biomedical devices capable of non-invasive disease diagnosis and treatment by detecting ocular biomarkers and enabling drug delivery, although the technology is still at an early stage of development [25]. Ongoing research is focused on exploiting the eye as a source of physical and chemical biomarkers while improving biosensing systems, wireless data transmission, drug delivery methods, and energy-storage technologies [26]. However, tear exchange between the ocular surface and contact lenses remains limited, particularly with soft lenses, which can result in debris accumulation and related complications. Despite advances in lens design and characterization techniques such as fluorophotometry, tear hydrodynamics and exchange mechanisms are still not fully understood [27].

2.5 Optimization algorithm for SCLs

The optimization framework is summarized in Figure 4, which provides a step-by-step description of the proposed methodology. The diagram defines the optimization problem through its objective functions, decision variables, and constraints, and presents the optimization algorithms together with their parameters, convergence criteria, stopping conditions, and computational complexity. The selected multi-objective approaches, namely

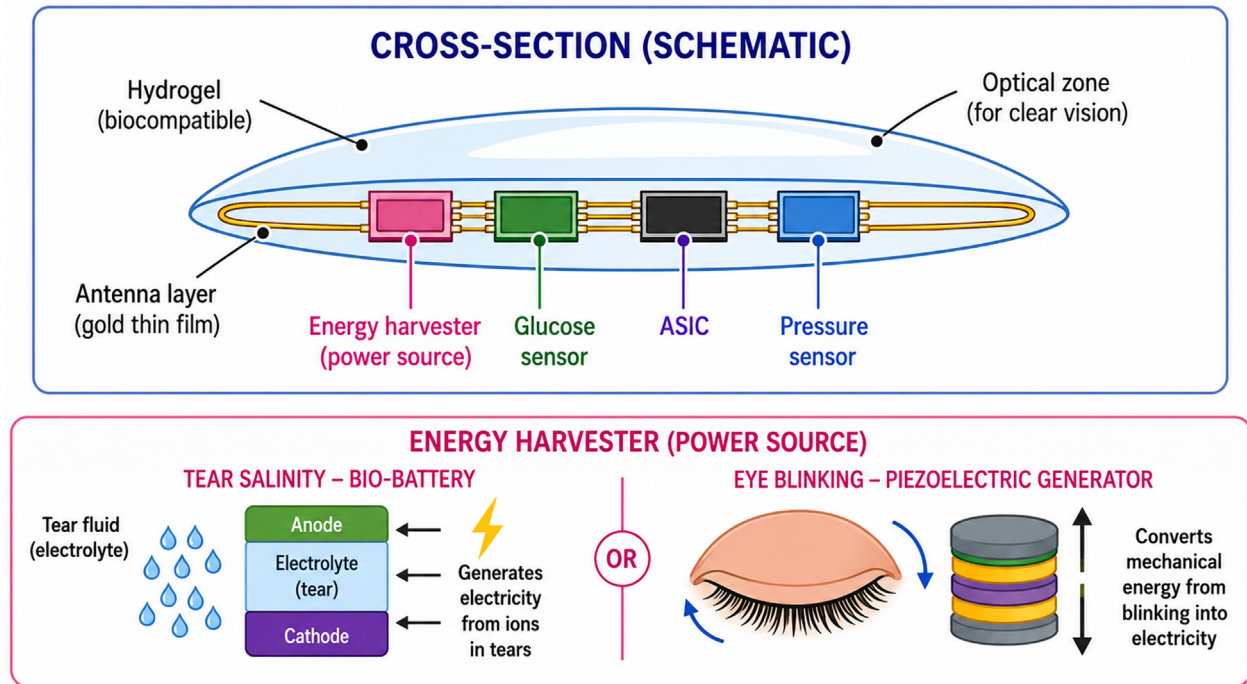


Fig. 2. Illustration the cross-section of SLC on upper part of the figure, and of the integration of micro-sources of energy base on tear salinity [14], on the left bottom of the figure, or eye's blinking [30], on the right bottom of the figure, for Hydrogel SCLs.

Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [28] and Multi-Objective Evolutionary Algorithm based on Decomposition (MOEA/D) [29], are chosen for their efficiency, stability, and ability to handle complex design trade-offs. In addition, the framework incorporates safety constraints, including the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits, which restrict human exposure to electromagnetic fields and ensure safe operation of the smart contact lens.

3 Autonomous powering with intrinsic energy sources for eye

The rapid progress of smart contact lens technology is closely linked to advances in biocompatible microelectronics and the demand for fully autonomous wearable systems. One of the most critical challenges remains the provision of a reliable, safe, and sustainable power supply within the extremely limited volume of a contact lens. This section reviews emerging strategies that exploit energy available directly from the eye or the human body. Section 3.1 focuses on electrochemical energy generation using tear fluid as a natural electrolyte. Section 3.2 examines the conversion of mechanical energy from blinking into electrical power through nano generators. Finally, Section 3.3 outlines additional possible energy sources, such as motion-related energy from daily activities, which could further support self-sufficient operation.

3.1 Energy from tear salinity

Tear fluid contains electrolytes, primarily sodium and potassium ions, that can serve as the basis for micro-scale

electrochemical power generation. Recent research demonstrates that biofuel cells embedded in contact lenses can continuously generate energy by utilizing this saline environment as discussed in introduction of this paper. Ultra-thin batteries coated with glucose can undergo redox reactions catalyzed by tear components, enabling prolonged operation. It should be emphasized that researchers in Republic of Singapore, including Seok Woo Lee and their collaborators at Nanyang Technological University (NTU), developed a prototype contact lens powered by a battery capable of operating for up to 13 h using only tear fluid as its energy source [14,15,30]. Their work demonstrates how recent progress in smart contact lenses has enabled advanced functionalities such as information overlay and blood glucose monitoring, both of which require reliable energy supplies.

Although lithium-ion batteries are commonly used, safety concerns have encouraged the exploration of alternative materials such as polymerized hydrogels based on Copper hexa-cyano-ferrate (short formula CuHCFe) and Prussian Blue, called *Preußischblau* by Germans. Prussian Blue is known in medicine for being an antidote for certain metal diseases related to poison and also in applications for electrochemical energy-storage systems [31]. Experimental results showed an energy-storage capacity estimated to 0.132 mAh, corresponding to the amount of current a battery can deliver over 1 h before complete discharge, when tested in tear-fluid liquids. Importantly, the lens maintained full bio compatibility and remained safe for extended wear.

