SmartLens: Sensing Eye Activities Using Zero-power Contact Lens

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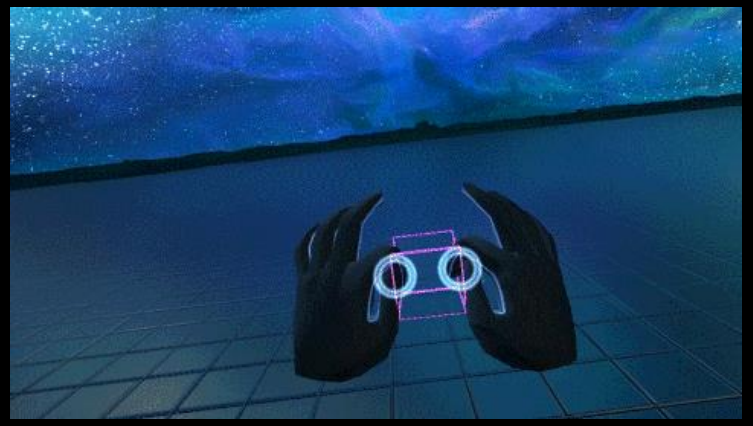
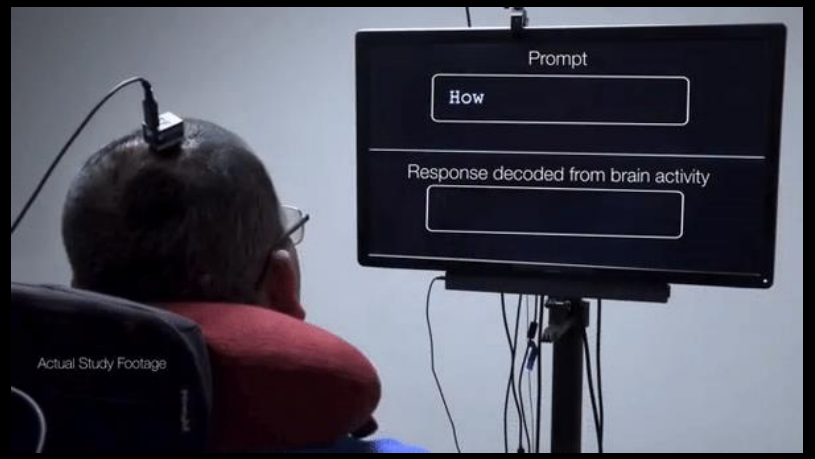
MobiCom 2022

Eye movement detection

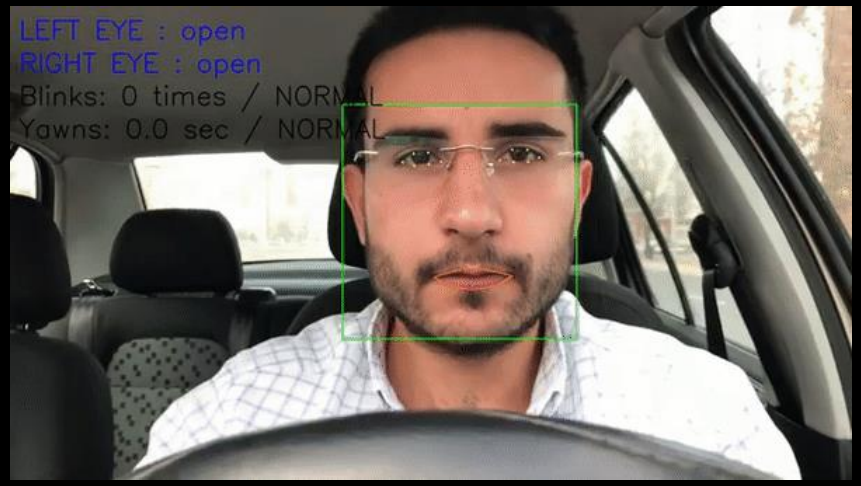


Human-Computer Interaction

Meta/Virtual Reality



Message Typing



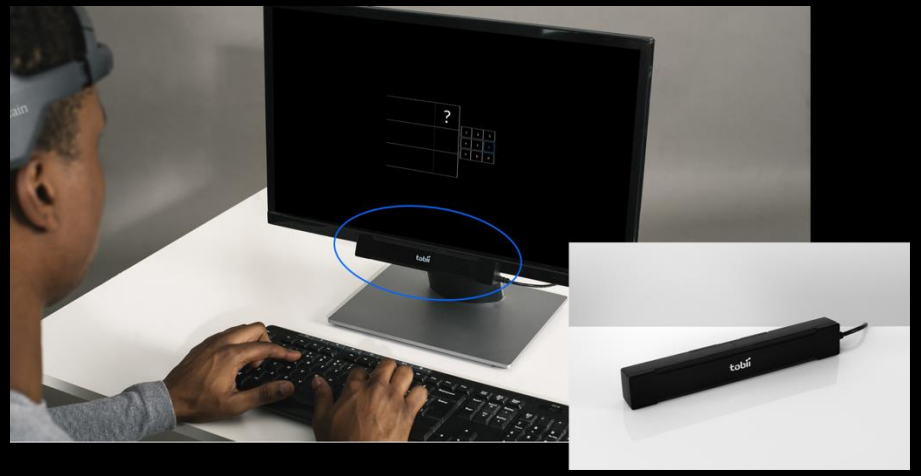
Driver Fatigue

Nervous System Dieases

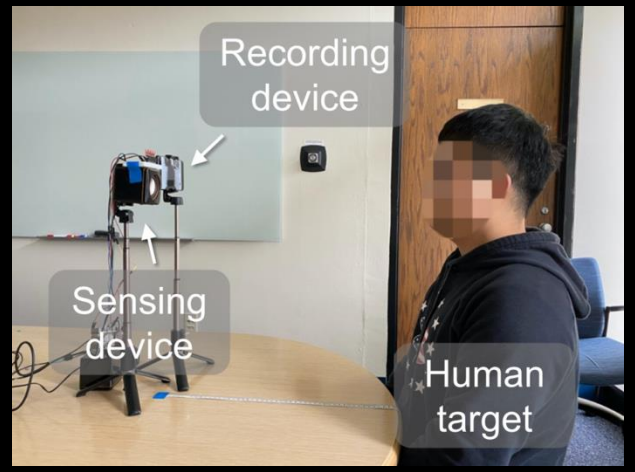
Prior works

Non-Contact based

EyeLink1000 Plus [1]



Tobii Pro X2-30 [2]



BlinkListener [3]

◆ Limit the user`s freedom ◆ Affected by the illumination ◆ Signal granularity

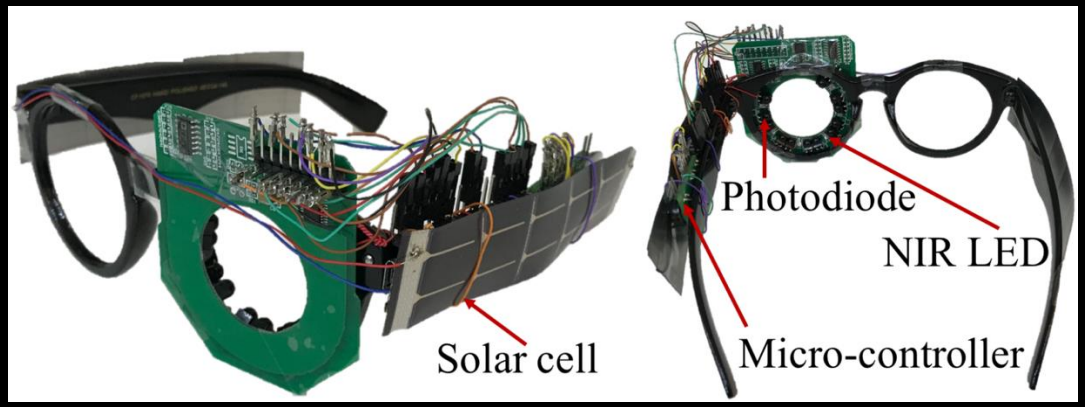
[1]. https://www.sr-research.com/zh/eyelink-1000-plus/
[2]. https://www.tobiipro.cn/product-listing/tobii-pro-x2/
[3]. BlinkListener: " Listen" to Your Eye Blink Using Your Smartphone. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 5.2 (2021)

Prior works

Contact based

Samsung Gear VR [4]

The Eye Tribe [5]



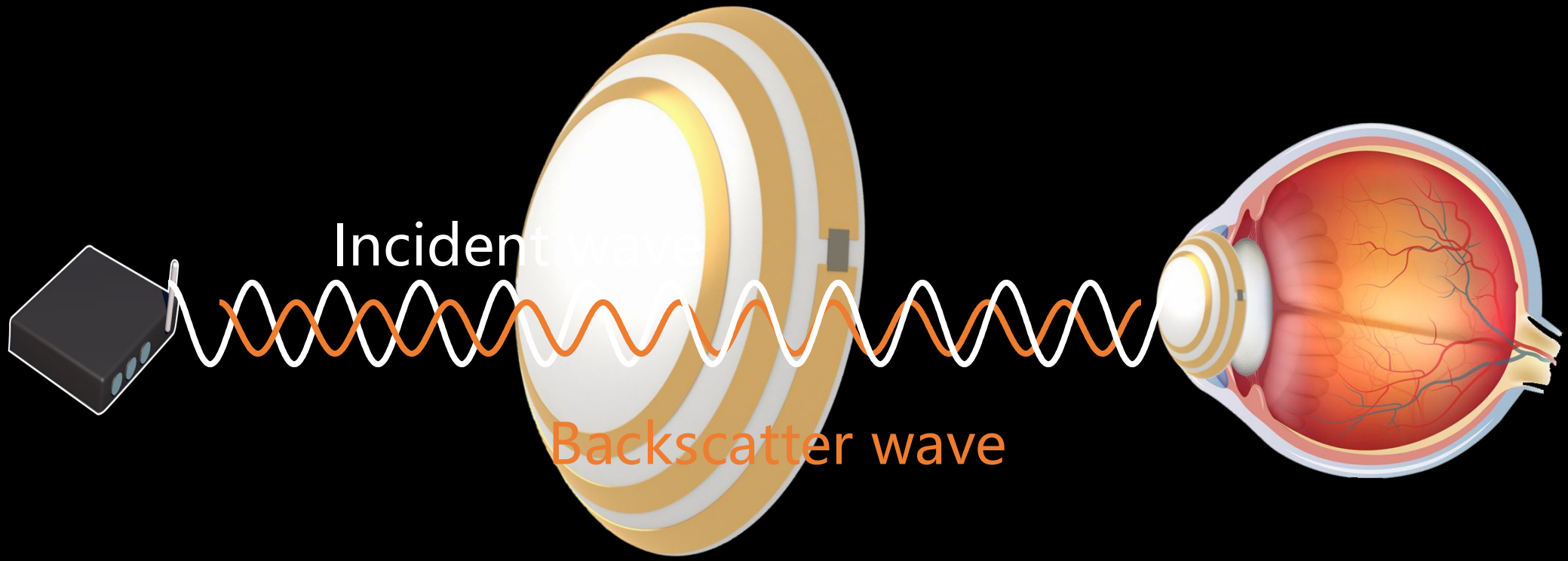
NIR LEDs [6]

- Uncomfortable over long periods
- Limited the view of sight
- Requires additional battery supply

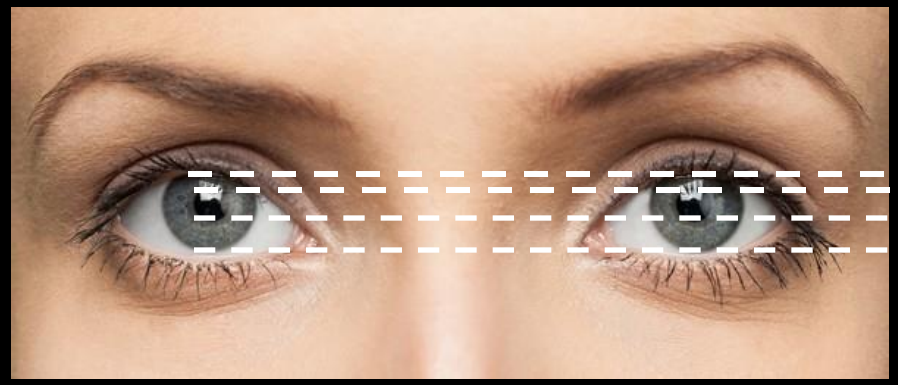
[4] www.samsungmobilepress.com
[5] https://en.wikipedia.org/wiki/The_Eye_Tribe
[6] Battery-free eye tracker on glasses. Proceedings of the 24th Annual International Conference on Mobile Computing and Networking. 2018.

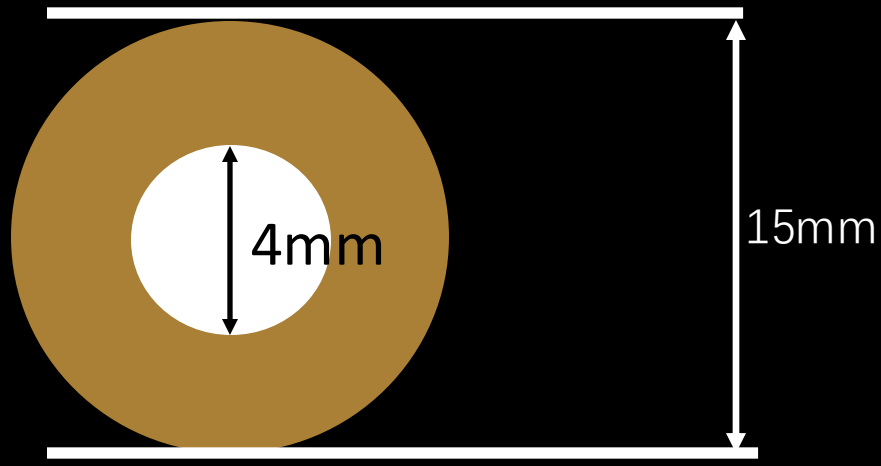
SmartLens：A passive，low-cost and battery-free eye movement sensing systems

