Optical sensing for the vectorial analysis of ultra-wideband electric field requirements, performances and applications

Gwenaël GABORIT
Involved entities

Université Savoie-Mont-Blanc
- 3 locations (Chambéry, Le Bourget-du-Lac, Annecy)
- 19 laboratories
- 14,000 students

IMEP-LAHC Laboratory
- 2 locations (Grenoble, Le Bourget-du-Lac)
- Activities in 3 thematics (CMNE, RFM, PHOTO)
- 57 (13) researchers
- 17 (1) engineers & technicians
- 69 (4) PhD students and post-doc

Kapteos S.A.S.
- Created in 2009
- Market segments:
  - Scientific
  - Healthcare
  - Energy
- Manpower: 10 workers
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KAPTEEOS S.A.S

→ Solutions provider and manufacturer of measurement instruments for research & industry in harsh environment

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KAPTEEOS S.A.S

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→ Some of our references:

- **Private companies:**

  - AIRBUS
  - EDF
  - ALSTOM
  - EFD Induction
  - ExxonMobil
  - Faiveley Transport
  - GE Aviation
  - LEM
  - NXP
  - SNCF
  - Thales Alenia Space

- **Public institutes:**

  - anses
  - CEA
  - CREATIS
  - DGA
  - ENEA
  - Fraunhofer IST
  - IFPEN
  - IMEP-LAHC
  - INP Grenoble
  - University of Alabama in Huntsville
  - University of Kiel
  - UQAC
  - University of Quebec à Chicoutimi

Gwenaël GABORIT — Optical sensing for the vectorial analysis of ultra-wideband electric field
KAPTEEOS S.A.S

→ State of the art EM measurement system

→ Comprehensive measurement system
Outline

1. Introduction

2. Electro-optic technique
   - Principle
   - EO probe description and performances

3. Applications

4. Conclusions
   - Summary
   - Outlooks and challenges
Outline

1. Introduction
2. Electro-optic technique
3. Applications
4. Conclusions
**Context**

Need of tools for the comprehensive characterization of the E-field

### Circuits

<table>
<thead>
<tr>
<th>EMC</th>
<th>Antenna</th>
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Gwenaël GABORIT — Optical sensing for the vectorial analysis of ultra-wideband electric field
## Context

Need of tools for the comprehensive characterization of the E-field

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Need of tools for the comprehensive characterization of the E-field
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Need of tools for the comprehensive characterization of the E-field

- Measurement of the E-field **UWB, non-invasive, vectorial** and offering **appropriate spatial and time resolution**
Existing technologies

- IR thermography
- Bolometer
- Antenna
- Franz-Keldysh

EO sensors competitive except concerning sensitivity
Existing technologies

Scale

Bolometer
Existing technologies

**Scale**

**Bolometer**

**Franz-Keldysh**

---

**Introduction**

**Electro-optic technique**

**Applications**

**Conclusions**

---

Gwenaël GABORIT — Optical sensing for the vectorial analysis of ultra-wideband electric field
Existing technologies

**Scale**

**Bolometer**

**Franz-Keldysh**

**IR thermography**
Existing technologies

- Scale
- Bolometer
- Franz-Keldysh
- IR thermography
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Existing technologies

Scale

Bolometer

Franz-Keldysh

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Antenna

EO sensor
Existing technologies

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EO sensor

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Outline

1. Introduction

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   - Principle
   - EO probe description and performances

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4. Conclusions
The electro-optic (EO) effect

- Discovery of the EO effect (Pockels)
- 1st ps pulse measurement (Auston)
- sub-ps EO sampling (Mourou)
- 1st EO 2D mapping (Whitaker)
- 1st EO simultaneous measurement of $E_x + T$ and of $E_x + E_y$
- 1st commercial instrument

Timeline:
- 1893
- 1972
- 1982
- 2000
- 2007/2008
- 2012
The electro-optic (EO) effect

