ULTRASENS–E

All–dielectric and ULTRASENSitive microwave Electric fields sensor based on the electro–optic effect

Project members

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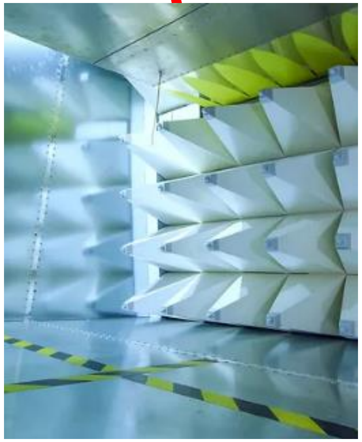
Exemples of application areas

Electric field mapping

SAR (Specific Absorption Rate)

Antennas



EMC (ElectroMagnetic Compatibility)

MRI (Magnetic Resonance Imaging)

http://www.kapteos.com/en/all-faqs/faq-applications/.

The existing

Make accurate E-field measurement with an interference-free optical RX antenna from 10 Hz up to 100 GHz

Absolute E-field measurement from mV/m up to MV/m in time & frequency domains

Compliant with all media such as liquids, biological tissues, vacuum, plasma...

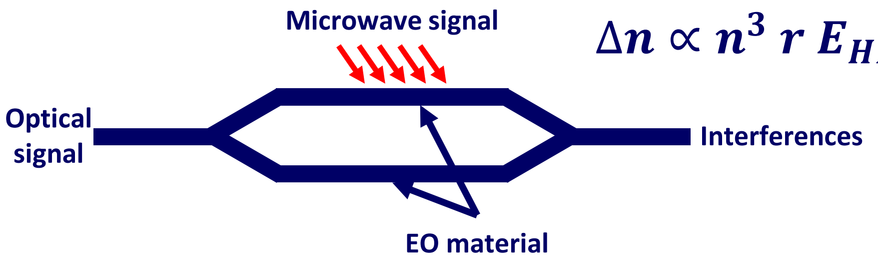
Ultra high damage threshold > 10 W/cm² & compliant with near-field measurement

Transverse, longitudinal and SAR probes for measuring E-field in low κ (gases, plasma, oils) or high κ media (aqueous liquids, biological tissues) and in harsh environment (vacuum, high pressure)

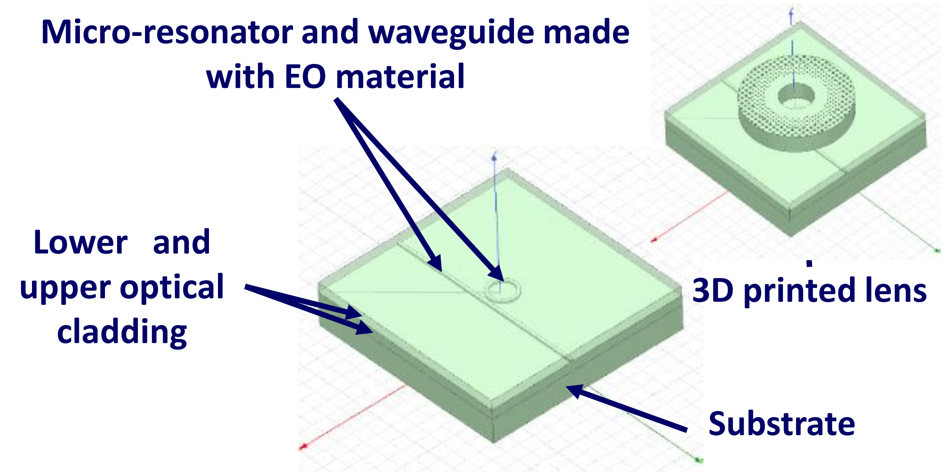
KEY PARTNER FOR ELECTROMAGNETISM
kapteos

The state of the art:
$\sim 10^{-3}$ $V.m^{-1}.Hz^{-1/2}$

Diagram of the integrated functional unit

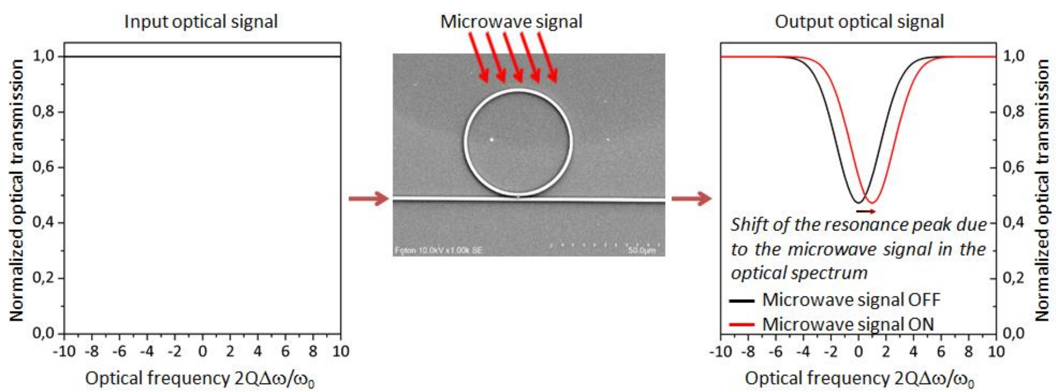


$$\Delta n \propto n^3\, r\, E_{HF}$$



$$P_{RFmin}^{-1} \propto Q_c Q_i n_0^2 n_e^2 r_{ij}^2 |\xi| P_{HF_{IN}}$$

- Q_c: Coupling quality factor
- Q_i: Intrinsic quality factor
- n_0, n_e : Ordinary and extraordinary refractive indices
- r_{ij}: Electro-optic coefficients
- A: Geometric variable
- ξ: Spatial overlap integral
- $P_{RF_{IN}}$: RF power