SmartLens： A passive, low-cost and battery-free eye movement sensing systems



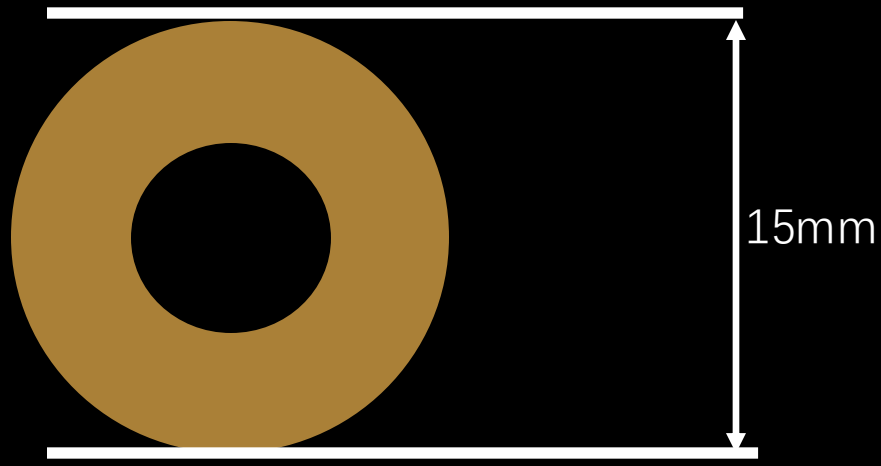
View blocking





The upper budget of the Smartlens

View blocking

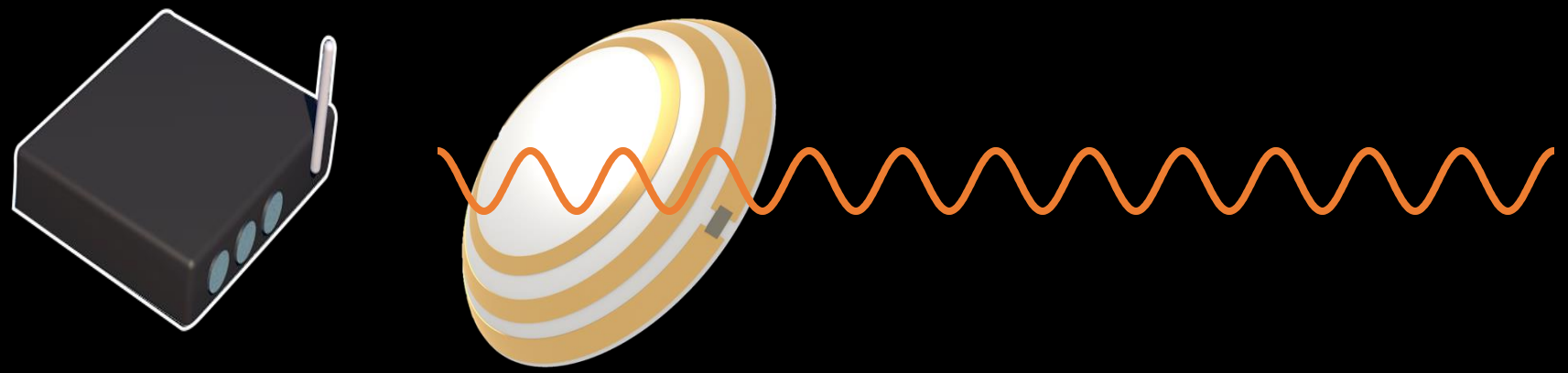


The budget of the Smartlens

The space budget of the SmartLens is extremely limited

Communication and sensing range

Require a certain communication distance

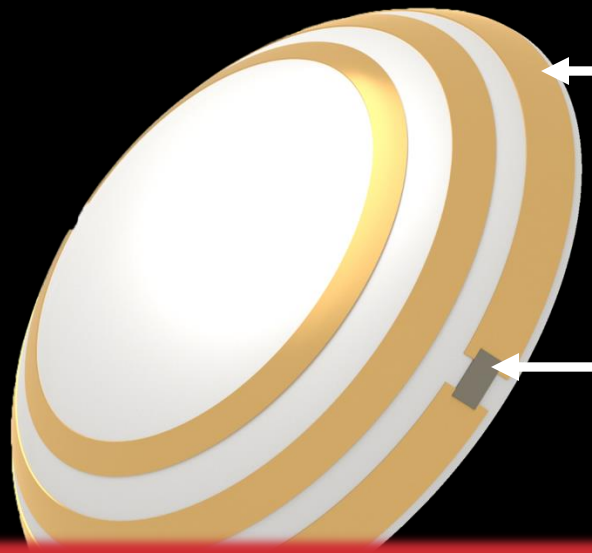


Tag antenna design significantly affects the backscattering efficiency

How can we design a tag that has similar size as contact lens and at the same time supports meter-level communication range?

Communication and sensing range

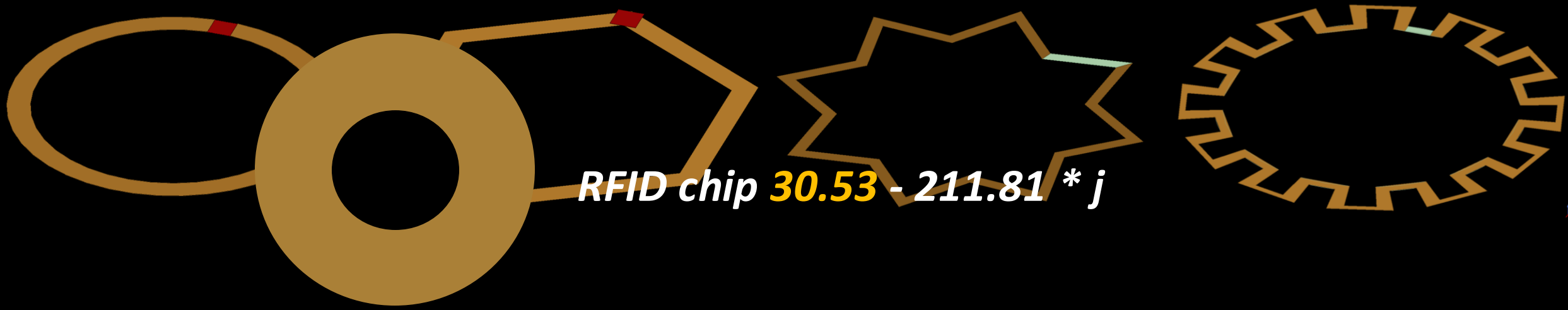
Impedance matching



Matching the impedance between the RF chip and tag antenna

Antenna design

Step one: selecting the basic shape

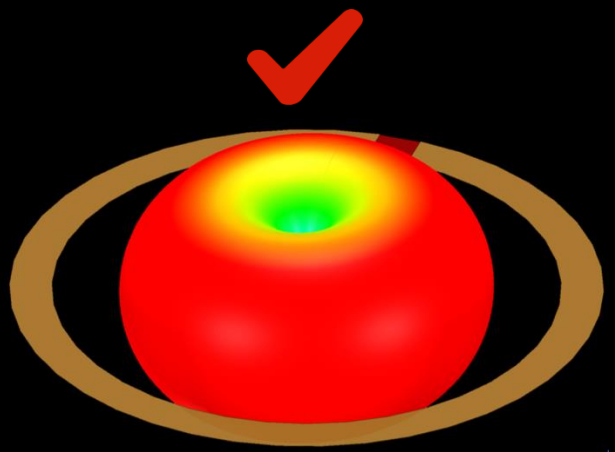


RFID chip 30.53 - 211.81 * j

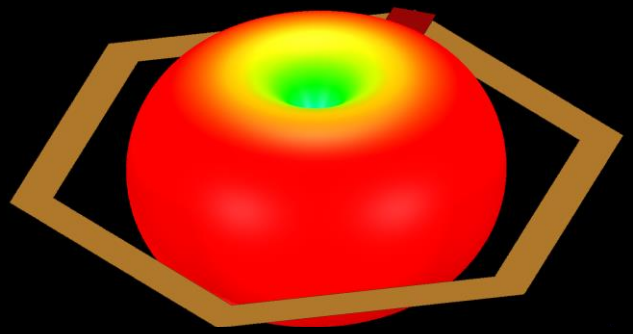
The budget of the Smartlens

Antenna design

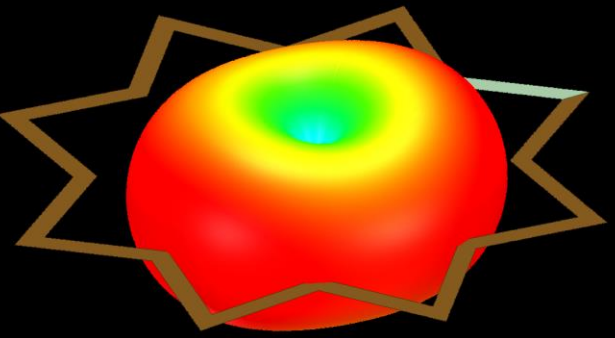
Step one: selecting the basic shape



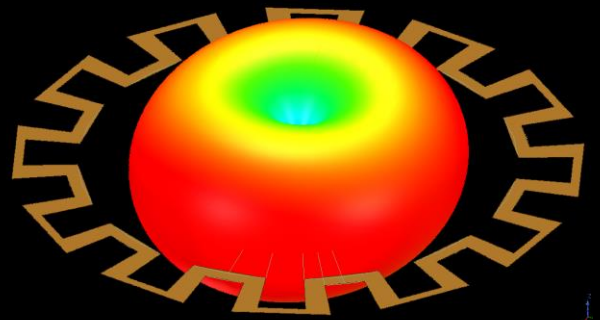
0.355 *+ 165 * j*



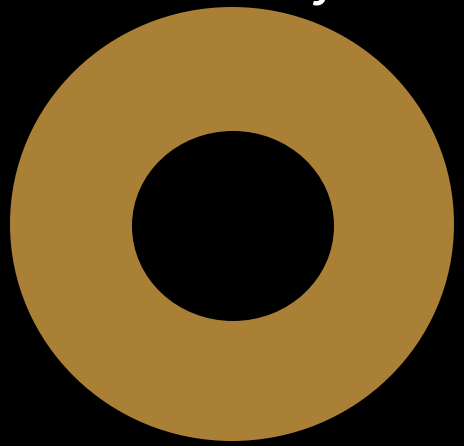
0.0185 *– 1751 * j*



0.0355 *+ 154 * j*



0.0499 *+ 198 * j*



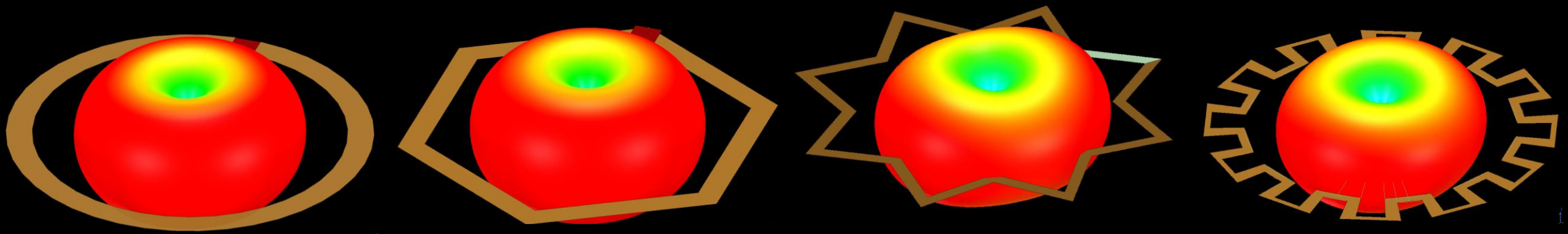
The budget of the Smartlens

∧

RFID chip 30.53 - 211.81 * j

Antenna design

Step one: selecting the basic shape



0.355 *+ 165 * j*

0.0185 *– 1751 * j*

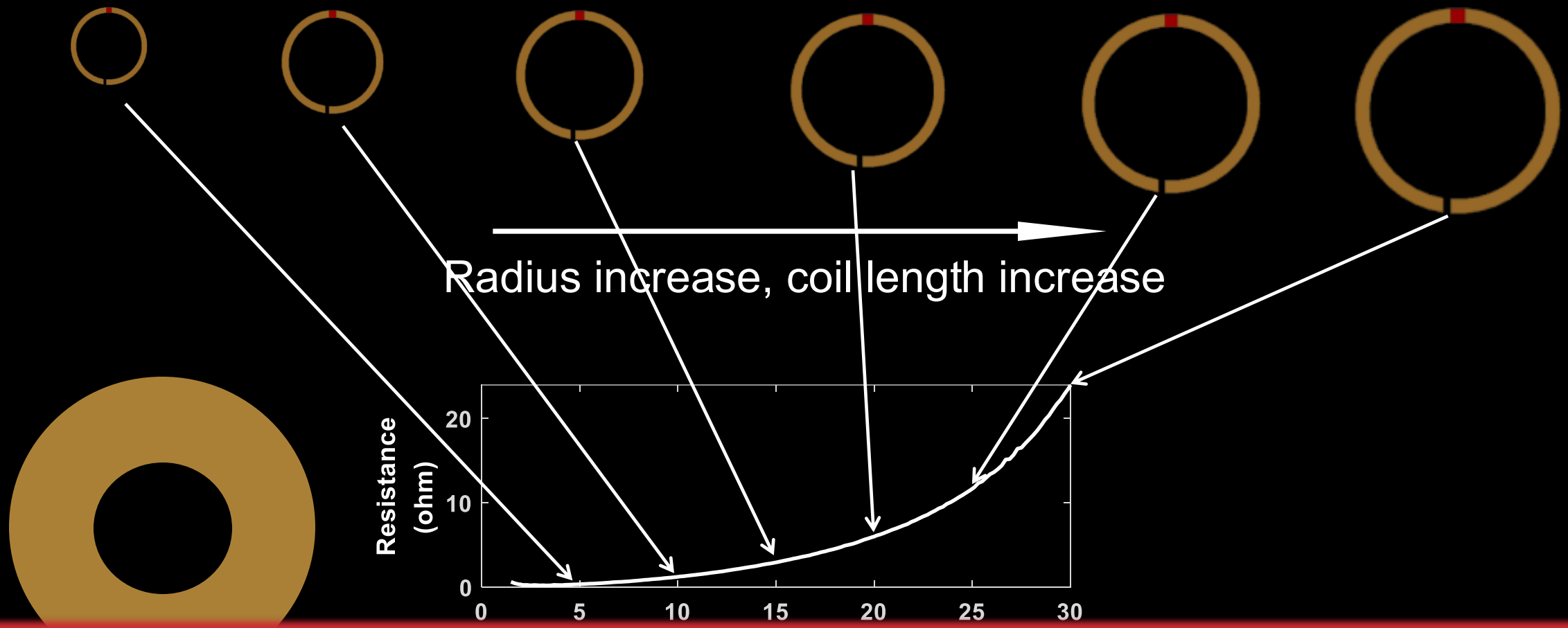
0.0355 *+ 154 * j*

0.0499 *+ 198 * j*

RFID chip **30.53** ***- 211.81 * j***

Antenna design

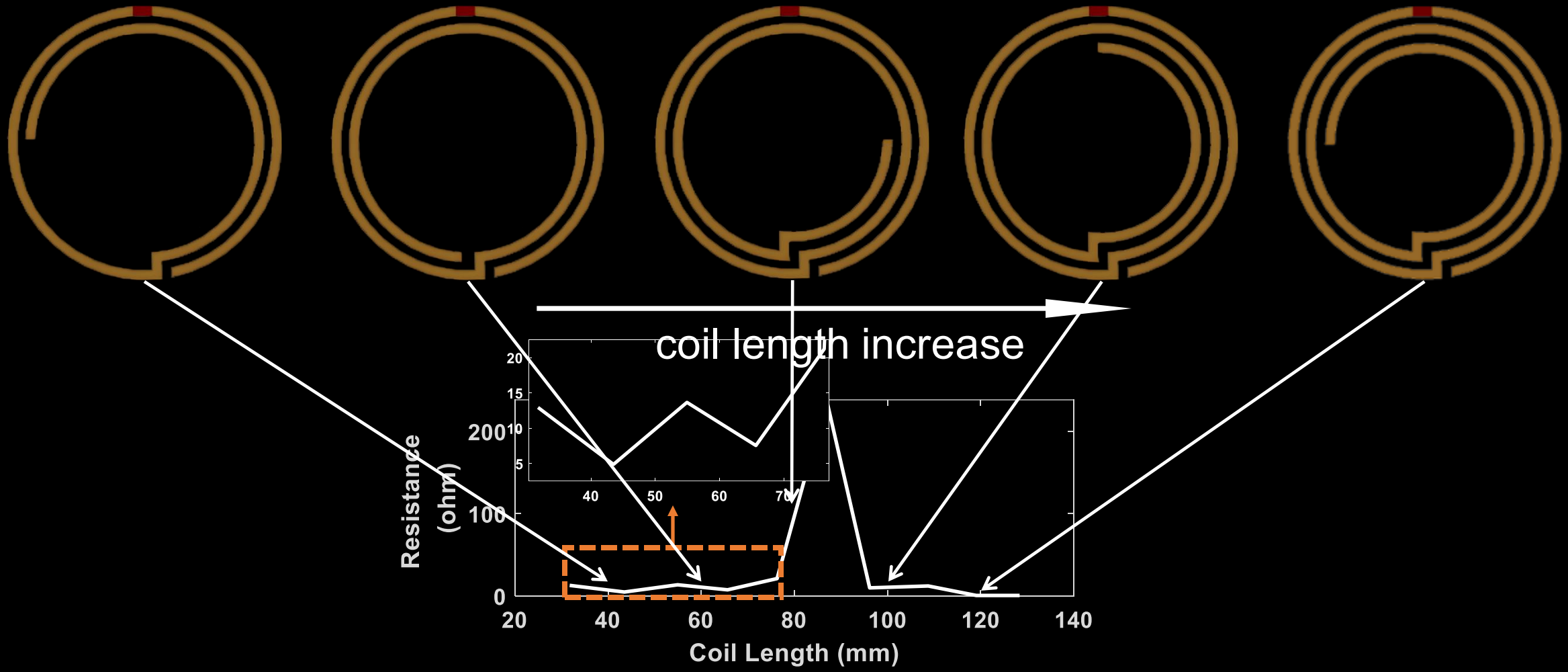
Step two: increase the physical length of the antenna