3.2 Energy coming from blinking

Blinking can also serve as a source of energy harvesting through biomechanical motion. Since eyelid blinking occurs tens of thousands of times each day, it can drive

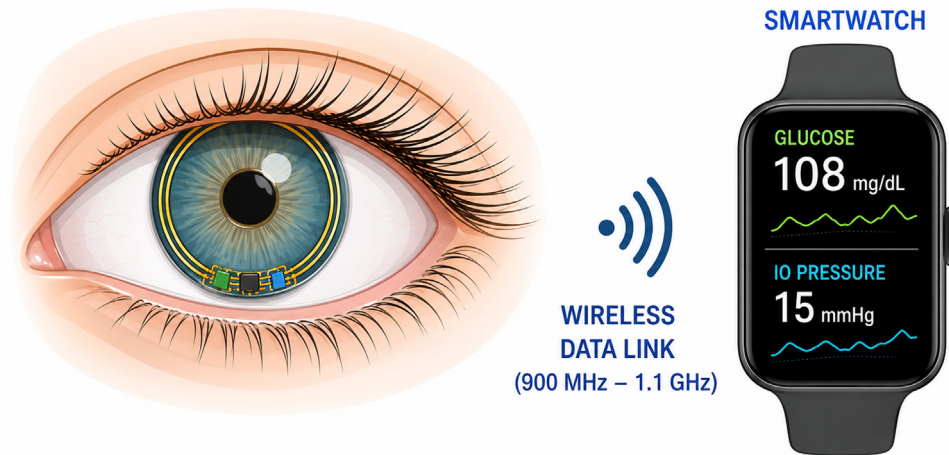


Fig. 3. Schematic representation of the communication link between a smart contact lens and a smartwatch. The indicated frequency bandwidth corresponds to the range discussed later in Part 5 of this article.

piezoelectric or triboelectric nanogenerators. Innovative hybrid systems integrating a flexible silicon photovoltaic cell with a blink activated Mg-O_2 collector have been proposed [32], enabling simultaneous optical and mechanical energy harvesting. This approach describes a hybrid power-generation platform for smart ocular devices that combines a flexible silicon solar cell with an eye-blinking-activated Mg-O_2 metal-air harvester. The system continuously produces electrical energy and delivers a stable DC output without external accessories, while integrated power-management circuits increase voltage levels to ensure a reliable energy supply for ocular electronics. Such harvesting technologies could enable fully autonomous, wireless smart lenses capable of recharging literally *in the blink of an eye*.

3.3 Other elastic energy sources

Beyond tear chemistry and blinking, other forms of energy available from the human body may be exploited. Movements such as walking, running, or head motion generate kinetic energy that could potentially be converted into electrical power for microsystems. From an energy perspective, normal human activity represents a continuous and largely untapped resource. The human body continuously expends energy, a phenomenon that can also be interpreted in terms of frequency-related processes [33]. Consequently, what is usually regarded as energy loss may instead become a potential energy source for powering microdevices. Harnessing elastic and kinetic energy associated with body motion could therefore complement existing strategies and contribute to the development of more robust and self-sustaining smart contact lens systems [34].

4 Frequency bandwidth constraints and technical expertise

The development of smart lenses, as devices capable of integrating various technologies for visual enhancement or information display, is a highly complex challenge. The

feasibility of creating these lenses hinges on expertise in multiple technical domains. Here is a deeper look into the Following five points:

- Evaluation of bio-compatible coatings materials & signal transmission: When designing smart lenses, careful attention must be given to how different materials interact, especially at interfaces that come into direct contact with biological environments such as ocular tissues and fluids. To avoid irritation, inflammation, or other negative reactions, the use of biocompatible coatings is essential. These coatings must not only be compatible chemically with eyes, but also capable of supporting efficient signal transmission—whether via wireless communication or optical pathways—without degrading over time. A thorough understanding of material interfaces [35–39] is crucial, as defects or inconsistencies at these junctions may result in diminished optical quality, unstable data transmission, or discomfort for the wearer. Consequently, ongoing research into biocompatible materials and coatings is fundamental to ensuring that smart contact lenses remain safe, reliable, and durable. For users of smart contact lenses (SCLs), it is particularly important to verify that the power emitted by components such as magnetic loop antennas stays within safe exposure limits to avoid potential biological harm. This consideration relates to the Specific Absorption Rate (SAR), which quantifies the rate at which the human body absorbs energy from RF electro-magnetic fields, expressed in watts per kilogram. The international guidelines establish SAR exposure limits for ensuring user safety. Within European Union, for instance, SAR threshold is set at 2 W/kg averaged over 10 g of tissue [40,41]. From both legal and medical perspectives, applying the precautionary principle is justified: since no SAR standard specifically addresses devices in direct contact with the eye, it is advisable to refer to existing standards such as IEC/IEEE 62209-1528:2020 [40] and IEC 62209-3:2019 [41], particularly the latter, which addresses human exposure to RF fields from handheld and body worn wireless devices. In the USA, Federal Communications