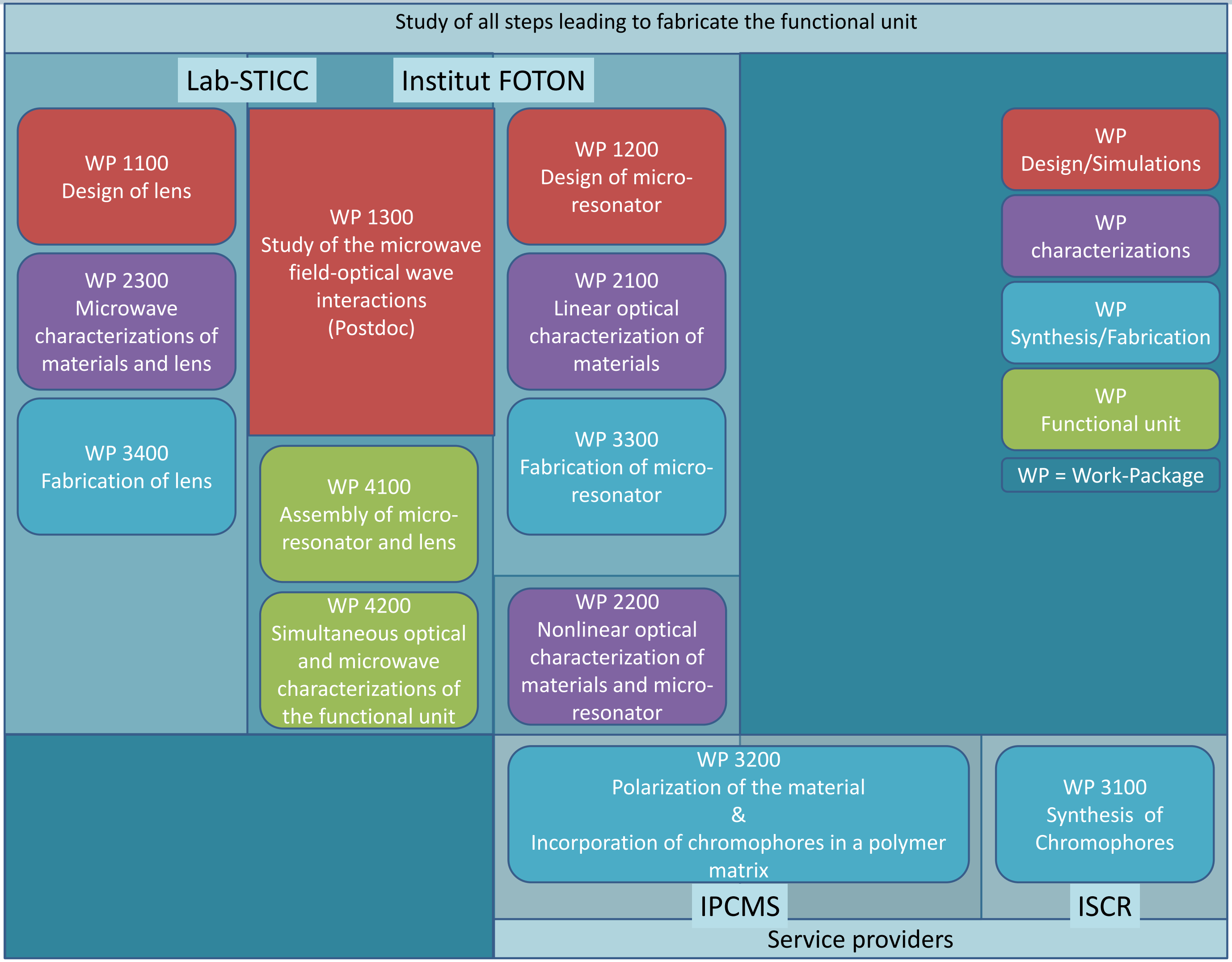


Our goal:

Sensitivity ~ 10^{-5} $V.m^{-1}.Hz^{-1/2}$

r_{ij} > 70 $pm.V^{-1}$

Schematic chart



Key Steps

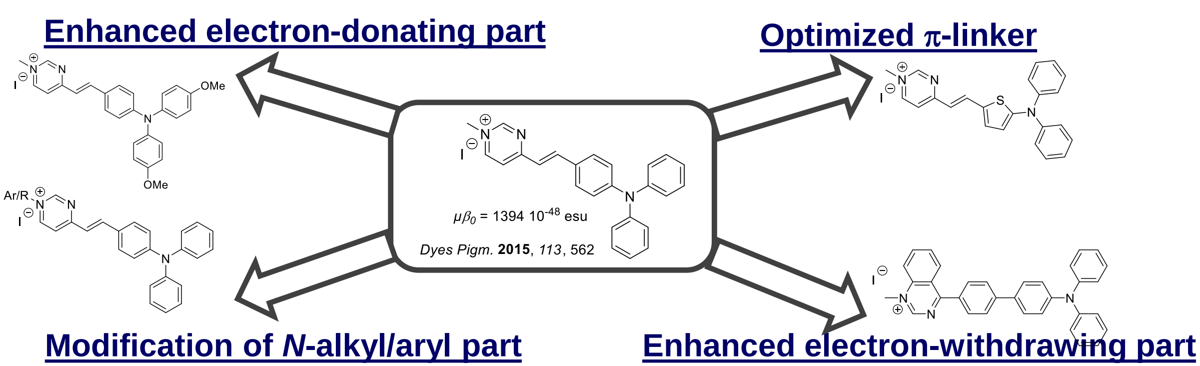
- Choose a good chromophore (dye) and synthesize it in sufficient quantity (a few grams)
- Integration, orientation of these chromophores in a host matrix and obtaining sufficient electro-optical coefficients
- Shaping of these new materials
- Design and realization of the micro-resonator
- Design and fabrication of the lens by 3D printing
- Microwave measurement bench automation
- Assembly of the whole

Key Steps

- Choose a good chromophore (dye) and synthesize it in sufficient quantity

Various structural modifications have been proposed to improve the NLO response of N-methylated styrylpyrimidinium dye:

- Reinforcing the electron-donating strength of the NPh2 group.
- Modifying the methyl in N1 of pyrimidine by other alkyl/aryl substuents.
- Optimizing the π-linker.
- Replacing the pyrimidine ring by quinazoline, a stronger electron withdrawing fragment.