Limited by the space budget, we cannot increase the radius of the circle infinitely

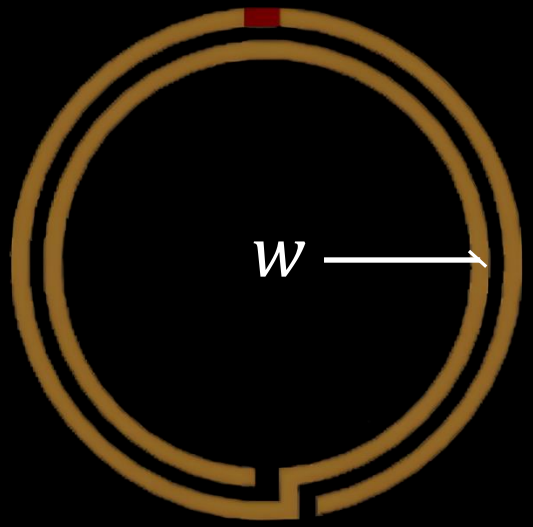
Antenna design

Step two: increase the physical length of the antenna

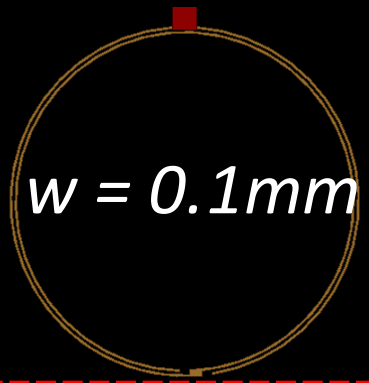


Antenna design

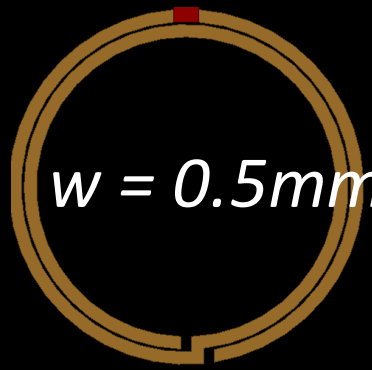
Step three: Fine tuning the antenna structure



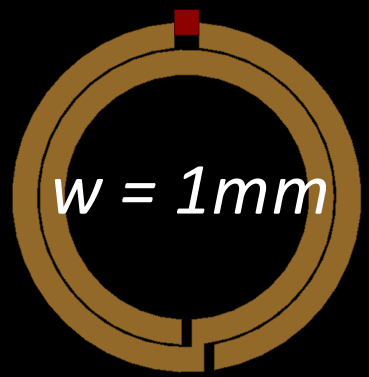
w is the width of the loop



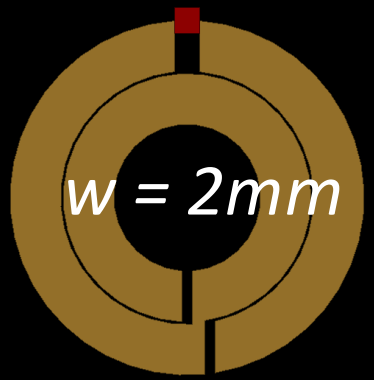
218.05 + 987.40 * j



5.59 - 102.68 * j



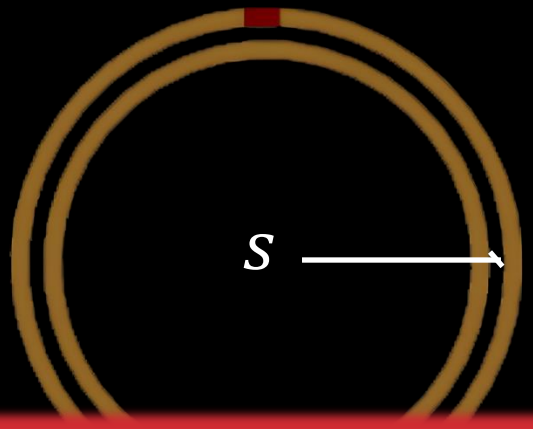
9.13 - 24.98 * j

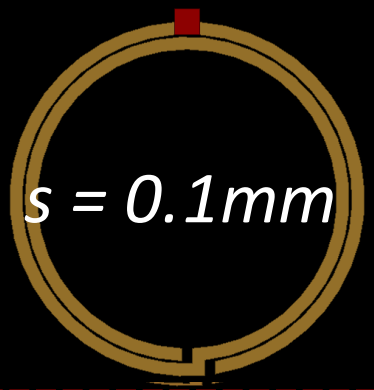


5.17 - 160.14 * j

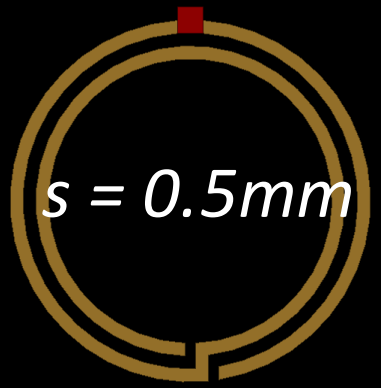
Antenna design

Step three: Fine tuning the antenna structure





24.99 + 180.36 * j



7.84 – 234.27 * j

The width and gap of the loop will significantly affect the impedance of antenna

loops

6.43 – 353.65 * j

5.62 – 497.96 * j

Fine-tuning the antenna structure

SmartLens antenna model.

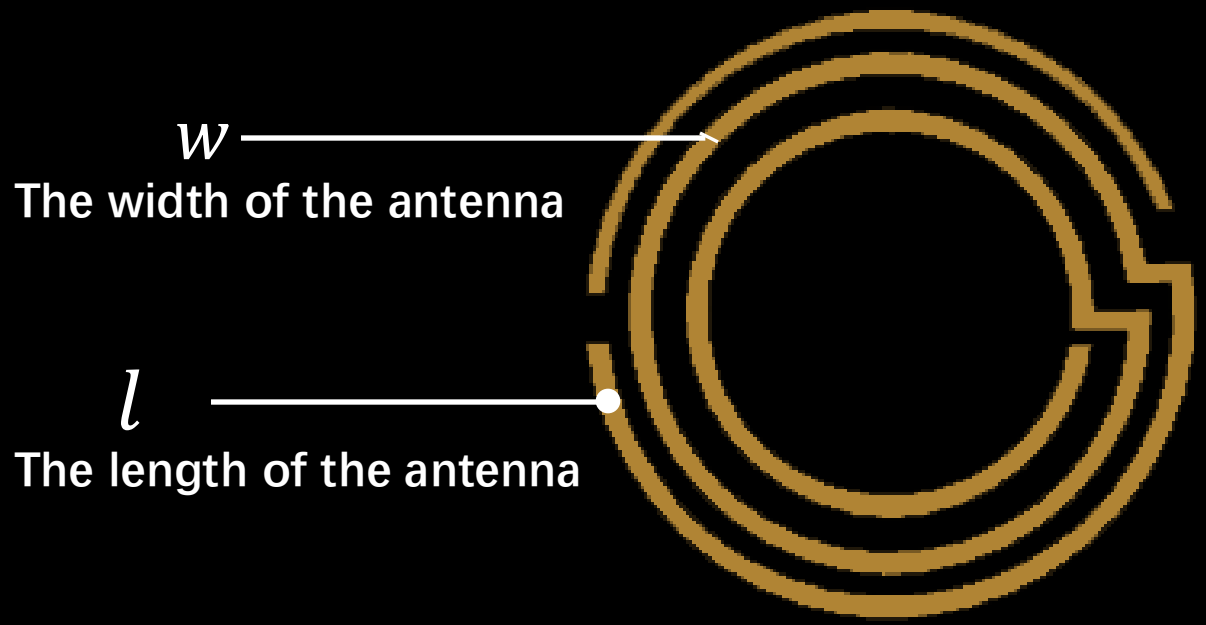
$$Z_a = Z_r + Z_i + Z_c$$

Resistance Inductance Capacitance

$$= R + j\omega L + \frac{1}{j\omega C}$$

Fine-tuning the antenna structure

Resistance



$$R = R_o \cdot \frac{d}{\delta(1-e^{-\frac{d}{\delta}}) \cdot \frac{w+d}{w}}$$

$$\delta = \sqrt{\frac{1}{\pi\sigma\mu f}}$$

$$R_o = \frac{1}{\sigma}\left(\frac{l}{wd}\right)$$

Resistance related to: the length and width of the antenna

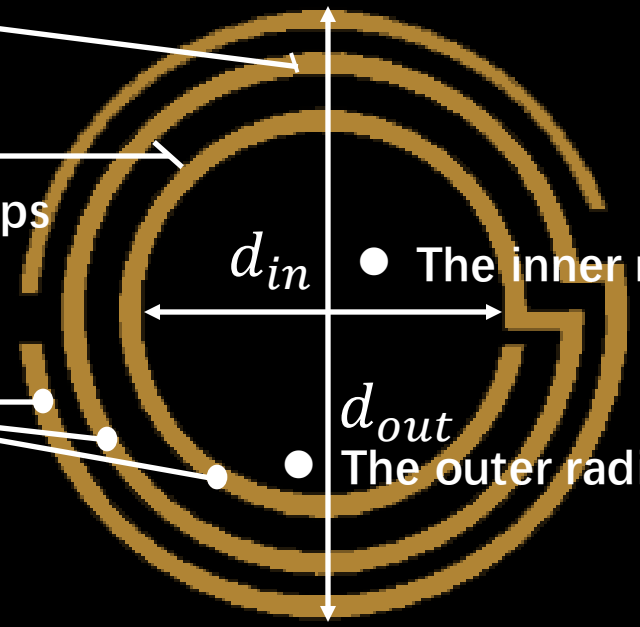
Fine-tuning the antenna structure

Inductance

w
- The width of the antenna

s
- The gap between two loops

n
- The number of the loops



d_{in}
- The inner radius of the antenna

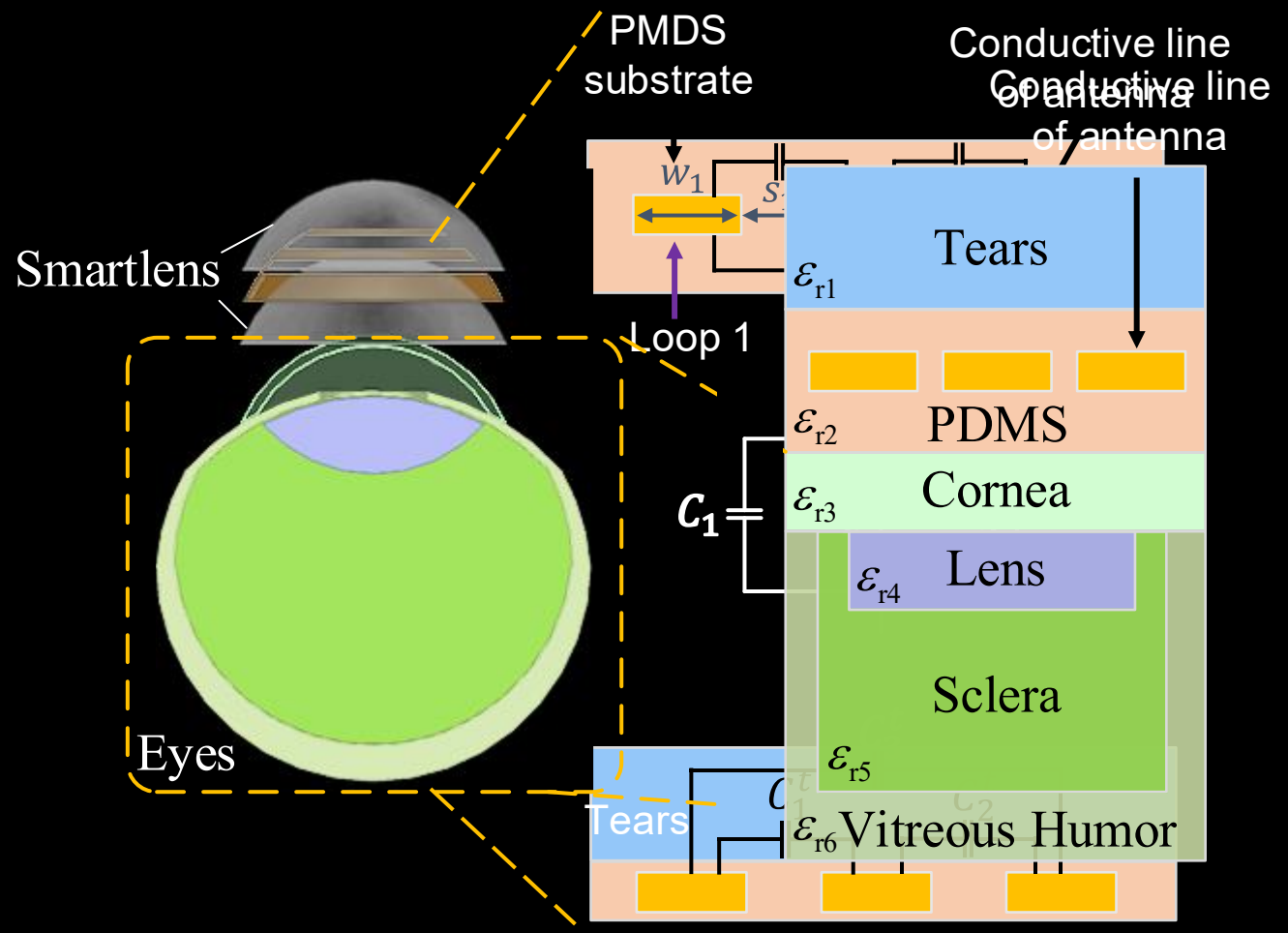
d_{out}
- The outer radius of the antenna

$$L = \frac{\mu n^2 d_{avg}}{2}(\ln(2.46/\rho) + 0.2\rho^2) \qquad d_{avg} = \frac{(d_{in} + d_{out})}{2} \qquad \rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$$