Optimization Algorithm for Smart Contact Lens Design

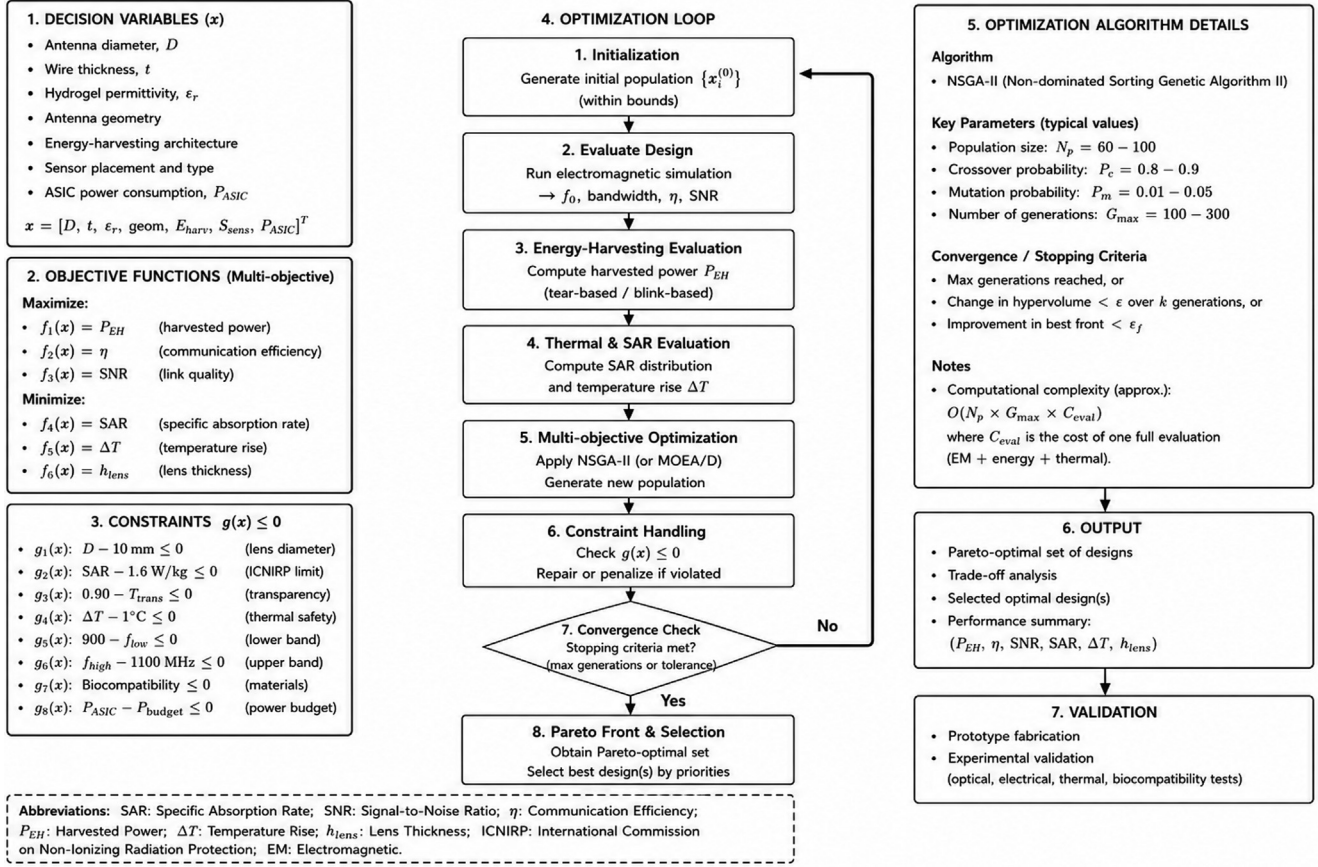


Fig. 4. Optimization algorithm for SCLs design diagram.

Commission enforces a SAR limit of 1.6 W/kg averaged over 1 g of tissue for mobile devices. People's Republic of China adopts a SAR maximum value of 2 W/kg over 10 g of tissue, aligning with European regulations and based on guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Similarly, India applies a 1.6 W/kg SAR limit for mobile devices. More broadly, World Health Organization (WHO) maintains updated information on SAR limits worldwide through its resource [42]. The specific absorption rate (SAR) expected for a typical smart contact lens can be estimated within the operating frequency range of interest. Assuming a hydrogel relative permittivity of 78, an antenna thickness of 10 μm , and a lens thickness of 600 μm , SAR values can be calculated at several operating frequencies. The corresponding results are summarized in Table 1 and demonstrate that the estimated SAR values remain below the maximum limit of 1.6 W/kg established by the U.S. Federal Communications Commission (FCC).

– **Microwave signal integrity diagnostics:** Smart lenses incorporate technologies that rely on optics signals to carry out functions such as image recognition, projection, and health monitoring. The effectiveness of these systems strongly depends on preserving signal integrity during transmission and reception. Disturbances [43,44] such as noise, interference, or attenuation can degrade

Table 1. Estimated specific absorption rate (SAR).

Frequency (MHz)	Mass (g)	SAR (W/kg)
900	1	0.72
1010	1	0.82
1100	1	0.94

performance and compromise functionality. Frequency analysis plays a key role in understanding signal behavior within lens components, particularly for wireless communication ranges (2.400–2.483.5 GHz for Bluetooth, 2400 MHz Wi-Fi supporting 450 and 600 Mbps, 5 GHz Wi-Fi reaching Gbps speeds, 900 MHz for 3G, 1800 MHz for 4G and 3.5 GHz for 5G microwave bands) as well as for power transfer. Signal integrity is essential to identify and resolve transmission issues, ensuring consistent and reliable operation of the smart lens over time. Seamless interaction between these components, is critical for proper device performance. In France, frequency band allocation is regulated by the National Frequency Agency, with the National Frequency Allocation Table defined by decree from the Prime Minister [45]. The communication band most likely used between smart lens components (SLCs) and devices such as

Table 2. Global navigation satellite system operating frequencies below 1300 MHz^{1,2}.

Attributed band designation / Centered frequency in MHz	Satellite Network ³	Range (MHz)
E5a-b	Galileo	1164–1215
L5 / 1176	GPS/NavIC/QZSS	1215–1234
G3	GLONASS	1189–1214
B2 / 1207	BeiDOU	1205–1209
L2 and L2C / 1228	GPS/QZSS	1215–1234
B3 / 1268	BeiDou	1258–1278
G2	GLONASS	1237–1254
L6 / 1278.75	QZSS	1258–1300
E6	Galileo	1260–1300

¹ Global Navigation Satellite System (GNSS) also operate at upper microwave frequency range although frequencies don't need to be mentioned as they have no interaction with 0.9–1.1 GHz bandwidth.

² In 2019, we note that signal in space ranging error was in the range of 1.6 cm (Galileo), 2.3 cm US Global Positioning System (GPS), 5.2 cm Russian Global Navigation Satellite System (GLONASS) and 5.5 cm Chinese Big Dipper (Bei Dou), using real time corrections with clocks & satellite orbits [54].