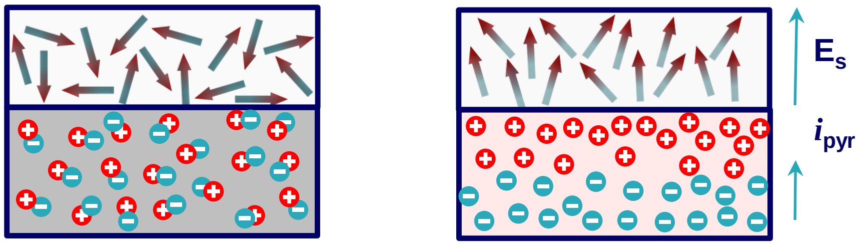
Few grams were synthetized

T. El al., “4-substituted push-pull quinazoline chromophores with extended π-conjugated linker”, J Heterocyclic Chem. 2024;61:358–364.

Key Steps

- Integration, orientation of these chromophores in a host matrix and obtaining sufficient electro-optical coefficients

Chromophore doped polymer on pyroelectric crystal



$T=T_{amb} < T_g$, $P = 0$, $E_s = 0$
Centrosymetric organisation
No electrooptic effect : $r = 0$

$T > T_g$, $P \neq 0$, $E_s \neq 0$
NONcentrosymetric organisation
Electrooptic effect : $r \neq 0$

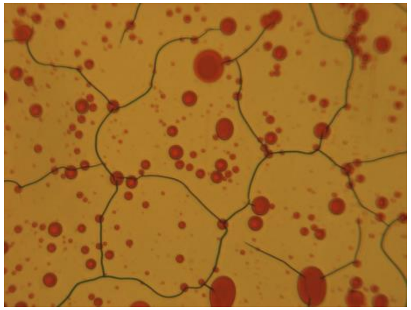
Usually PMMA (Tg<110°C) is used at IPCMS
BUT
in our case,
the polymer must be subjected to temperatures of 115°C during the optical microring-resonator manufacturing process

⇒ Choice of a new matrix: PC (Relative Temperature Index = 150°C)

PMMA: Polymethyl Methacrylate
PC: PolyCarbonate

Key Steps

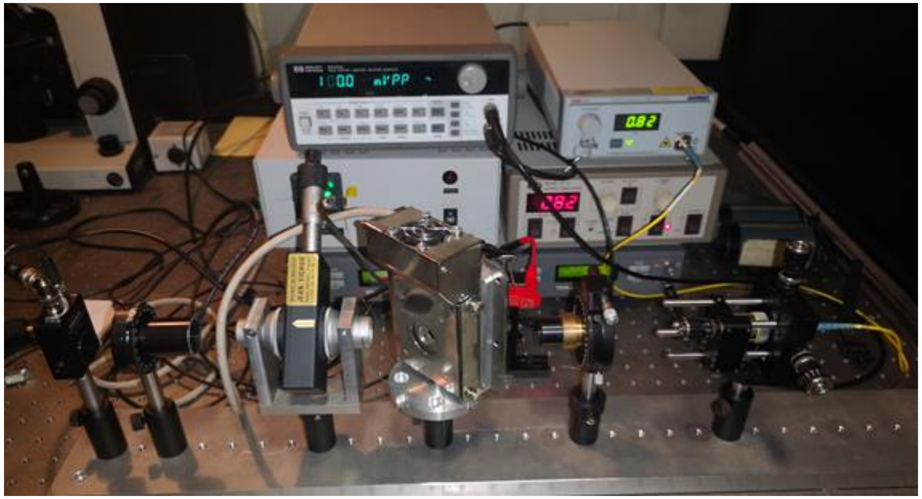
- Integration, orientation of these chromophores in a host matrix and obtaining sufficient electro-optical coefficients



Made at IPCMS on $LiNbO_3$ subsrate

No significant recrystallization of chromophores, but there are areas of segregation linked to the polymers used

Ellipsometer for EO effect measurement

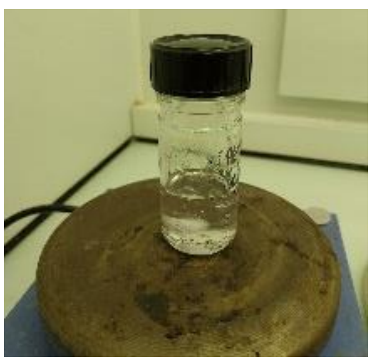


The tests didn't produce films of sufficient quality to make the EO measurements.