Inductance related to: the number of loops, the width and gap of antenna, and the diameter of the inner and outer radius of the antenna

Fine-tuning the antenna structure

Capacitance



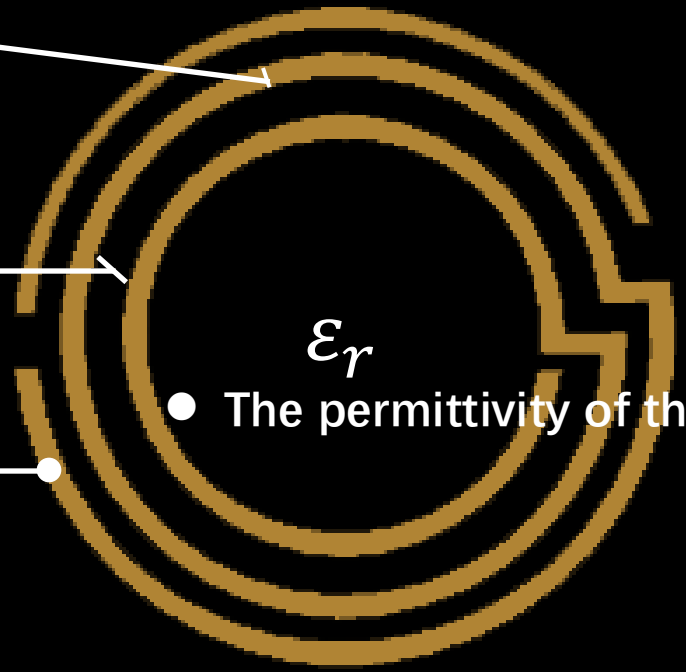
Fine-tuning the antenna structure

Capacitance

w
- The width of the antenna

s
- The gap between two loops

l
- The length of the antenna



ε_r
- The permittivity of the eyes

$$C = \frac{\varepsilon_r \, l \ln\left(2\frac{\left(1+\sqrt[4]{1-k^2}\right)}{\left(1-\sqrt[4]{1-k^2}\right)}\right)}{377\pi v_0}$$

$$C_a = C_1 + C_2 + C_3$$

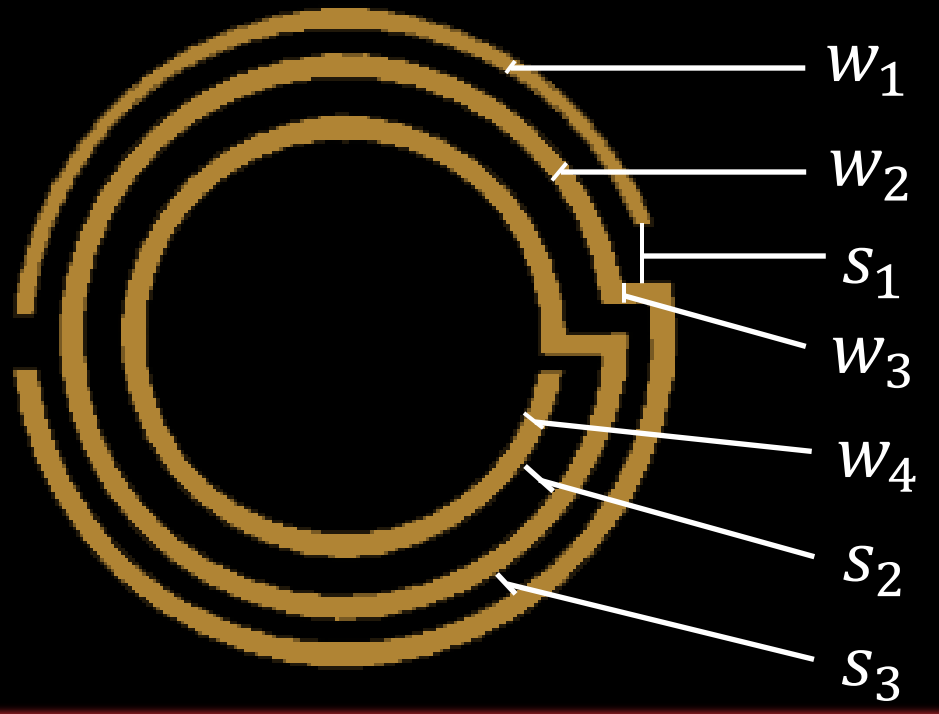
$$C_a = C_1^t + C_2^t + C_3^t$$

$$C = C_a + C_t + C_c + C_l + C_s + C_v$$

Capacitance related to: The length of the antenna, the line width of each loop, the gap between loops and the permittivity of the eyes

Fine-tuning the antenna structure

Overall parameter affecting antenna impedance

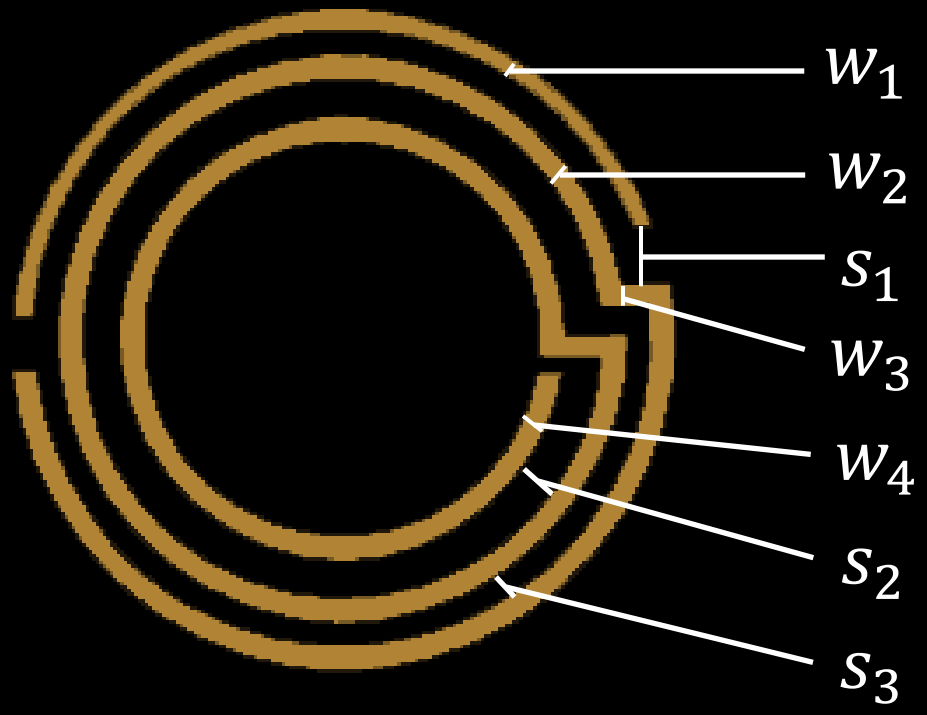


Seven parameters that affect antenna impedance

Fine-tuning the antenna structure

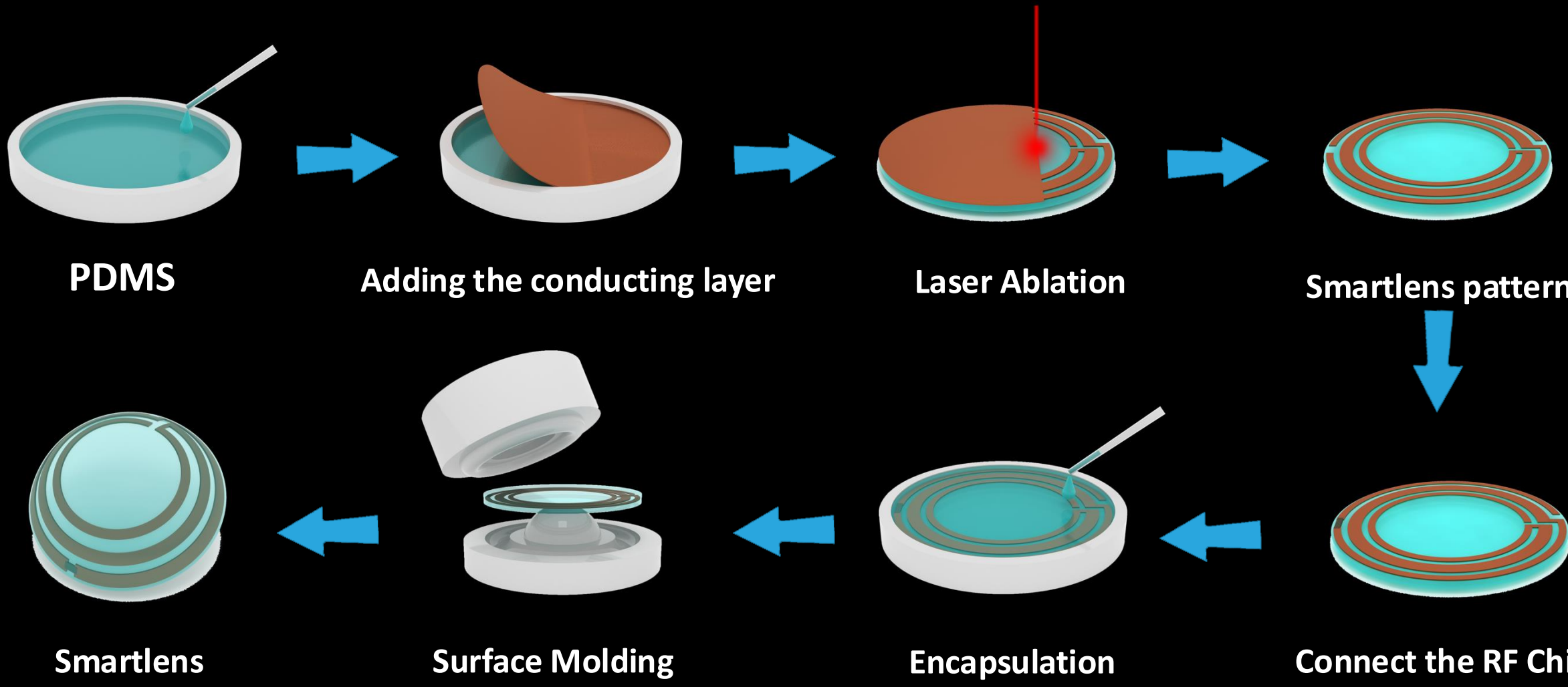
Solving the impedance matching equation

$$Z_a = Z_g$$



w1	w2	s1	w3	w4	s2	s3	Re	Im
0.1	0.5	0.6	0.9	1	1.1	1.3	27.635	212.46
0.1	0.3	0.5	0.8	0.9	1.1	1.3	23.965	198.44
0.3	0.4	0.5	0.9	1	1.1	1.3	27.563	215.84
...	...	...	...	...	...	...	...	...
0.1	0.3	0.6	0.7	0.8	1	1.4	24.175	198.96
0.2	0.5	0.6	0.9	1	1.1	1.3	27.373	214.14
0.1	0.3	0.6	0.8	0.9	1	1.4	24.234	199.23
0.1	0.3	0.6	0.8	1	1.1	1.3	24.01	198.37

Tag fabrication



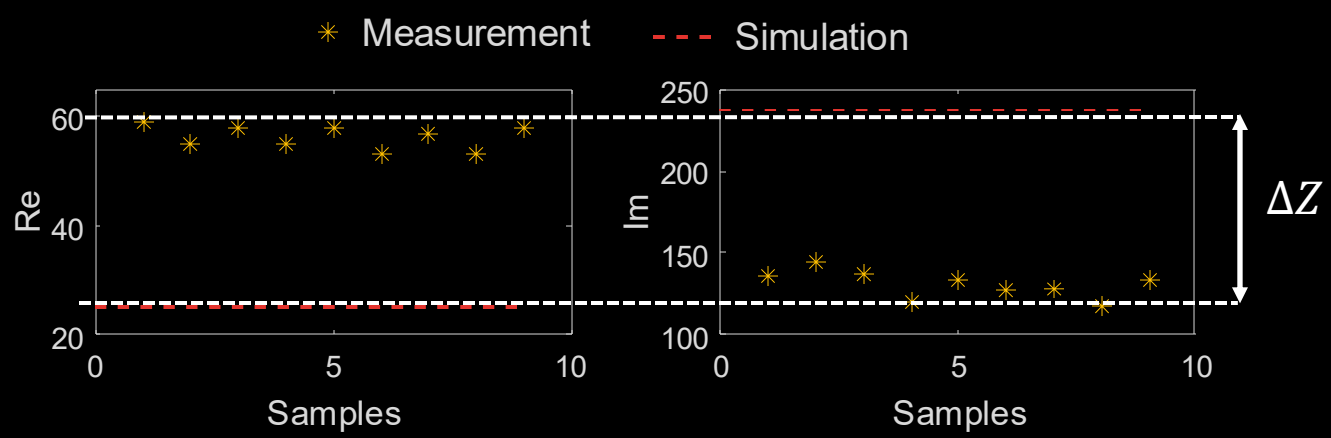
Iterative refinement

Compensating engineering error

The simulation impedance of the tag : $Z_{simulation}$

The fabrication tag : Z_{tag}

$$\Delta Z = \left| Z_{simulation} - Z_{tag} \right|$$

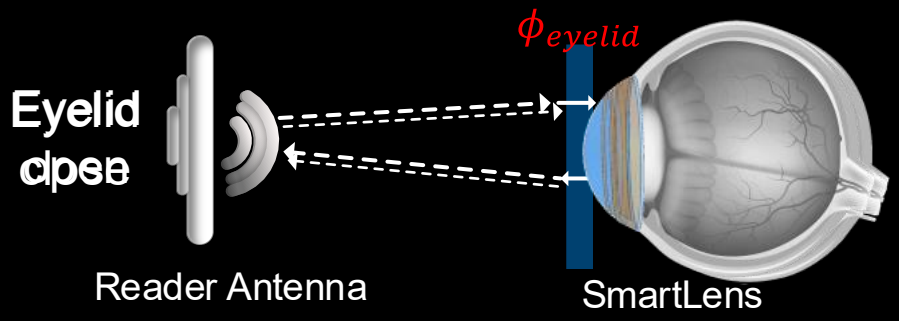


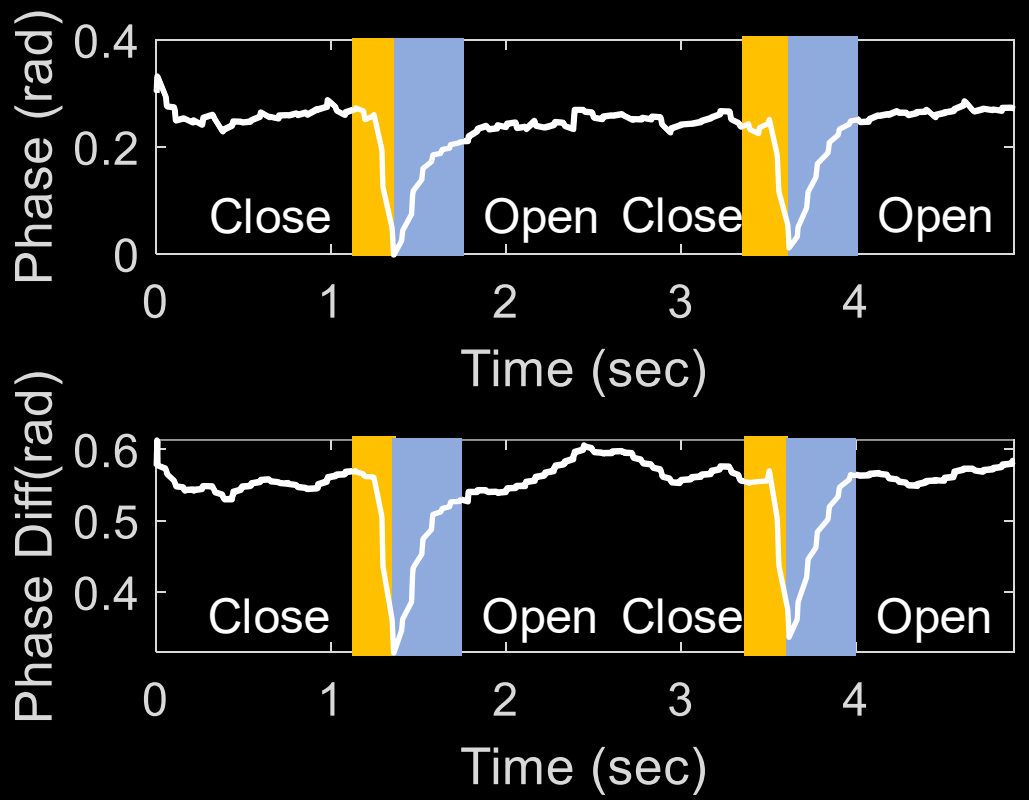
How to detect the eye movement?