³ Four operative world GNSS: GPS (United States of America), BeiDou (China), GLONASS (Russia), Galileo (European Union); two operatives regional GNSS: Navigation with Indian constellation (NavIC) (India), Japanese Quasi zenith satellite system (QZSS) (Japan).

smartphones or smartwatches lies around 1 GHz, as discussed in Part 5. This makes it important to manage risks related to intermodulation effects. Such effects have been widely studied, including passive intermodulation distortion in antennas [46], and interactions involving electronic amplifier components [46–50]. Slightly above 1 GHz, major application is the Global Navigation Satellite System (GNSS) [51–54]. The lower portion of L-Band (1151–1214 MHz) includes L5 GPS and E5 Galileo signals, with E5a and L5 sharing same frequencies. Other signals, such as GPS L2, GLONASS G2, and Galileo E6, fall within the 1216–1350 MHz range. These frequency ranges are summarized in Table 2. They are allocated primarily to radiolocation services for ground radar systems, as well as to aeronautical radio navigation and satellite navigation services, making them particularly sensitive to interference affecting transmission / reception below approximately 1.1 GHz.

– Assessing uncertainty analysis in low microwave systems: Uncertainty is an unavoidable aspect of all engineering systems, particularly those combining multiple advanced technologies. In the case of smart lenses, it can influence parameters such as light intensity, sensor outputs, optical alignment and even user interactions. Evaluating and quantifying these uncertainties enables engineers to design systems that anticipate errors and performance variability. Through methods like error modeling and statistical analysis, developers enable ensuring that SLCs maintain dependable and consistent operation despite factors such as manufacturing tolerances, environmental changes, or long-term wear. This process is critical to preserving measurement accuracy and overall device performance. Our approach builds on established expertise in uncertainty evaluation for complex microwave optical systems [55–60].

– Understanding the patent landscape to protect innovation and attract funding: Intellectual property (IP) plays a central role in the development of cutting-edge technologies like smart lenses [61,62]. Having a thorough understanding of existing patents allows developers to safeguard their innovations while avoiding infringement on prior work. Moreover, a well-developed IP portfolio strengthens the project's credibility and can be decisive in attracting investment or institutional support by highlighting a clear competitive edge. In the smart lens domain, patents may cover aspects such as lens architecture, integrated technologies (including microelectronics, sensors, and wireless communication), and fabrication methods. Monitoring patent trends secure and broad protect for new ideas and can provide a significant strategic benefit.

The areas of expertise must come together to enable the creation of practical, safe, fully functional prototypes for energy autonomous SLCs. Achieving this requires the seamless integration of thin coating films, optoelectronic components, bio-compatible materials and reliable signal processing, all guided by effective intellectual property strategies and rigorous uncertainty assessment. For instance, a lens designed with advanced optical coatings to improve vision must also incorporate embedded electronics and sensors that operate efficiently, are self-powered, and communicate reliably with external systems without signal loss or interference. Beyond technical performance, considerations of safe and usable use are equally important. Ultimate objective is to deliver prototypes that are not only operational but also safe, energy-efficient (autonomous), and suitable for large-scale manufacturing. Developing smart lenses is therefore inherently multidisciplinary, requiring coordinated

expertise in materials science, electronics and optics, patent strategy and systems engineering to produce high safe performance and commercially viable solutions.

5 Frequency range operation

To introduce this section and the following section, we underline that [Sections 5](#) and [6](#) deal about antenna calculations and theoretical estimations that appear original and based on our work, rather than purely review-based as in the previous parts. It is necessary to present the whole review to make it coherent.

This section describes technical features of a compact double stacked loop-antenna developed for directional reception & transmission of electromagnetic waves. A loop antenna, also referred to as a magnetic loop antenna, primarily responds to the magnetic component of the electromagnetic field, which explains its designation. Its operating principle is directly derived from the Lenz Faraday law, where induced we have a voltage proportional to the magnetic flux passing through the loop. For this reason, loop antennas are classified as flux-measuring devices. Although antennas are fundamental elements in telecommunications, control systems, and data acquisition, their behavior can also be analyzed from a theoretical perspective [\[63–65\]](#).

The proposed design consists of two circular loops positioned one above the other along a vertical axis. Together, they act as magnetic dipoles operating in phase. This arrangement improves directional radiation characteristics, making the antenna well-suited for applications that require focused signal transmission or precise sensing. Each loop has a 9.5 mm diameter, a dimension selected to remain compatible with typical lens sizes while avoiding obstruction of the field of view. According to small loop antenna theory, this geometry corresponds to a resonant frequency close to 1.01 GHz. The antenna operates effectively over a 0.9–1.1 GHz frequency range providing a band width suitable for various modern communication applications. Its radiation pattern is optimized along the axis perpendicular to the plane of the loops (vertical or broadside direction), where the strongest transmission and reception occur at angles $\theta = 0^\circ$ or 180° . This directional behavior enhances both signal gain and accuracy in targeted use cases. This section presents the key theoretical foundations, physical parameters and practical aspects of the design, including the role of the speed of light in determining wavelength and frequency. The study contributes to a deeper understanding of antenna performance, design limitations, and potential applications within the GHz frequency range.

5.1 Antenna structure, dimensions, range and resonant frequency

Stacked double-loop antenna is composed of two vertically aligned circular loops that act as magnetic dipoles. This configuration is commonly employed for directional transmission and reception because the two magnetic dipoles operate in phase.

For a loop antenna with a diameter D of 9.5 mm, radius is calculated as $r = 4.75$ mm. The loop circumference C is therefore $2\pi r$, we get 0.0298 m. According to small-loop antenna theory, resonance generally occurs when the circumference is close to one-tenth of the wavelength. The estimated resonant wavelength is therefore equal to 10 times C , it means 0.298 m.

For a small-loop antenna, the key requirement is that the loop circumference remains negligible compared with the wavelength. Assuming a loop diameter of 9.5 mm, the resonant frequency can be estimated using the speed of light

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8}{0.298} = 1.01 \text{ GHz}. \quad (1)$$

Using light speed as 3×10^8 m/s, resonant frequency is therefore approximately 1010 MHz. Since antennas are reciprocal devices, they exhibit identical operating characteristics in both transmission and reception modes. Consequently, the anticipated frequency range for this antenna extends from 900 to 1100 MHz. The exact usable bandwidth may nevertheless vary depending on factors such as the antenna Q-factor and impedance-matching components.