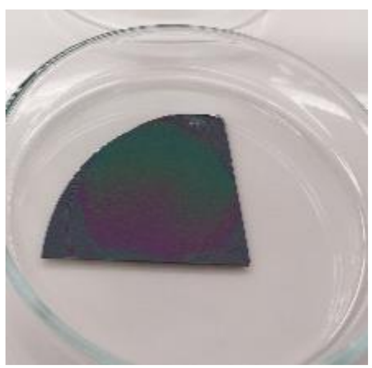
Key Steps

- **Shaping of these new materials**
  - **Deposition of PC on Si-substrate (choice of the good solvent and deposition parameters)**

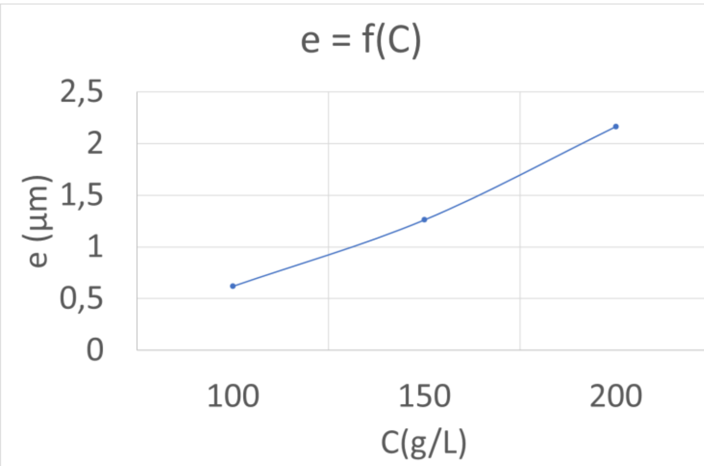
PC / THF solution



PC / TCE solution



PC layer



Evolution of thickness of deposited PC according to the concentration of PC / TCE solution

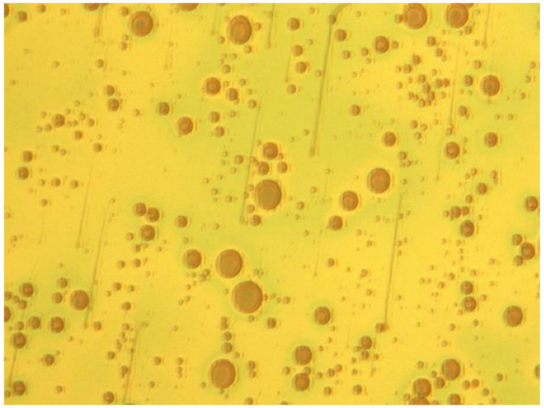
n = 1,5934 (0,0005)

THF: Tetrahydrofuran
TCE: Trichloroethylene

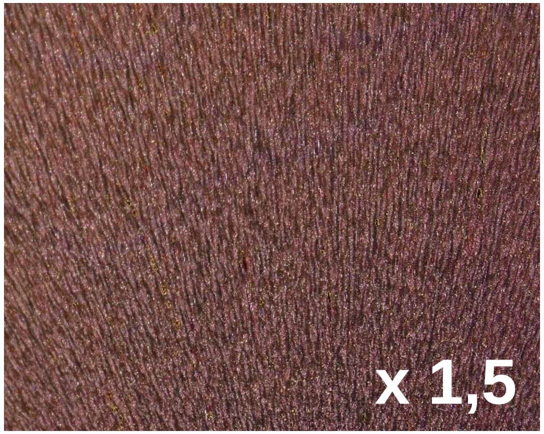
Key Steps

- **Shaping of these new materials**

  - **Test of deposition of PC / chromophore**



PC / TCE (200g/L) 10%$_w$Chromophore
Segregation



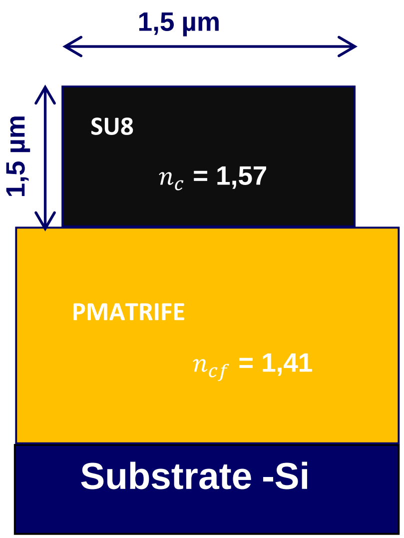
PC / TCE (200g/L) 20%$_w$Chromophore
Non apparent Segregation but non-homogeneous layer

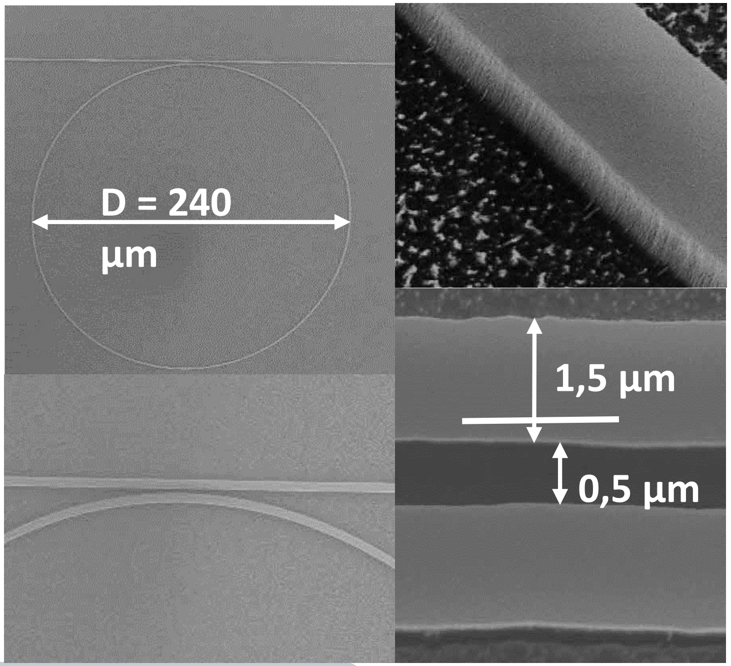
Key Steps

➢ **Design and realization of the micro-resonator**

No insurmountable problem for this stage provided a stable material is available beforehand

The optimization of optical micro-resonator designs and the other stages of the production process (photolithography + etching) have long been well mastered at FOTON Institute.