Smartlens attempts to detect the eyes movement based on **phase information**

Eye movement detection

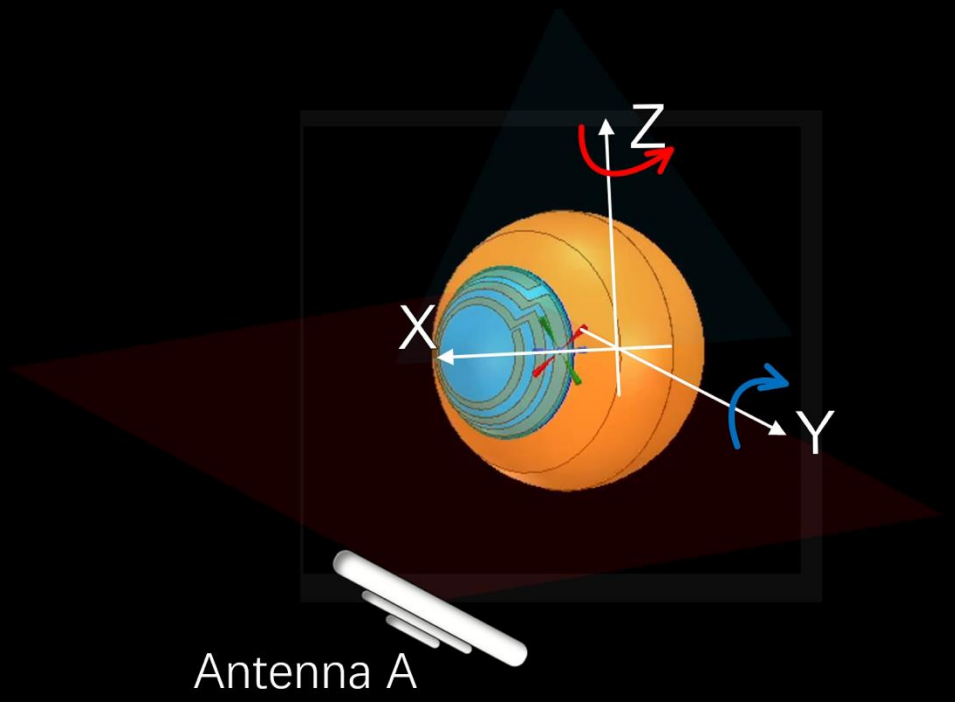
Sensing the blink

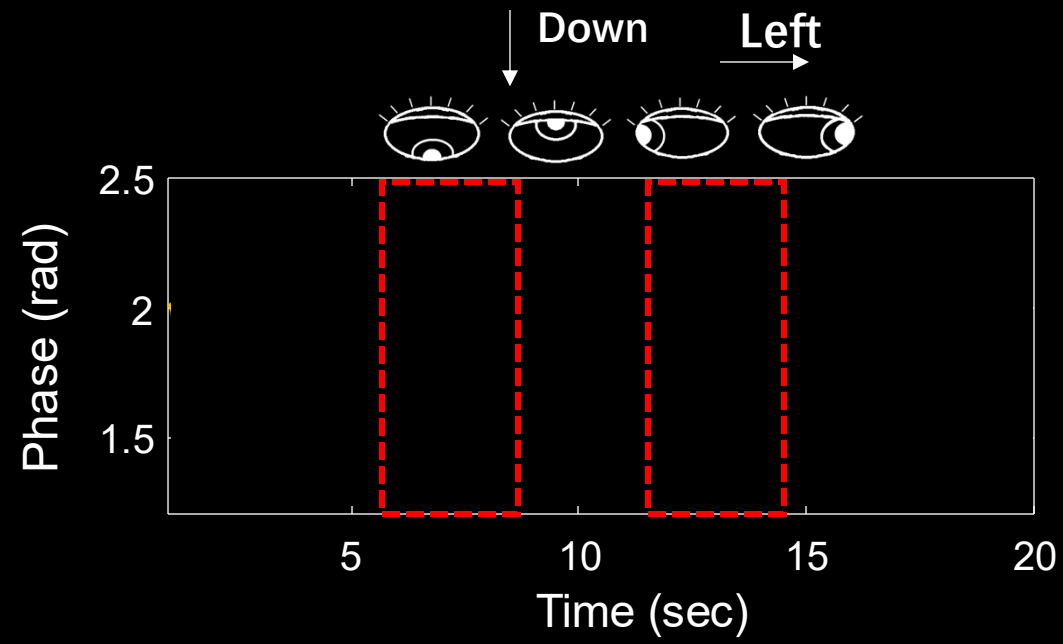




Eye movement detection

Sensing the eye movement

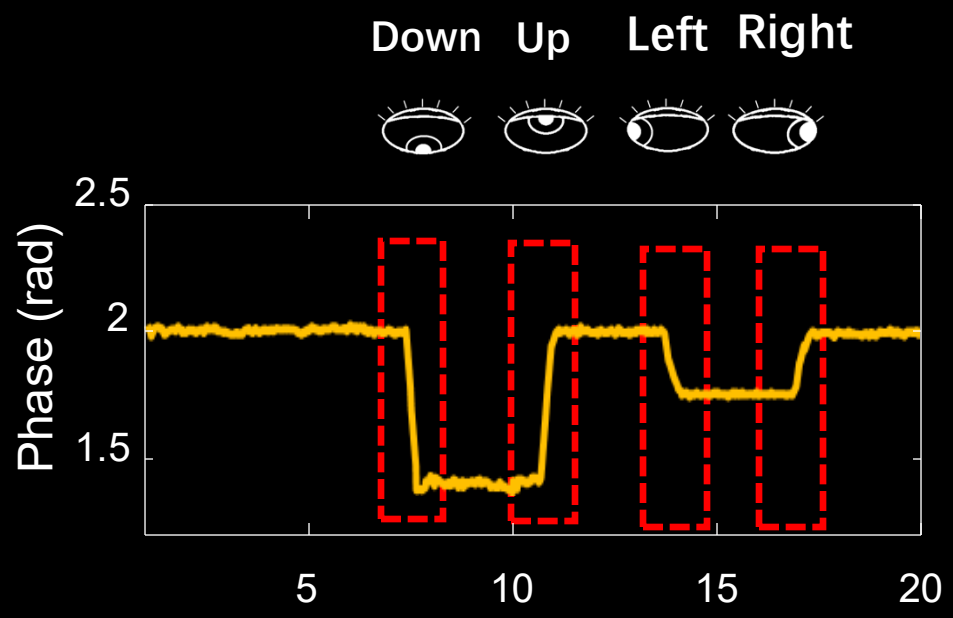




The phase variations caused by polarization direction mismatch

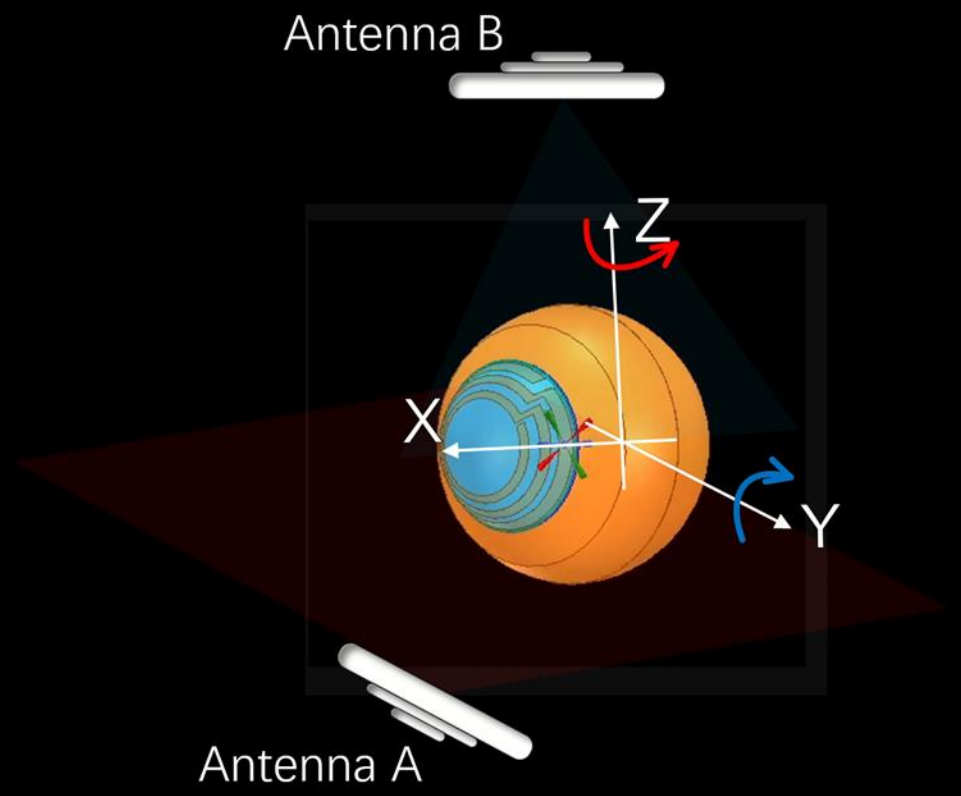
Eye movement detection

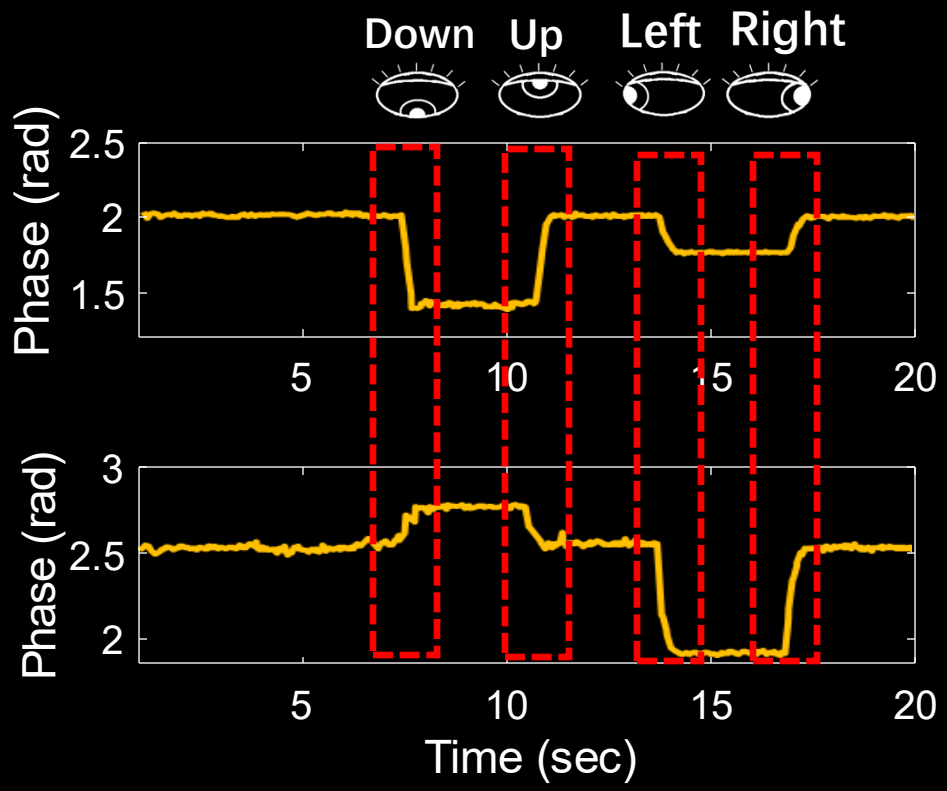
Sensing the eye movement



Eye movement detection

Sensing the eye movement

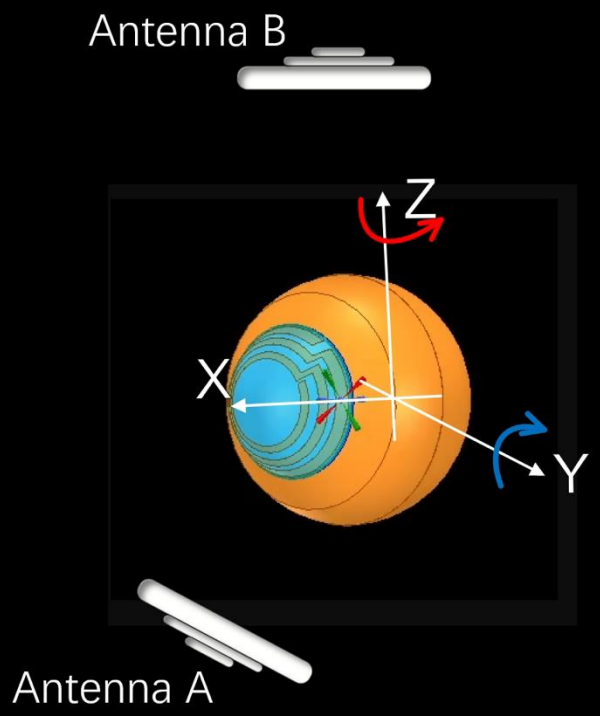




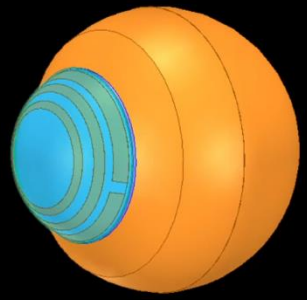
Deploy another antenna on the elevation plane to remove the ambiguity and identify four direction of eyeball rotation