5.2 First approach for Q-factor, preferred angles and directional properties

The radiation profile of a single loop antenna exhibits a toroidal, donut-like, shape, with peak emission occurring perpendicular to the loop plane. In contrast, when loops are arranged in a stacked configuration, pattern naturally becomes more focused, with a maximum radiation directed along vertical axis relative to the loop plane. Consequently, the preferred emission and reception directions align with the axis of the loop stack, corresponding to θ of 0° and 180° . Configuration enhances both directivity and gain along these directions, improving the antenna's performance for targeted communication or sensing applications. When two loops are stacked, the radiation is further strengthened along this axis. A single loop antenna, on the other hand, is radiating most efficiently in plane perpendicular to its own axis. The quality factor of the small loop antenna is commonly approximated by

$$Q = \frac{f_0}{\Delta f}. \quad (2)$$

Given $f_0 = 1010$ MHz with $\Delta f = 200$ MHz at -3 dB bandwidth, estimated Q-factor is $Q = \frac{1010}{200}$. It gives $Q = 5.05$. This is of course low, so, favorable for large band operation and it suggests that antenna is efficient for its communication application.

Then theoretical small loop antenna Q-factor using the radiation resistance R_r and loss resistance R_l is:

$$Q = \frac{2\pi f L}{R}. \quad (3)$$

It requires to estimate loop inductance (L), by knowing or approximating resistance (R). r is the radius of a single turn circular loop made of a thin conductor. So loop inductance is:

$$L = \mu_0 \cdot r \cdot \left[L n \left(\frac{8r}{a} \right) - 2 \right] \quad (4)$$

With for numerical values, r of 4.75 mm, wire radius of 25 μm , μ_0 of $4\pi \times 10^{-7}$ H/m.

We can deduce that L is in nH range and combined with expected loss resistance of several ohms, the deduced Q factor is of 5 to 10 maximum, which is reasonable for such designed compact antennas. It gives $L=5.96\text{nH}$.

5.3 Discussion

Uncertainty must be evaluated in a systematic manner, as already discussed in Part 4 of this manuscript [55–59]. It is essential to emphasize that this type of system generally operates within a frequency band ranging from 900 to 1100 MHz. The upper bound of 1100 MHz corresponds to physical limitation for small loop operation when using loops of 9.5 mm. This frequency interval is well suited for control systems based on compact & portable electronic circuits. Then in this section we outline the key parameters defining both the operating frequency range and the antenna orientation, as summarized in Table 3. The configurations are fully compatible with data transmission toward portable devices such as smartphones and smartwatches.

6 Electrical and thermal effects of antennas

The polar plot given in Figure 5 shows the normalized radiation pattern of the antenna in the far-field. It's a typical donut-shaped (toroidal) pattern characteristic of small loop antennas, with maximum radiation perpendicular to the plane of the loop and nulls along the axis. Classic small loop pattern proportional to $\sin^2(\theta)$, indicating nulls along the axis of the loop and maximums in the plane of the loop. Radiation pattern of the small loop antenna, showing the classic toroidal shape (donut-like structure) where radiation is strongest in the plane of the loop and nulls occur along the axis perpendicular to the plane.

For an over-view on the geometry of antenna, this work builds on insights from F. Callias regarding magnetic loop antennas and microtechnology more broadly [66]. In [67], Callias provides an in-depth study of shortwave loop antennas, covering their design principles, theoretical background, and real-world uses. The reference includes analyses of free-space transmission balance, impedance behavior in transmitting loops, and noise contributions affecting shortwave reception. It also offers practical instructions for building both passive and active wideband receiving loop antennas.

The behavior of small microwave loop antennas is examined following the contributions of K. Siwiak. Their efficiency and frequency bandwidth characteristics are illustrated in Figure 6. References [68] and [69] deliver essential studies on near-field and radiation properties of

Table 3. Settings for directivity and frequency band operation.

Parameters	Determined	Data
Frequency band ¹	Tx / Rx	900–1100 MHz
Estimated resonant freq.	$f = c / \lambda$	1010 MHz
Radiation angles		0° and 180°

¹ Estimated operational bandwidth given at –3dB.

annular antennas, with particular relevance to vehicular systems. In [68], Siwiak and Rohde expand on this by introducing practical tuning strategies for electrically small antennas, which are important for improving loop antenna performance in real-world conditions. Furthermore, [70,71] investigates minimum-coupling antenna arrays and proposes techniques to limit mutual interference in multi-antenna configurations, an important consideration for compact loop antenna systems in modern communication setups. Reference [72] presents a dipole antenna design that achieves ultra-wideband operation while maintaining good impedance matching and reduced size. Based on Siwiak's body of work, we present our own results related to loop antenna performance. Finally, [73] introduces a non-uniform loop antenna optimized for C-band operation, showing improved bandwidth and radiation behavior compared to conventional uniform loop designs.

At these dimensions, where the loop size is much smaller than the wavelength, loop antennas can be modeled as magnetic dipoles. Their mutual inductive coupling depends on several factors, including separation distance, relative orientation, loop surface areas, positioning, such as offset versus concentric arrangements, and the mutual inductance M . The coupling coefficient k is given by

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (5)$$

where M is the mutual inductance and L_1 , L_2 are respectively self-inductances of the large and small loops.

Self-inductances are estimated as for small single-turn circular loops as in equation (6) relatively to r is the loop radius, a is the wire radius (25 μm), $\mu_0 = 4\pi \times 10^{-7}$ H/m.

So, for the larger loop, $L_1 = 5.96\text{nH}$, and for the smaller loop, $L_2 = 4.68\text{nH}$. The coupling coefficient with equation (7) gives $k = 0.2$. This is moderate to strong coupling, but less than if they were concentric. Results for self-inductances are given in Table 5.