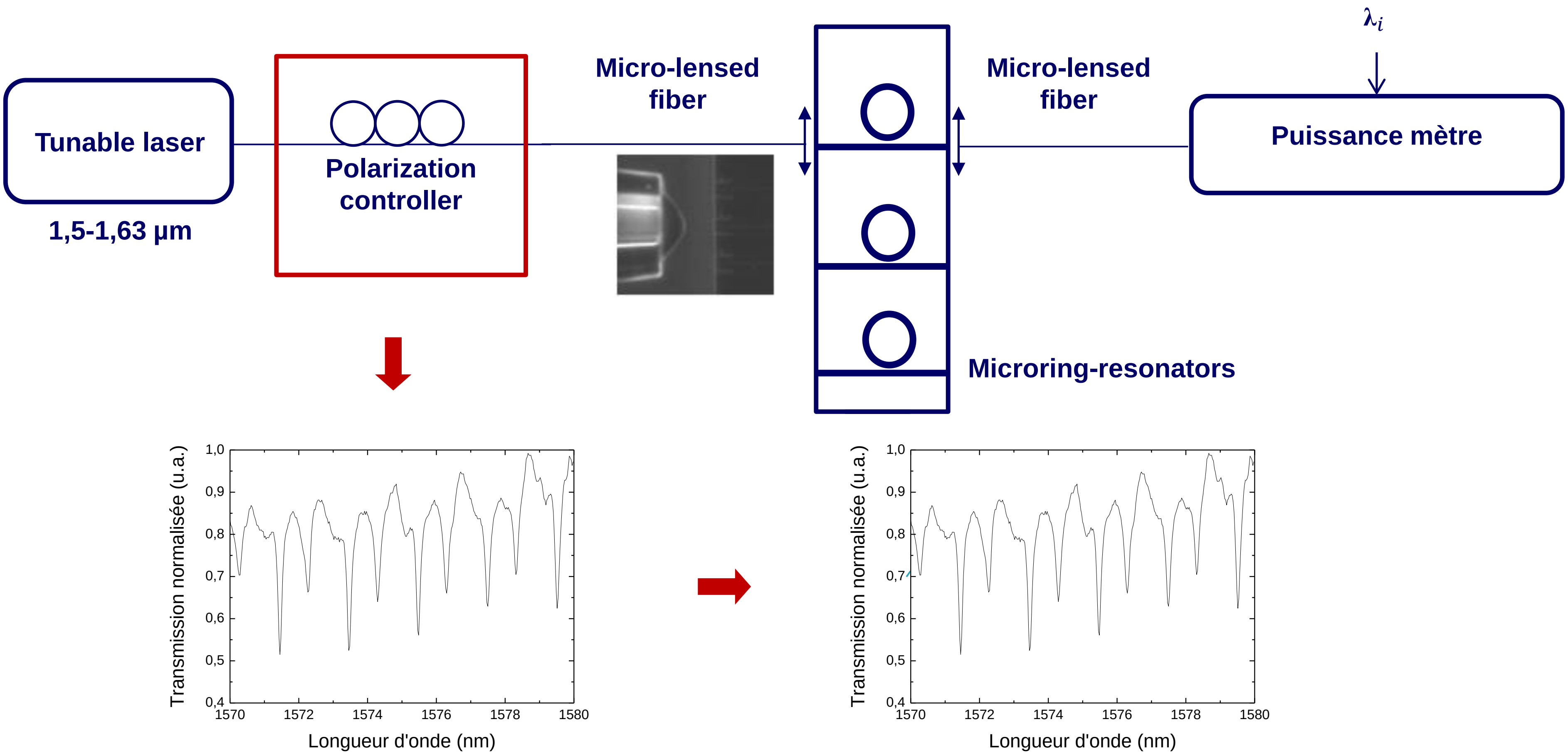
SEM photos

Example of a SU8 structure manufactured at FOTON Institute on Si-substrate, during this project

Key Steps

- **Design and realization of the micro-resonator**

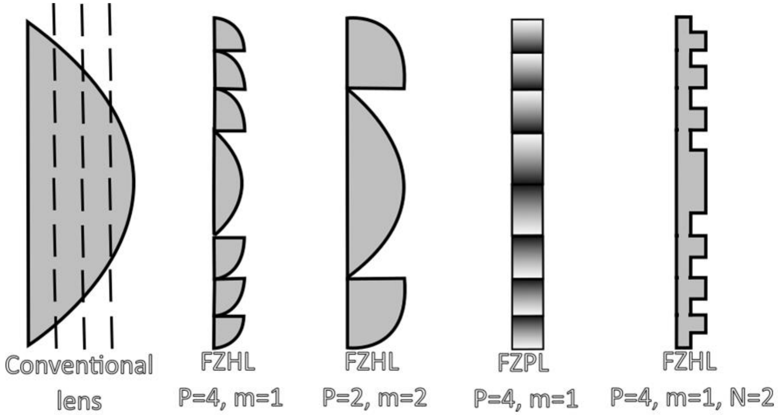
Example of optical characterization bench



Key Steps

- **Design and fabrication of the lens by 3D printing**
  - **Choice of Fresnel lenses for their :**
    - **Compactness**
    - **Lightweight**
    - **Efficient focalization energy**
    - **<u>Ease of manufacture</u>**