Eye Movement Detection

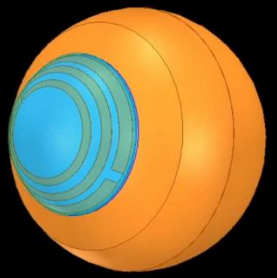
Sensing the single direction



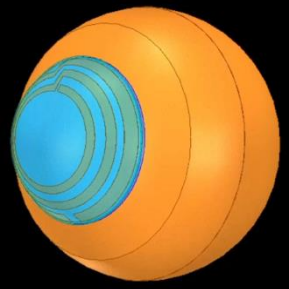
Sensing the rotation



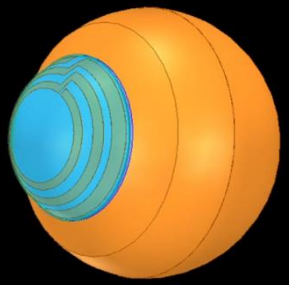
Rotation from up to right



Rotation from right to down



Rotation from down to left

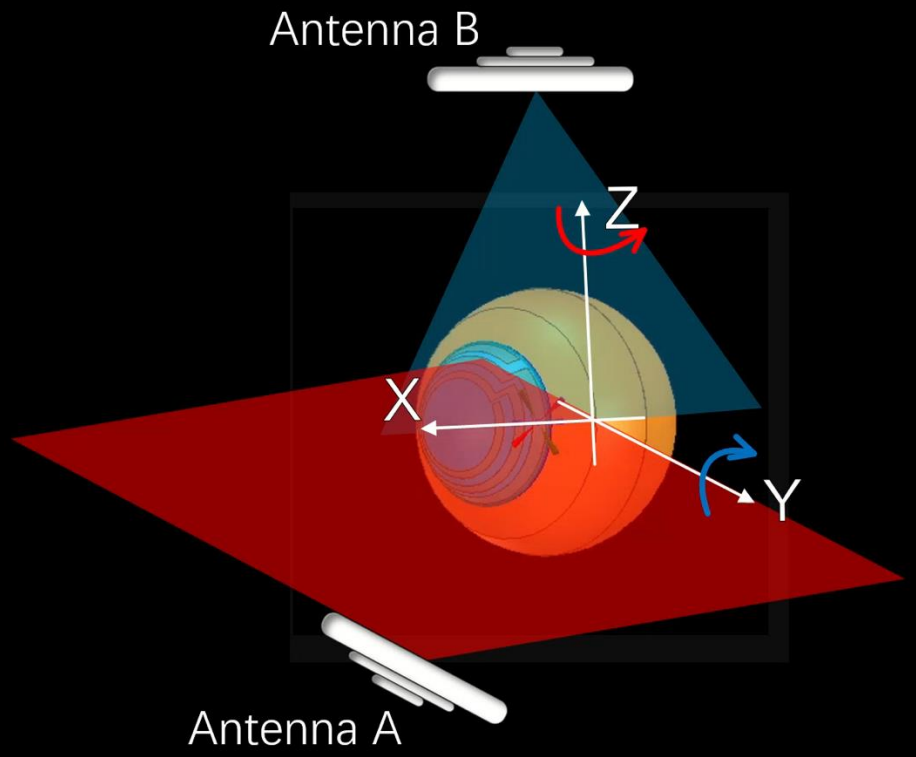


Rotation from left to up

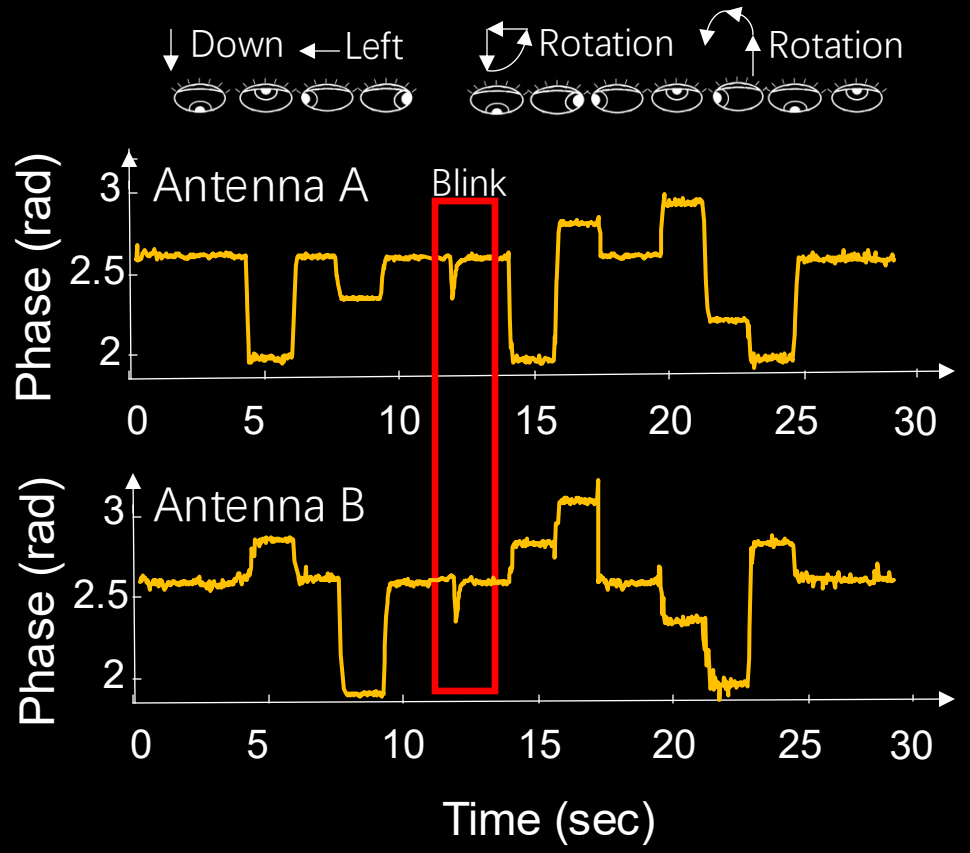
Eye Movement Detection

Sensing the single direction and rotation

The type of eye movement



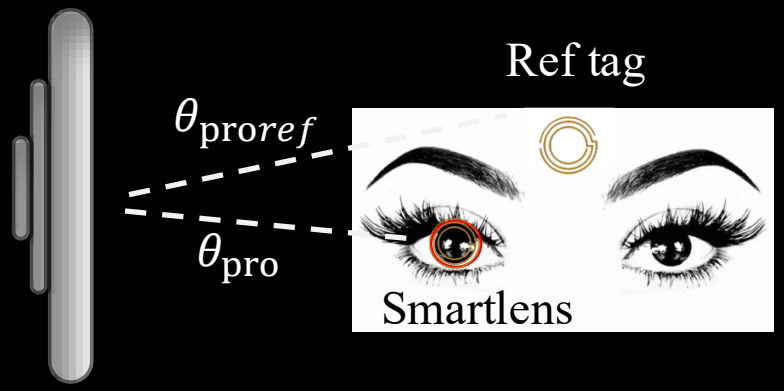
Signal received by the reader

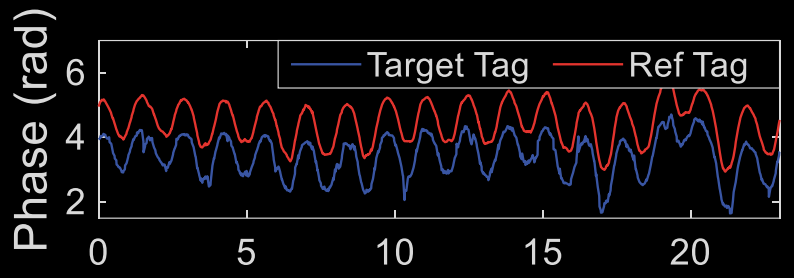


How to eliminate the interference?

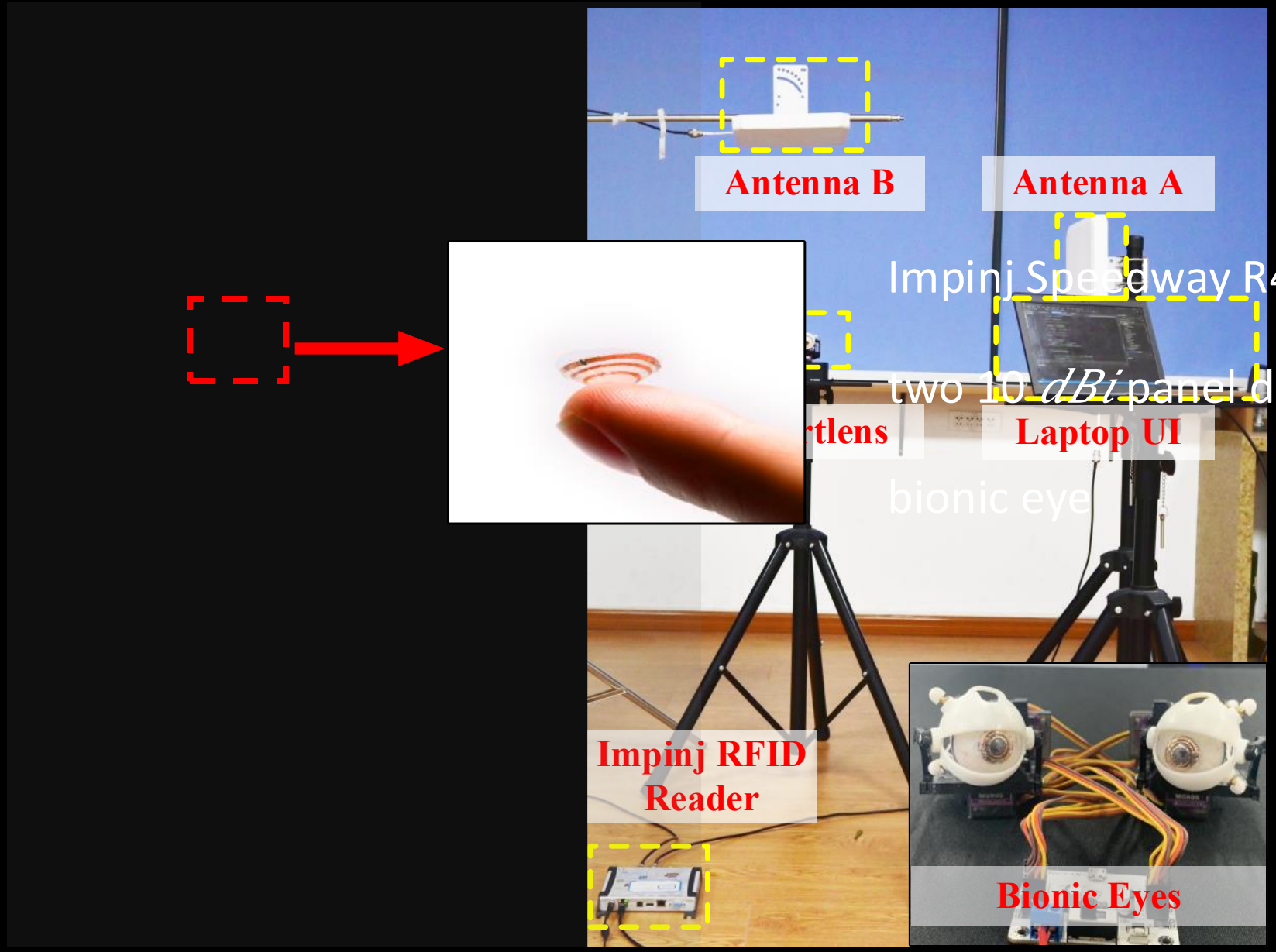
Elimination of environmental interference

By adding reference tags :