Mutual Inductance M can be determined as follow. If the loops were coaxial and centered, we could approximate M using

$$M = \frac{\mu_0 \cdot (A_1 A_2)}{2\pi \times d^3}. \quad (6)$$

But since the small loop is placed at the bottom edge of the large loop, mutual coupling is reduced due to non-concentricity. Let's model the reduction using a simplified geometric factor γ , where:

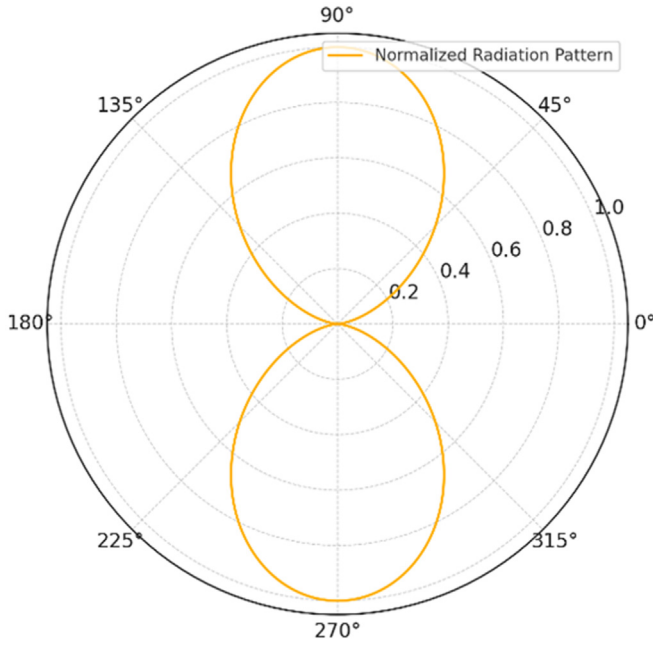


Fig. 5. 9.5 mm D loop antenna of normalized radiation pattern.

$$M_{\text{offset}} \approx \gamma \cdot M_{\text{centered}}. \quad (7)$$

Typically, for close proximity but off-centered configurations, γ is from 0.3 to 0.5, depending on distance, we keep the value $\gamma=0.4$. Assuming $A_2 = \pi \cdot r^2 = 2.83 \cdot 10^{-6} \text{ m}^2$ and distance between centers $d=r_1-r_2=3.8 \text{ mm}$, then $M = \gamma \cdot 4\pi \times 10^{-7} \cdot [(7.09 \times 10^{-5} \times 2.83 \times 10^{-6}) / (2\pi \times 0.0033^3)]$. It gives for the Mutual Inductance: $M=0.42 \text{ nH}$, reported in Table 5. As discussed in reference [18], microwave signal received by loop antenna relies on inductive coupling. Thermal and Resistive Effects are determined considering materials. Gold is a good conductor, but the antennas are very small, so skin effect and resistive losses are still important at 1.01 GHz. Information concerning skin depth is given in Table 5. Skin depth is:

$$\delta = \sqrt{\frac{2\rho}{\mu_0 \cdot \omega}} = 0.7 \mu\text{m}. \quad (8)$$

Most of the current is confined within roughly the outer $1 \mu\text{m}$ of the conductor. Since δ is much greater than $50 \mu\text{m}$, the skin effect clearly dominates. As a result, the effective resistance R rises because the usable cross-sectional area is reduced by this effect. The system therefore exhibits significant losses, with behavior primarily governed by near-field reactive coupling. The coupling coefficient remains moderate, around 0.59, yet actual power transfer is strongly constrained by these losses. Despite this, mutual inductance remains notable due to the proximity of the loops and their respective areas. Radiation from each loop is very weak because of their poor radiation efficiency. Although the smaller loop is positioned off-center, which reduces M , the reduction is not severe and the inductive coupling remains relatively strong. The interaction is thus

dominated by near-field magnetic effects rather than far-field radiation. In summary, the electromagnetic interaction between the two loops can be described as moderately strong from an inductive standpoint. The displacement of the smaller loop weakens the mutual inductance but does not eliminate it. However, power transfer or re-radiation is greatly restricted due to several factors: first point, the loop dimensions are much smaller than the wavelength ($\ll \lambda$); second point, conductor losses are high due to very thin gold wires and increased resistivity at GHz frequencies caused by the skin effect; and third point, the radiation resistance is extremely low. Consequently, this configuration is better suited for applications such as near-field sensing, inductive energy transfer, or implantable communication, rather than efficient RF transmission.

Now consider a smartwatch located 80 cm away from the antenna, and estimate the received signal strength. The double-loop antenna embedded in the smart contact lens operates near 1 GHz and tends to radiate primarily along the vertical direction, which theoretically allows transmission toward a smartwatch positioned about 80 cm away within the same plane. Nevertheless, this setup is not optimal because a small loop antenna exhibits a radiation null in its own plane. Therefore, if the smartwatch is not aligned with the vertical radiation lobes, the coupling becomes very weak. At a distance of 80 cm, the separation corresponds to approximately 2.7 wavelengths ($\lambda = 0.3 \text{ m}$), placing the system in the far field region for such a small antenna. Considering the extremely low radiation efficiency of the lens antenna (η between 0.02% and 0.71%) and its very small radiation resistance ($R_r = 0.127 \text{ m}\Omega$), the radiated power is reduced by several tens of decibels compared to the input power supplied by the ASIC. For example, if the ASIC delivers 0 dBm (1 mW) to the antenna, only about 200 nW to $7 \mu\text{W}$ is actually radiated. The free-space path loss at 1 GHz over a distance of 0.8 m is approximately 30 dB, which implies that the received power at the smartwatch antenna would fall within a range of about -70 dBm , depending on efficiency and alignment. Although such signal levels may still be detectable with a sufficiently sensitive receiver, they approach the threshold for reliable communication. Several challenges arise in this scenario: there is a strong sensitivity to antenna orientation, since the smartwatch must align with the vertical radiation lobes; there are absorption and detuning effects caused by the lossy hydrogel material and surrounding eye tissue; and there are significant resistive losses due to the skin effect in the thin gold conductors. Altogether, these considerations indicate that communication over 80 cm is achievable, but in practice the link budget remains tight and would require careful optimization of antenna matching, receiver sensitivity, and potentially the use of near-field inductive coupling for shorter-range, more dependable communication. To enhance communication between a SCL and a smartwatch, several optimization strategies can be implemented, focusing on antenna performance, receiver sensitivity, and coupling methods. Improving antenna matching and efficiency is essential [78], as adaptive matching networks can compensate for detuning caused by the surrounding eye tissue, while high-conductivity materials and optimized antenna geometries