- **2 kinds of Fresnel lenses have been studied : FZHL (Fresnel Zone Homogeneous Lenses) and FZPL (Fresnel Zone Plate Lens)**



$$\varphi(r) = k_0(\sqrt{F^2 + r^2} - F) \quad (1)$$

$$r_{max} = \sqrt{\left(\frac{2\pi}{k_0} + F\right)^2 - F^2} \quad (2)$$

$$t(r) = -\frac{\lambda_0}{\sqrt{\varepsilon_m} - \sqrt{\varepsilon_0}} * \frac{\varphi(r)}{2\pi} + \frac{\lambda_0}{\sqrt{\varepsilon_m} - \sqrt{\varepsilon_0}} \quad (3)$$

$$t_{max} = \frac{\lambda_0}{\sqrt{\varepsilon_m} - \sqrt{\varepsilon_0}} \quad (4)$$

$$\varepsilon(r) = -(\varepsilon_m - \varepsilon_0) * \frac{\varphi(r)}{2\pi} + \varepsilon_m \quad (5)$$

the focal length of the lens, ε_m and ε_0 the permittivity lly, refraction index $n = \sqrt{\varepsilon\mu}$ is used in all these equations and permeability of the material, respectively. In our case, we will use notation $\sqrt{\varepsilon}$.

Fresnel lens (FZHL and FZPL) with P zones (P≥1), the p ase distribution of each zone, the radius of each zone is al

$$\varphi_P(r) = \varphi(r) + 2\pi(P-1), \quad r_{P-1} < r < r_P \quad (6)$$

$$r_P = \sqrt{\left(\frac{2\pi P}{k_0} + F\right)^2 - F^2} \quad (7)$$

radius of the zone P.

, for m-order lens each zone must create a phase shift of 2π for each zone can be adjusted from the previous equation 8 a

$$\varphi_P(r) = \varphi(r) + 2\pi(P-1)m, \; r_P < r < r_{P+1} \quad (8)$$

$$r_P = \sqrt{\left(\frac{2\pi Pm}{k_0} + F\right)^2 - F^2} \quad (9)$$

the process of fabrication, additional discrete subdivisions ca FZPL) or steps (FZHL). For instance, a FZL with two steps is refe ile one with four steps is named quarter-wave phase lens, and nses are shown in Figure **1**. Each ring corresponds to a speci rete FZL include the radius of each ring r_j, the number of zone e N, with j representing the ring number ($j = 1, 2, \ldots, N * P$) a e unique lens thickness is t_{max} and the phase shift for each ri mittivity ε_i ($i = 1, 2, \ldots, N$). On the other hand, for FZHL, the p ess t_i. ε_i and t_i are then repeated for subsequent zones. V s 10 to 13 [5], [23]:

$$r_j = \sqrt{2Fj\frac{\lambda_0}{N} + \left(\frac{j\lambda_0}{N}\right)^2} \quad (10)$$

$$t_{max} = \frac{\lambda_0(N-1)}{N(\sqrt{\varepsilon_m} - \sqrt{\varepsilon_0})} \quad (11)$$

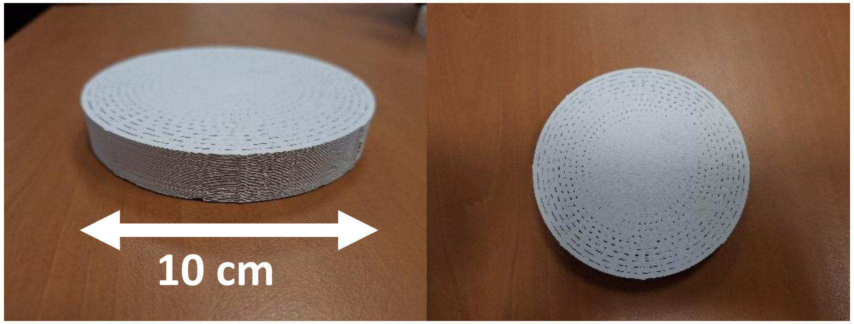
$$\varepsilon_i = \left(\frac{\lambda_0}{N t_{max}} + \sqrt{\varepsilon_{i-1}}\right)^2 \quad (12)$$

$$t_i = \frac{\lambda_0(i-1)}{N(\sqrt{\varepsilon_m} - \sqrt{\varepsilon_0})} \quad (13)$$

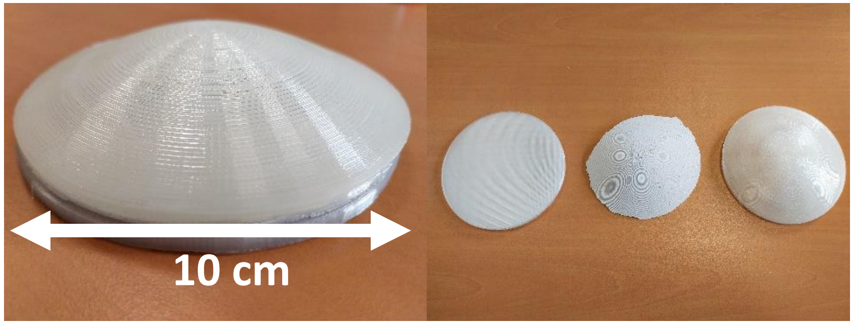
Key Steps

- **Design and fabrication of the lens by 3D printing**

- **A study was carried out to explore diverse approaches to amplify gain or minimize the bulk and weight within microwave frequency ranges**
- **C. Vong et al., “Optimisation d’une lentille de Fresnel entièrement diélectrique pour des applications micro-ondes en champ proche”, JNM, 5-7 juin 2024 – Antibes Juan-Les-Pins**
- **This study will give rise to a publication (currently being drafted, 12 pages have already been validated, with the manufacturing and measurement still to be integrated).**