Implementation



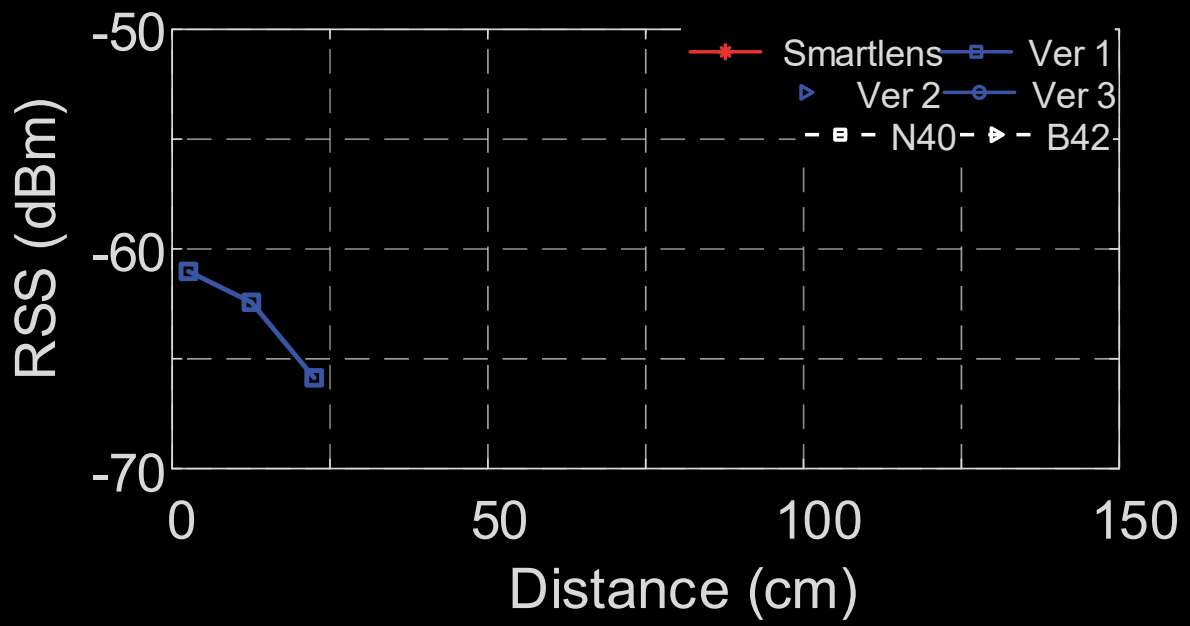
Impinj Speedway R420 RFID reader

two 10 *dBi* panel directional antennas

bionic eye

Evaluation results

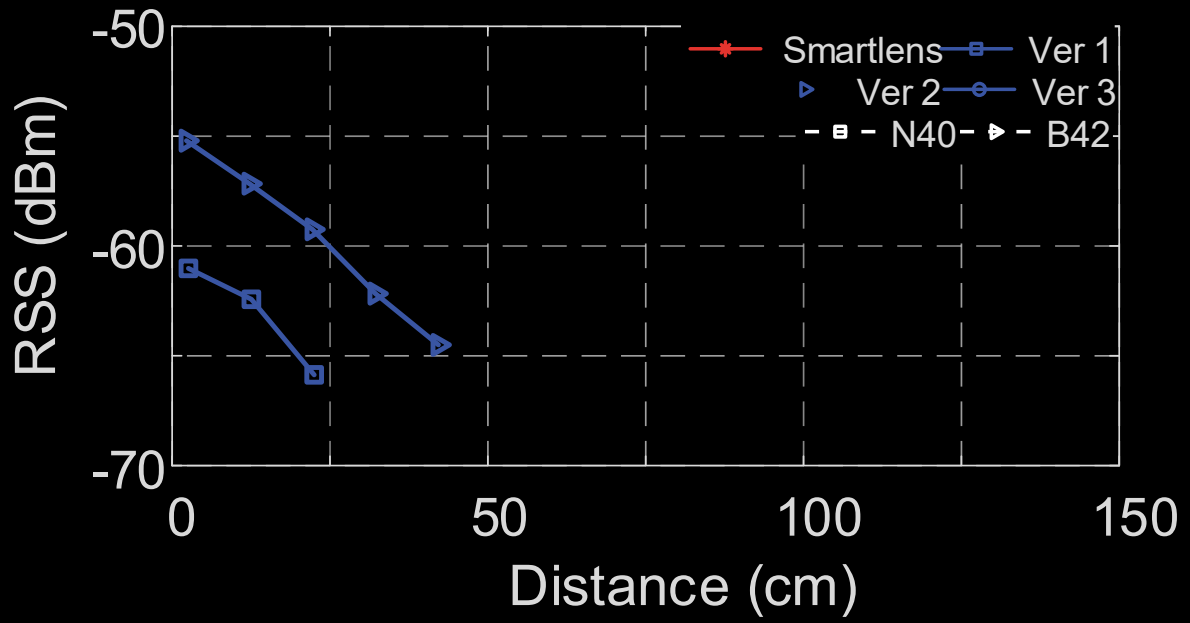
End-to-end performance



Version 1

Evaluation results

End-to-end performance

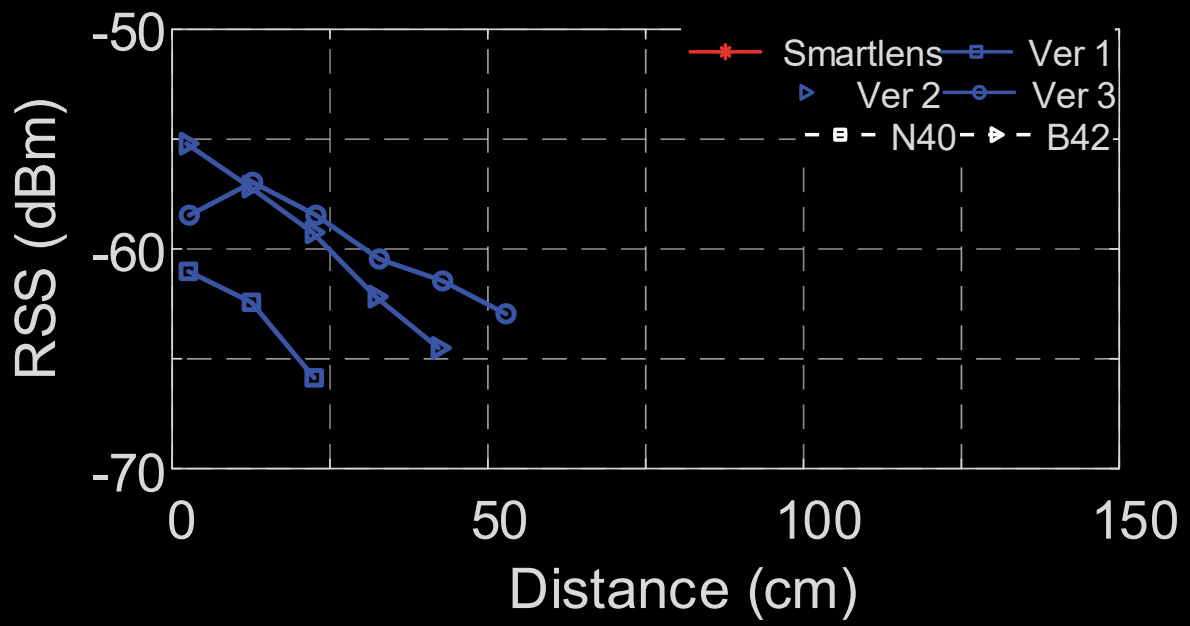


Version 1

Version 2

Evaluation results

End-to-end performance



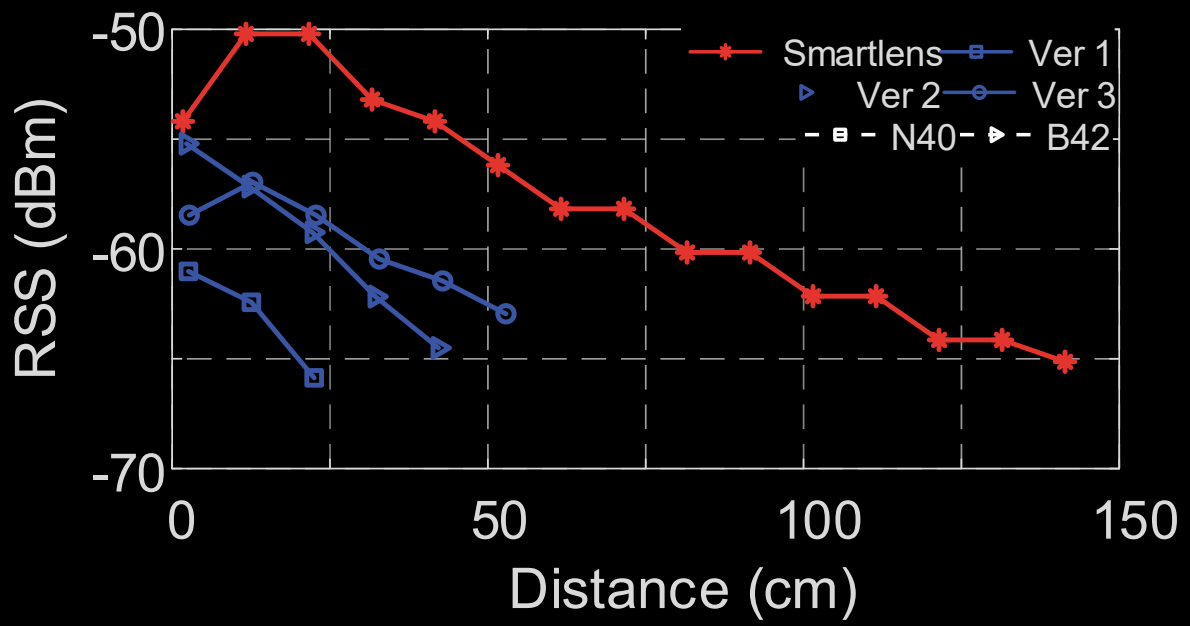
Version 1

Version 2

Version 3

Evaluation results

End-to-end performance



Version 1

Version 2

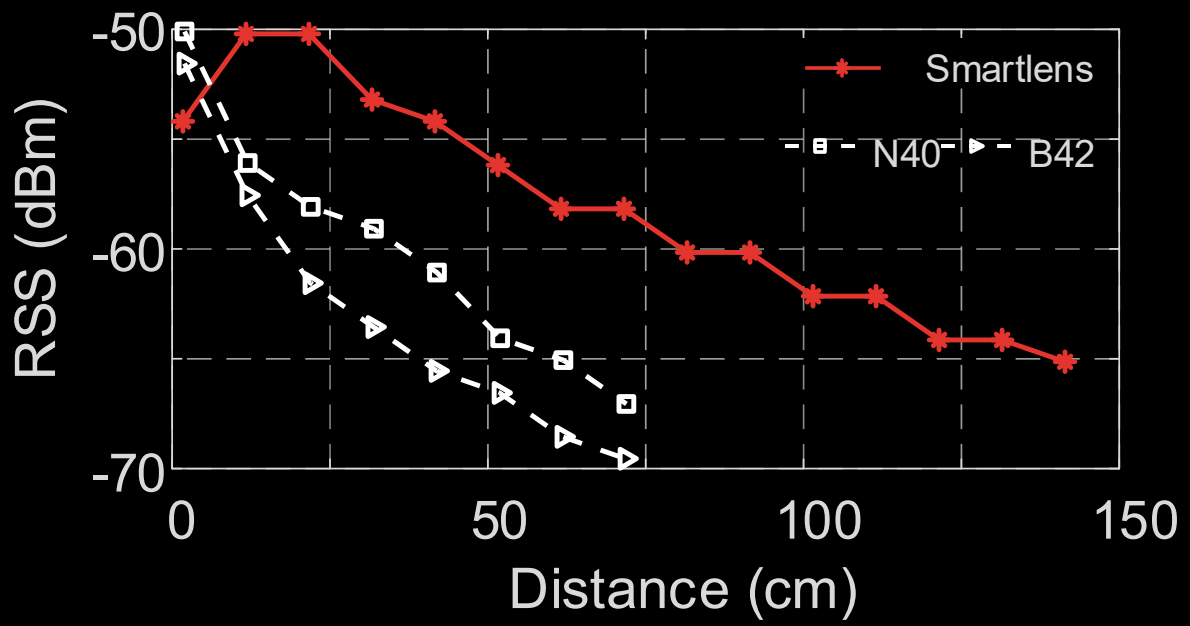
Version 3

Smartlens
Version 8

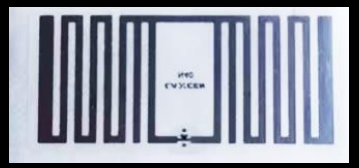
It is necessary of optimizing the structure of tag antenna