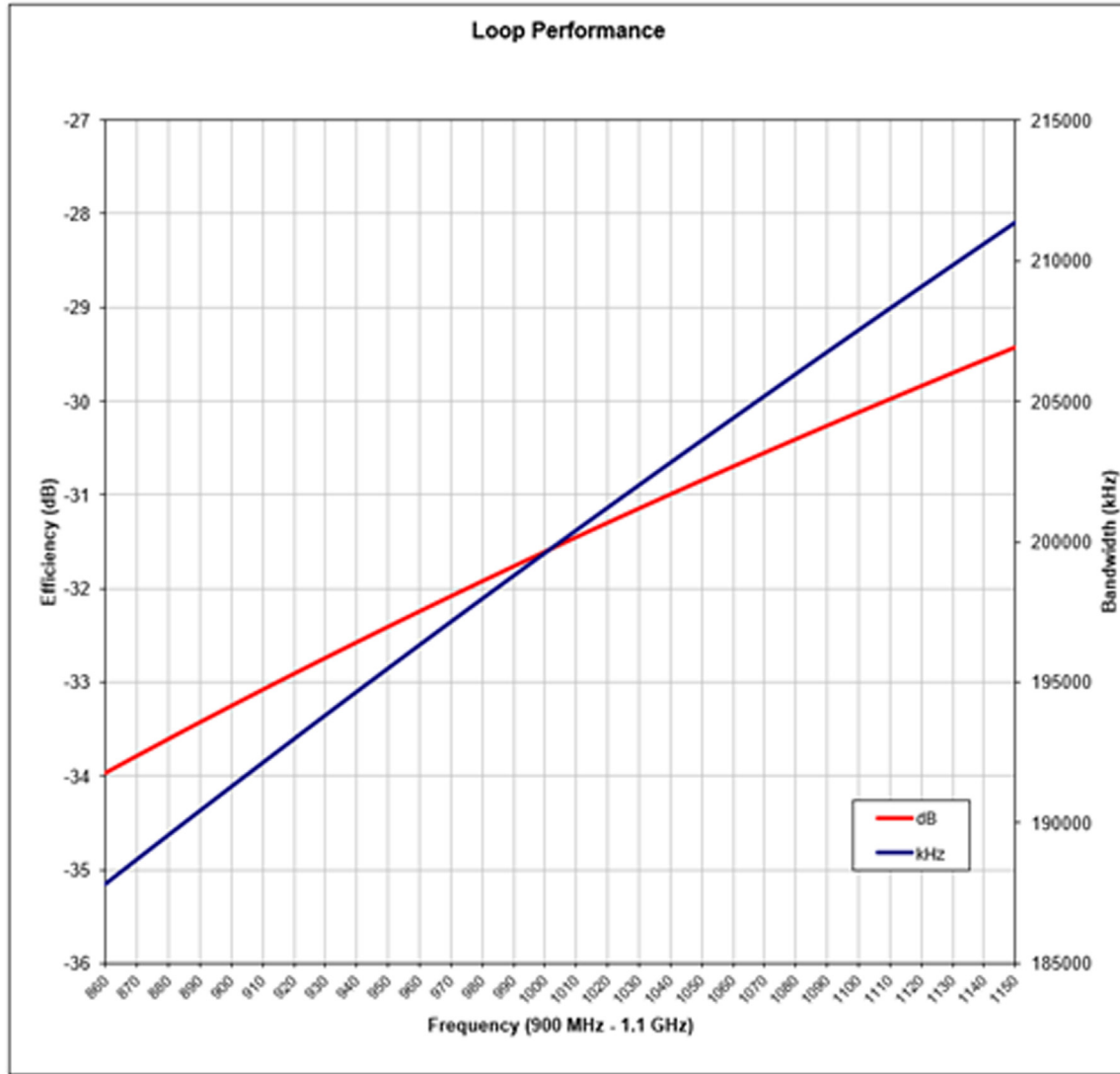


Fig. 6. Efficiency (in dB) and frequency bandwidth (expressed in kHz) of the main loop antenna versus frequency expressed in MHz is determined according to the 1.01 GHz centered frequency, 9.5 mm diameter, Gold electrical parameters (see Tab. 4), and based on the work of. Q-factor is predicted at 5.05 and measured at 4.98.

reduce resistive losses and improve radiation resistance; approaches such as high-impedance surfaces have also been shown to enhance impedance matching in wearable antennas. At the receiver side, improving smartwatch sensitivity [79] involves optimizing antenna design to minimize wrist-related effects and refining front-end electronics to reduce noise, with compact dual-band wearable antennas demonstrating high gain and efficiency. For short-range links, near-field inductive coupling [80] can provide more reliable and energy-efficient communication than purely radiative methods, particularly when integrated couplers combine near-field communication with wireless power transfer. Overall system performance benefits from a holistic optimization of both the lens and smartwatch components [81], including efficient antenna designs with appropriate radiation patterns, improved receiver sensitivity, and the integration of near-field communication technologies, with emerging

nanomaterial-based wearable antennas offering promising opportunities for further improvement. We can also rely on complex systems optimization strategies with a hybrid approach [82].

Recent advances in smart contact lenses (SCLs) have accelerated their transition from laboratory prototypes toward commercial ophthalmic platforms, particularly through the integration of advanced nanomaterials and wireless technologies. Khosravi et al. [83] demonstrated that MXene-based contact lenses combine high electrical conductivity, mechanical flexibility, and biocompatibility to enable multifunctional devices capable of monitoring physiological parameters such as intraocular pressure and glucose concentration while providing therapeutic functions, including antimicrobial protection and photothermal treatment. Nevertheless, the authors emphasized that large-scale commercialization still requires improvements in long-term stability, manufacturing scalability, and

Table 4. Settings for parameters of antennas¹.