FZPL (Gain = 12 dB)
Gain = 13.6 dB with adaptation layers

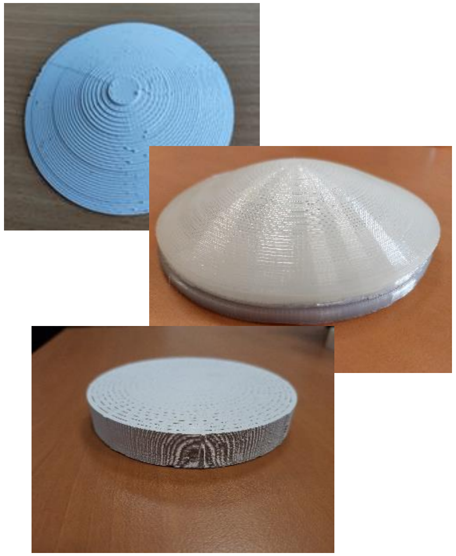


FZHL (Gain = 11.2 dB)
Gain = 14.2 dB with adaptation layers

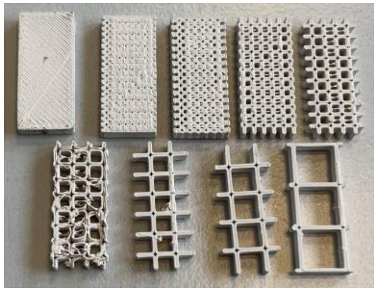
Key Steps

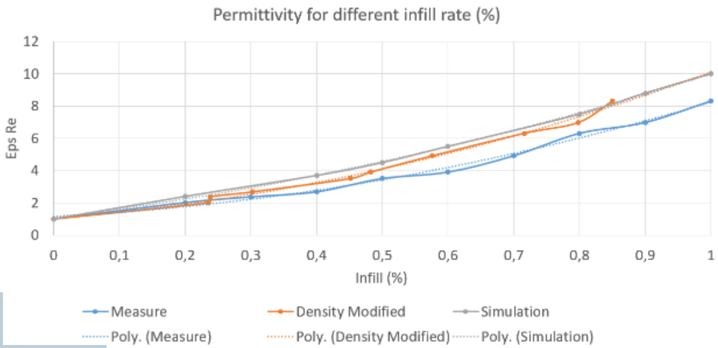
- **Design and fabrication of the lens by 3D printing**
  - **Fabrication by 3D printing**

Preperm™ ABS1000 :
ε_r=10
tanδ=3.10^{-3}
PLA (for adaptation layers):
ε_r=2.67
tanδ=7.5 10^{-3}



FZPL: Need to create zones with different effective permittivity ⇒ Use of air cavities.



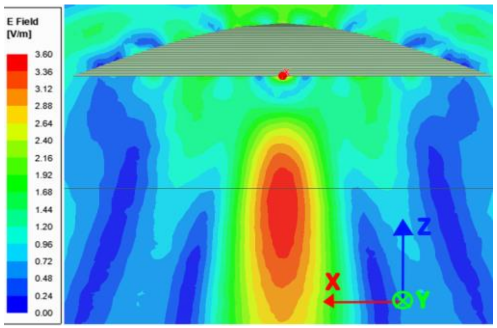


EM characterization as a function of fill rate

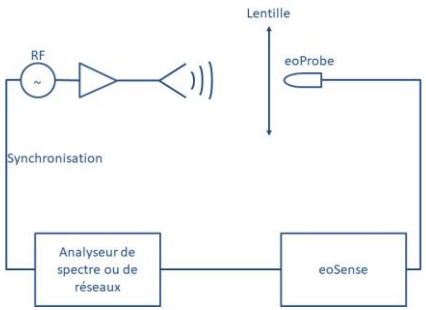
Key Steps

- **Microwave measurement bench automation**

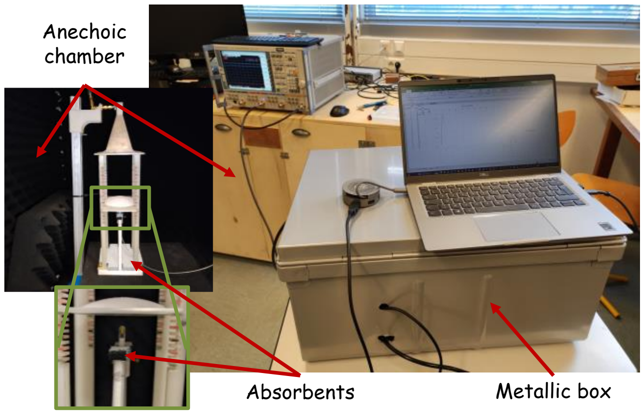
- **In order to characterize the microwave lenses (near-field measurement), a measuring bench from Kapteos was purchased as part of this project.**

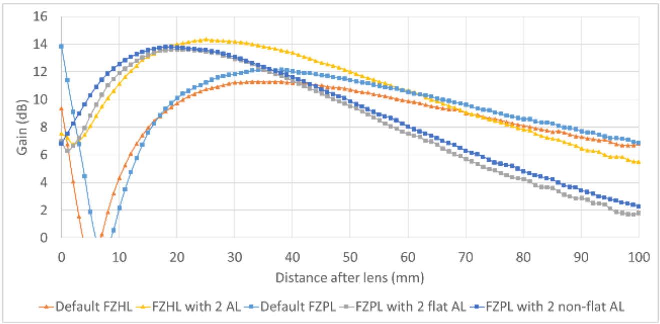


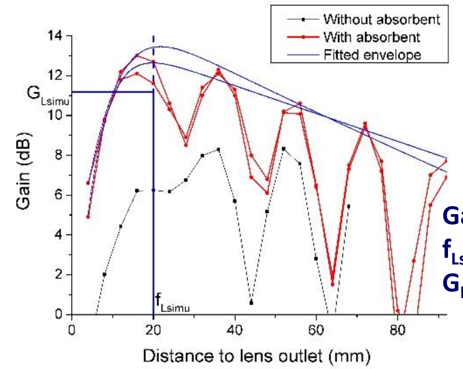
Simulation : E-field profil after the lens