Evaluation results

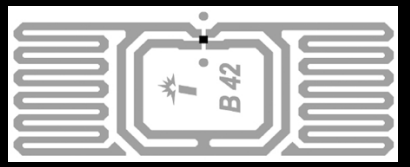
End-to-end performance



Smartlens



N40



B42

1.87 times greater than the commercial tags

Evaluation results

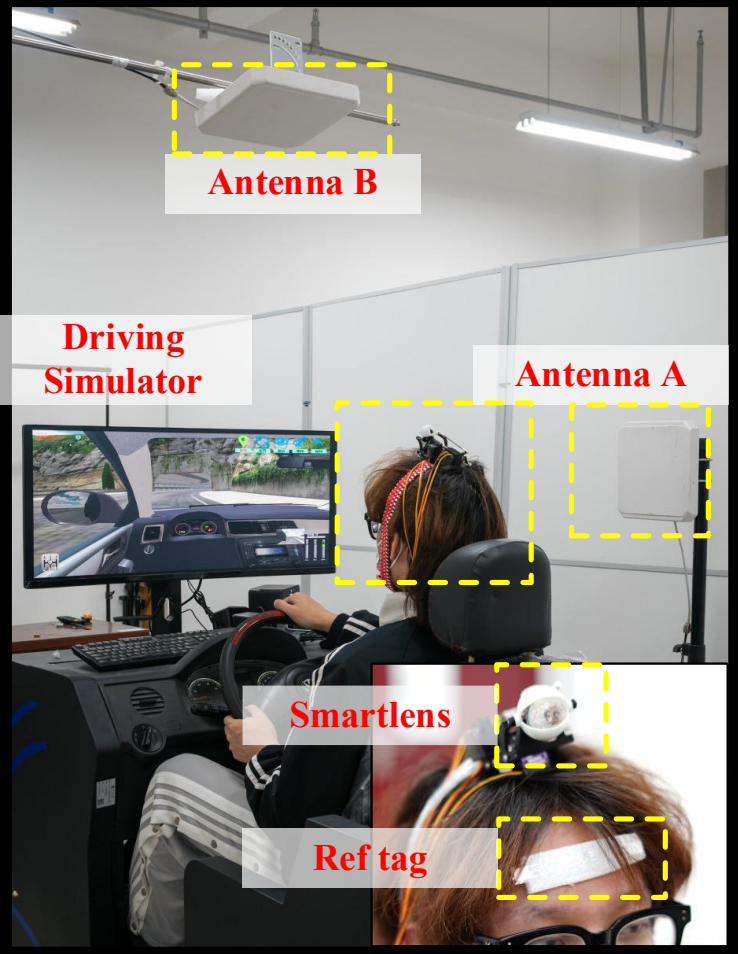
End-to-end performance

89% and 92% detection accuracy

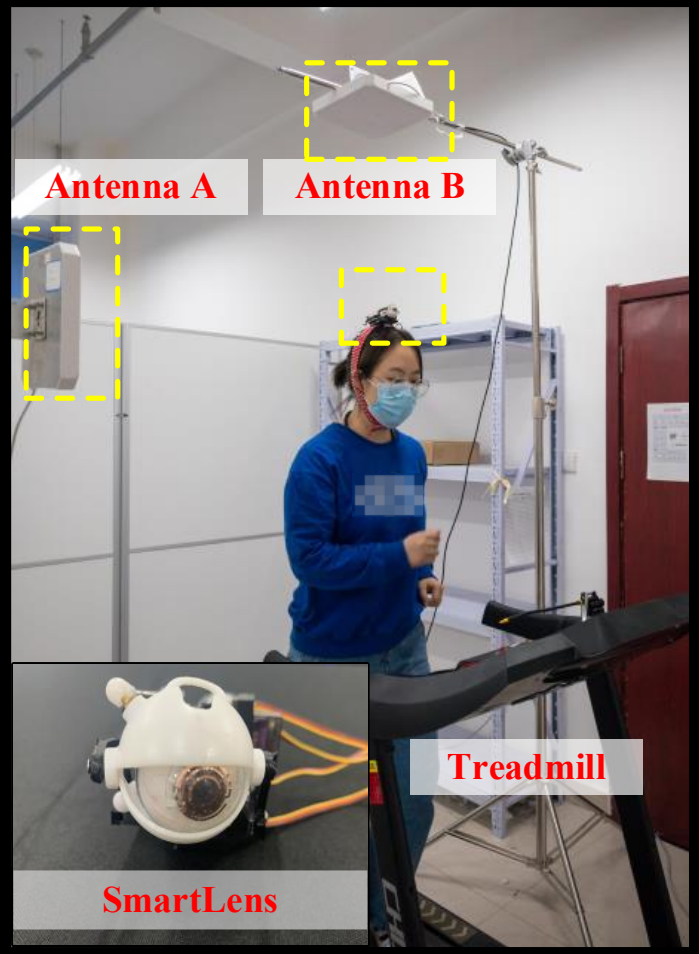
Evaluation setup

✓ Experimental scenarios

Subtle movement



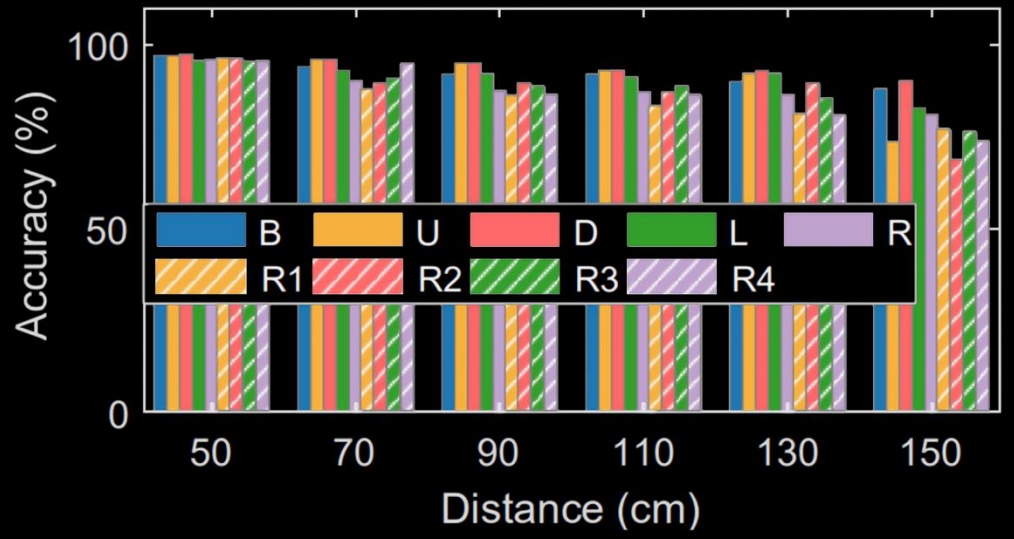
Moderate movement



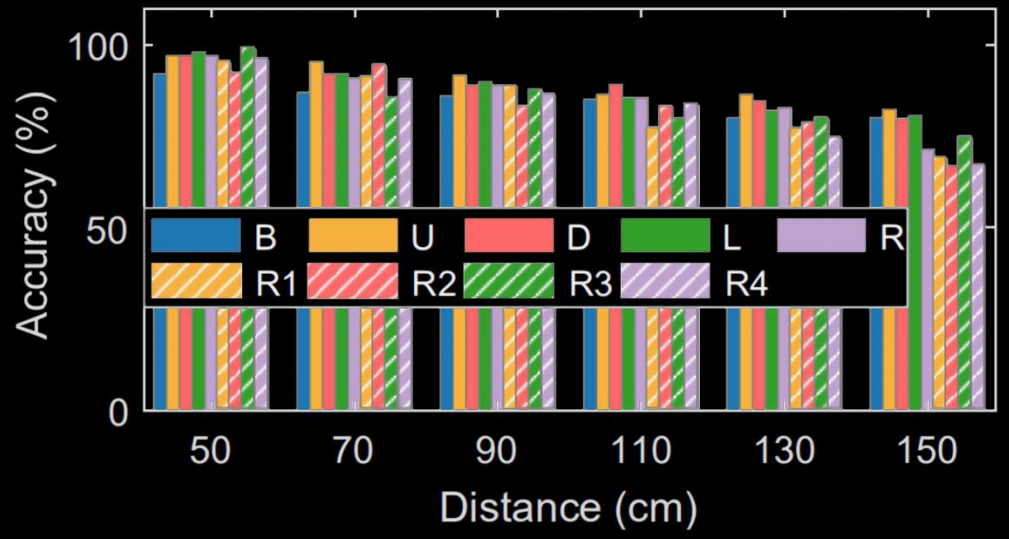
Highly dynamic movement

Evaluation results

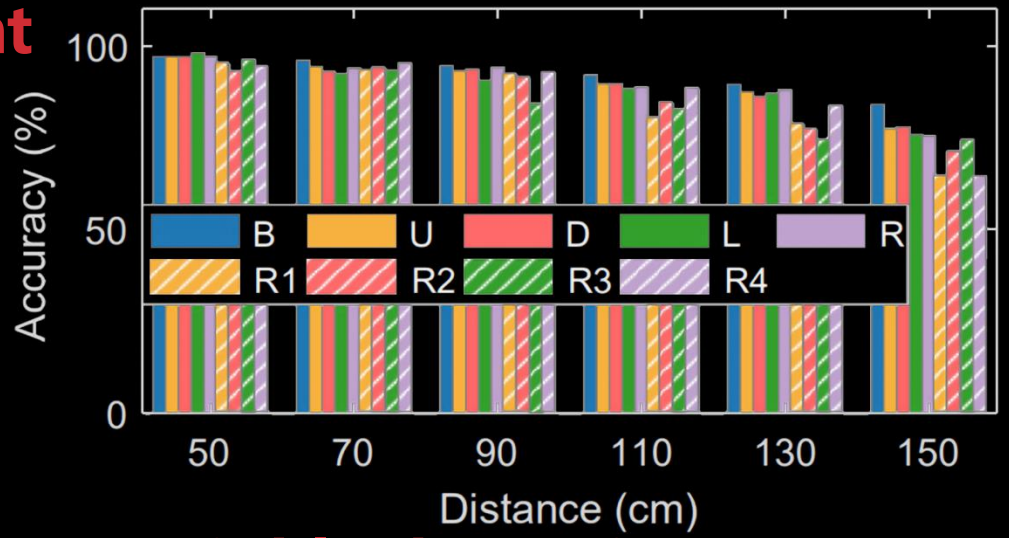
✓ Sensing accuracy under different distance



Subtle movement



Moderate movement

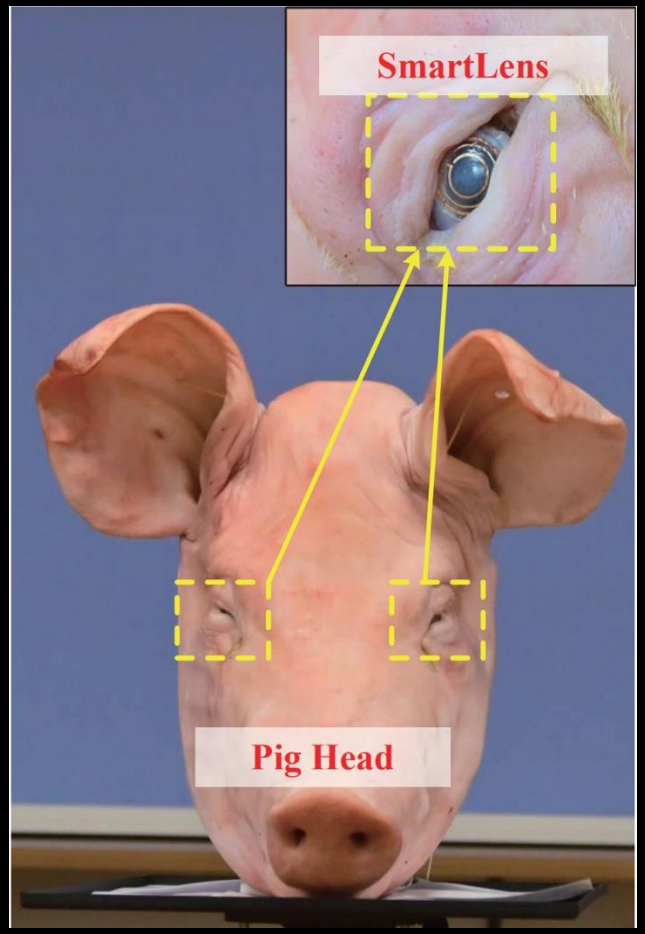


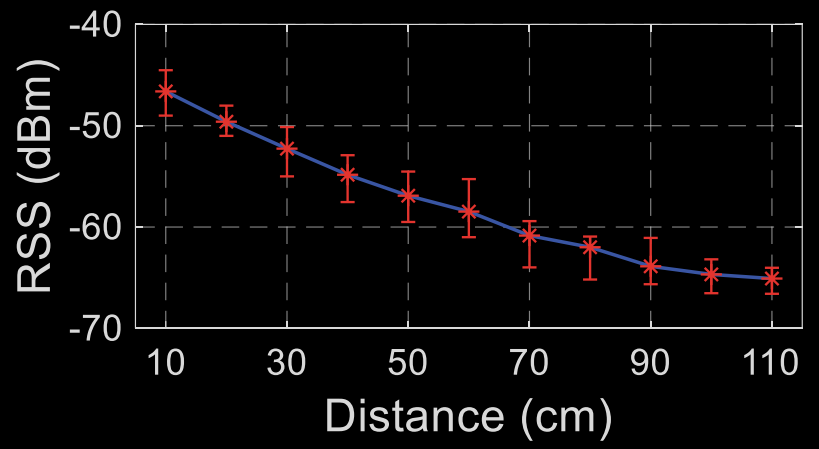
Highly dynamic movement

80.51% detection accuracy at the distance of 140cm

Biological Impact on the Performance

✔ **The impact of pig eyes and eyeball shapes.**

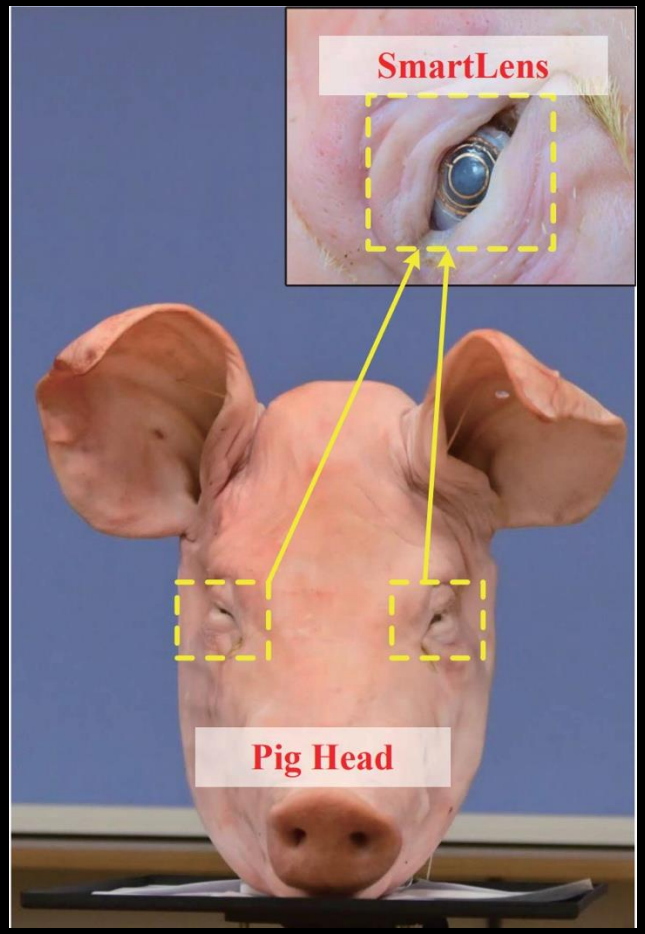


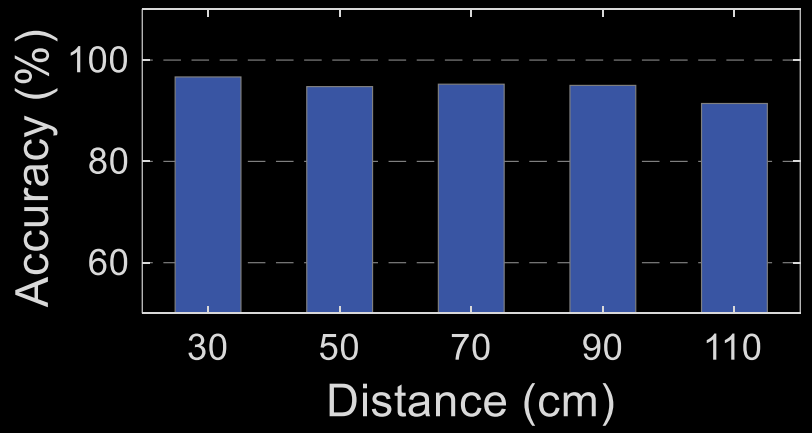


The performance is stable

Biological Impact on the Performance

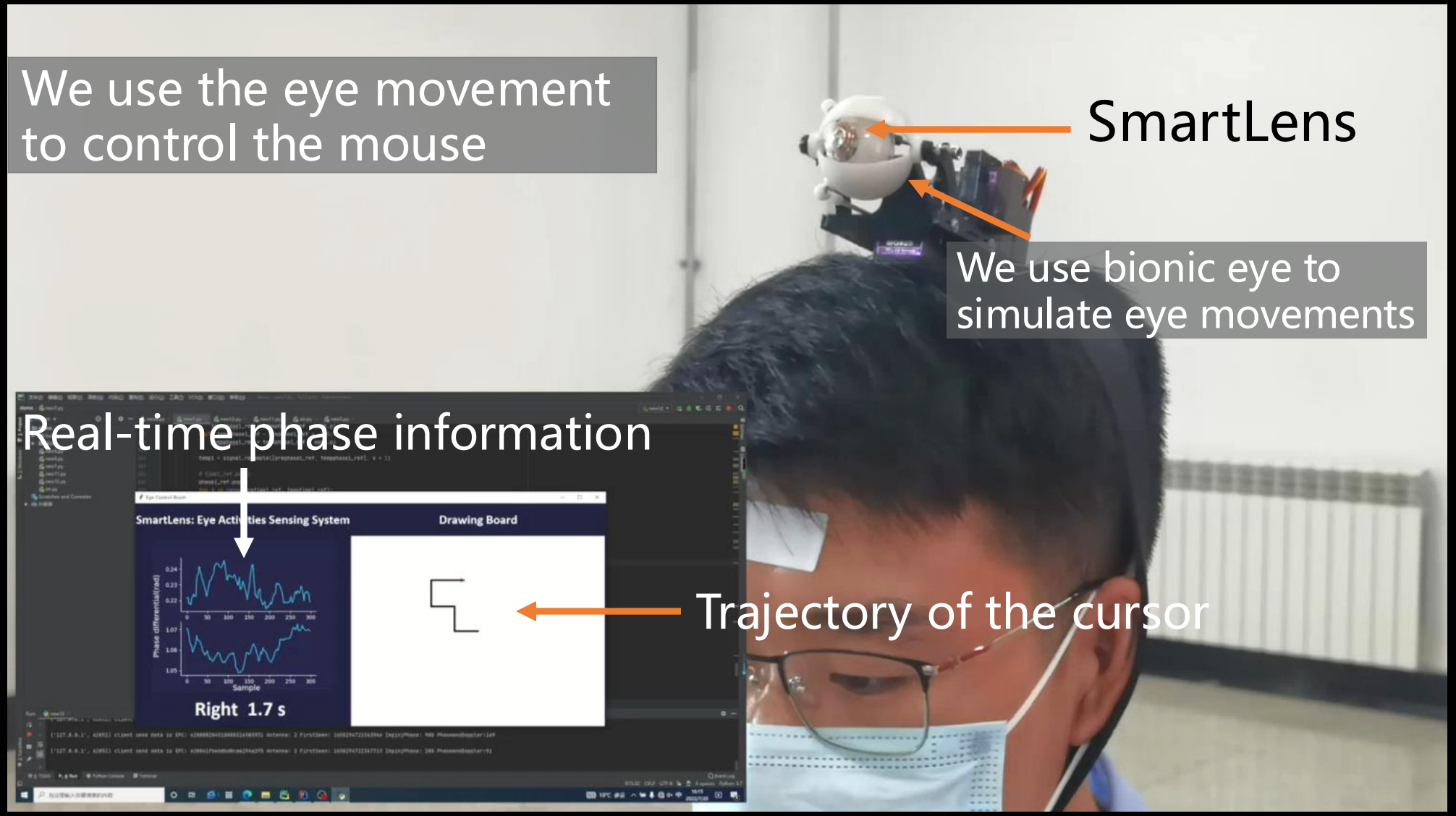
✔ **The impact of pig eyes and eyeball shapes.**





94.61 % detection accuracy

Case study: Controlling the Cursor



Q & A

SmartLens: Sensing Eye Activities Using Zero-power Contact Lens

In Mobicom 2022, Sydney, Australia , October 17-21

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