Parameter	Designation	Value (Range)
Hydrogel contact lens diameter	D_L	10 mm
Radius of large loop antenna	r_1	4.75 mm
Radius of smaller loop antenna	r_2	0.95 mm
Wire thickness	$2a$	50 μm
Wire radius	a	25 μm
Large loop antenna area	A_1	$7.09 \times 10^{-5} \text{ m}^2$
Smaller loop antenna area	A_2	$2.83 \times 10^{-6} \text{ m}^2$
Thermal conductivity of Gold	κ	318 W/mK
Electrical resistivity of Gold	ρ	$2.44 \times 10^{-8} \Omega \cdot \text{m}$
Electrical conductivity of Gold	σ_{Au}	$4.52 \times 10^7 \text{ S/m}$
Electrical conductivity of Hydrogel	σ_H	0.3 S/m
Relative permittivity of Hydrogel in 900 – 1100 MHz range GHz	ϵ_H	79
Vacuum permeability	μ_0	$4\pi \times 10^{-7} \text{ H/m}$

¹ References for parameters of Gold [74] and Hydrogel [75–77].

Table 5. Calculated parameters¹.

Parameter	Designation	Value (Range)
Centered frequency ¹	F_0	1.01 GHz (900 MHz – 1.1 GHz)
Wavelength ¹	λ	0.297 m
Self-Inductance of large loop antenna	L_1	5.96nH
Self-Inductance of smaller loop antenna	L_2	4.68nH
Simplified geometric factor	γ	0.4
Mutual inductance	M	0.42nH
Coupling Coefficient	k	0.59
Skin depth	δ	0.7 μm
Large loop antenna area	A_1	$7.09 \times 10^{-5} \text{ m}^2$
Smaller loop antenna area	A_2	$2.83 \times 10^{-6} \text{ m}^2$
Radiation resistance	R_r	0.127 m Ω
Radiation efficiency	η	0.020 – 0.71%

¹ See part 5 - Operating frequency range.

wireless communication integration. Similarly, Hu and Hu [84] reviewed recent developments in graphene-enhanced smart contact lenses, highlighting their applications in electrochemical diagnostics, electromagnetic shielding, ocular protection, and wireless data transmission through transparent graphene-based hybrid electrodes. Their work identified graphene as a key material for future commercial SCLs because of its unique combination of optical transparency and electrical performance. In parallel, wireless power transfer and telemetry systems have undergone significant progress. Xiao et al. [85] recently reported an ultra-sensitive smart contact lens integrating a cracked PEDOT:PSS resistive sensor with a 70 MHz double-loop gold antenna and parity-time-symmetry wireless technology, achieving real-time intraocular-pressure monitoring with sensitivities approximately fifteen times greater than conventional approaches. Their successful in vivo experiments demonstrated the feasibility of continuous, non-invasive monitoring and highlighted the

critical role of efficient wireless power transfer and communication systems in the future commercialization of smart contact lenses for personalized healthcare and early disease diagnosis. Moreover, the analysis could rely on PRISMA-style flow diagrams [86] to be more strengthened.

7 Conclusion

This paper explores the multidisciplinary challenges and opportunities in developing self-powered smart contact lenses, a field combining optics, electronics, biomedical engineering, and wireless communication. It shows how smart lenses are evolving from passive vision correction devices into platforms for real-time biosensing, health monitoring, and augmented vision. A key focus is autonomous energy harvesting within the strict spatial and biocompatibility constraints of the eye. Unconventional sources such as tear salinity, eyelid blinking,

and body motion show promise for sustainable power. In particular, tear-based electrochemical cells and blink-driven nanogenerators offer safe, miniaturized alternatives to conventional batteries. These advances are supported by compact, low-profile antennas operating in the 900 MHz-1.1 GHz range, enabling wireless communication with devices like smartphones and smartwatches. A 9.5 mm antenna design fits within a soft contact lens and supports efficient directional transmission along vertical axes at θ of 0° and 180° , with a low Q-factor of 5, enabling wideband communication while remaining spatially constrained. These features are crucial for bidirectional data transfer. We also highlight the importance of materials science, particularly biocompatible polymers such as PDMS, and fabrication methods like 3D printing and microfabrication. Integrating antennas, sensors, and ASICs into a 10 mm diameter lens requires careful control of thermal, mechanical, and electromagnetic effects. Our modeling shows that small double-loop antennas can achieve reliable near-field communication despite limited radiation efficiency. Prior work in metrology and optics helped evaluate noise, but also inter-modulation, as well as thermal stability in such microsystems. Overall, the pathway going toward viable self powered SLCs is traced clearer. Combining bio-energy harvesting, compact radio frequency systems and adaptive optics materials opens strong potential for applications in health monitoring, some real time interaction and vision enhancement. Continued inter-disciplinary work is then essential to turn the prototypes into optimized safe and functional devices. Future research should follow a multidisciplinary roadmap aimed at increasing energy autonomy, improving wireless power transfer and communication efficiency, optimizing biocompatible materials and micro-fabrication processes, ensuring long-term ocular safety, and incorporating intelligent sensing and data-processing capabilities, ultimately enabling the transition of smart contact lenses from proof-of-concept devices to clinically validated and commercially scalable healthcare technologies.

Abbreviations

Abbreviations are used in this manuscript:

SCL	Smart Contact Lens
CMOS	Complementary Metal-Oxide-Semiconductor
PDMS	Polydimethylsiloxane
ASIC	Application-specific integrated circuit
SAR	Specific Absorption Rate
ICNIRP	International Commission on Non-Ionizing Radiation Protection
Wi-Fi	Wireless Fidelity
3G, 4G, 5G	Third, fourth and fifth generation of wireless mobile
GPS	US Global Positioning System
GNSS	Global Navigation Satellite System
GLONASS	Russian Global Navigation Satellite System
BeiDOU	Chinese Big Dipper
NavIC	Navigation with Indian constellation
QZSS	Japanese Quasi zenith satellite system

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Conflicts of interest

We declare no conflicts of interest.

Data availability statement

Data is available upon reasonable request.

Author contributions statement

Conceptualization, P.S.; methodology, P.S.; figures, L.S. and P. S.; validation, P.S.; formal analysis, P.S.; investigation, P.S.; functional principles, P.S. and E.P.; 3D-printing investigation, A. M.B.; simulation, P.S., L.S., A.M.B., resources, P.S.; writing draft preparation, P.S.; writing-review and editing, P.S.; supervision, P.S.; project administration, P.S.; funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

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