Measurement bench schematic diagram







$Gain_{dB} = G_{dB\,(with\,lens)} - G_{dB(without\,lens)}$
f_{Lsimu} : Focal length
G_{Lsimu} : Gain at focal length

Horn antenna : 15dB
Absorbents : -20 dB
VNA : ROHDE & SCHWARZ ZVA67
eoSense et eoProbe : Kapteos
f = 10 GHz
P = 20 dBm
Span : 1 Hz
Average : on 10 runs

C. Vong et al., "Etude de lentilles hyperfréquences et cartographie du champ électrique en champ proche", JCMM, Tours, 3-5 Avril 2023.

Key Steps

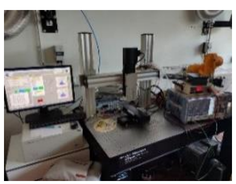
➢ **Microwave measurement bench automation**

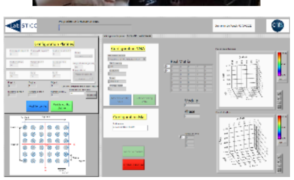
Difficulty: The eoSense EO converter is also very sensitive to stray $E_{Microwave}$ fields.

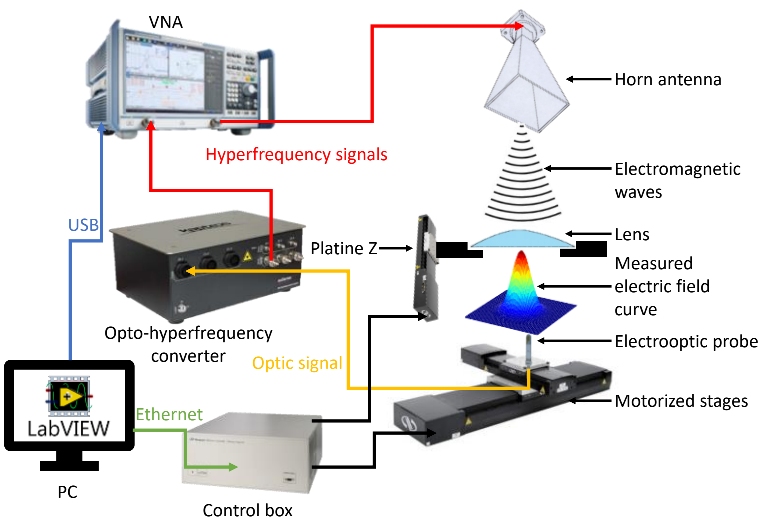
⬇

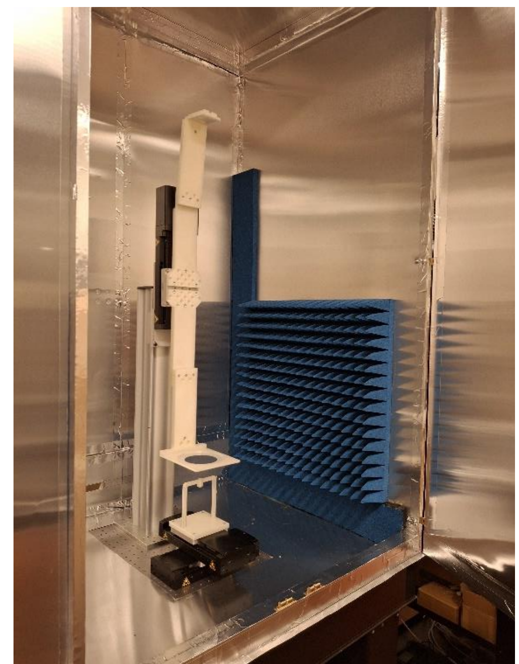
Improving the measurement environment: in progress, about to be completed.

Measurement bench automation: 10-week IUT internship funded by the SMART team of Lab-STICC









Anechoic chamber

Key Steps

- 🙂 Choose a good chromophore (dye) and synthesize it in sufficient quantity (a few grams)
- ☹️ Integration, orientation of these chromophores in a host matrix and obtaining sufficient electro-optical coefficients
- 😐 Shaping of these new materials
- 🙂 Design and realization of the micro-resonator
- 🙂 Design and fabrication of the lens by 3D printing
- 🙂 Microwave measurement bench automation
- 😐 Assembly of the whole

Future prospects: as a first step

- **Continue ongoing studies**
  - **Waiting for the latest IPCMS results from deposits**
  - **Continue the microwave lens study (manufacture the last lenses, finish the anechoic chamber assembly, characterize the various lenses manufactured and submit the publication to a scientific journal).**

Future prospects: in a second step

- **Way 1: Decide on the hard point, the polymer, and most probably choose other, inorganic materials for a potential follow-up.**

These materials are much better mastered, but all studies show that their bandwidth remains much lower than that of polymers. However it all depends on the efficiency required above a certain frequency.

  - **Find a new partner for the shaping of these inorganic materials (INSA Rennes, for example) and start discussions on a potential ANR project.**

- **Way 2: we could get closer to an IMN team that has succeeded in stabilizing chromophores in polymers by adding nanoparticles of inorganic EO materials.**

The materials used are basic NL optics materials, but the results obtained on these materials look very promising.

  - **We could start discussions on a potential ANR project.**

Thank you !