Pockels effect: Linear variation of the refractive index induced by the electric-field

\[ \delta n = \vec{K} \cdot \vec{E} \]

with \( \vec{K} \) the sensitivity vector* depending on:
- the EO crystal
- the orientation of the optical wavevector/crystal

* Duvillaret et al., JOSA B, 2002.
The electro-optic (EO) effect

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* Duvillaret et al., JOSA B, 2002.
**EO effect - crystals**

Crystals and index ellipsoid:

\[
\tilde{E} = \tilde{0} \quad \Rightarrow \quad x^2 \left( \frac{1}{n_x^2} \right) + y^2 \left( \frac{1}{n_y^2} \right) + z^2 \left( \frac{1}{n_z^2} \right) = 1
\]

- The indices \( n_i \) are dependant on \( T \)
- \( n_x = n_y = n_z = n_0 \) for an isotropic
**EO effect - crystals**

**Crystals and index ellipsoid:**

$\vec{E} \neq \vec{0} \Rightarrow x^2\left(\frac{1}{n_x^2} + \delta_1\right) + y^2\left(\frac{1}{n_y^2} + \delta_2\right) + z^2\left(\frac{1}{n_z^2} + \delta_3\right) + yz\delta_4 + xz\delta_5 + xy\delta_6 = 1$

- The variations $\delta_i$ are function of $\vec{E}(E_x, E_y, E_z)$
- $\delta_i \approx 10^{-10} E_j$
**EO effect - crystals**

**Crystals and index ellipsoid:**

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\vec{E} \neq \vec{0} \implies x^2\left(\frac{1}{n_x^2} + \delta_1\right) + y^2\left(\frac{1}{n_y^2} + \delta_2\right) + z^2\left(\frac{1}{n_z^2} + \delta_3\right) + yz\delta_4 + xz\delta_5 + xy\delta_6 = 1
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**Index ellipsoid and electric field**

- **Anisotropic crystals** (LiTaO\(_3\), LiNbO\(_3\), ...)
- **Isotropic crystals** (ZnTe, BSO, ...)

---

Gwenaël GABORIT — Optical sensing for the vectorial analysis of ultra-wideband electric field
EO effect - crystals

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- \( \delta_i \approx 10^{-10} E_j \)

Index ellipsoid and electric field

- Anisotropic crystals (LiTaO\(_3\), LiNbO\(_3\), ...)
  \( \Rightarrow \) sensor \( E_j \) and \( T \)

- Isotropic crystals (ZnTe, BSO, ...)
  \( \Rightarrow \) sensor \( |E_\perp| \) and \( \gamma_{E_\perp} \)
The EO effect (2)

**Index ellipse**

EO measurement via:

\[ n_+ \text{ ou } n_- \text{ ou } \Delta n = n_+ - n_- \]

**Anisotropic crystal**

\[ \Delta n_{ \text{aniso}} \text{ is function of:} \]

- Temp. \( T \) (quasistatic)
- 1 comp. of \( \vec{E} \) (dynamique)

**Isotropic crystal**

\[ \Delta n_{ \text{iso}} \text{ is function of:} \]

- \( E_x \text{ AND } E_y \) (dynamic)

⇒ Anisotropic EO crystal → measurement of \( E_x \) and \( T \)

⇒ Isotropic EO crystal → measurement of \( E_x \) and \( E_y \)
EO modulation techniques

Phase modulation

- Wellproven (modulator)
- Compatible with integrated optics
- Control of the reference path
- Sensitivity
EO modulation techniques

**Phase modulation**

- Wellproven (modulator)
- Compatible with integrated optics
- Control of the reference path
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**Amplitude modulation**

- Sensor size
- Sensitivity
- Sensor realization
- Stability
**EO modulation techniques**

- **Phase modulation**
  - Wellproven (modulator)
  - Compatible with integrated optics
  - Control of the reference path
  - Sensitivity

- **Amplitude modulation**
  - Sensor size
  - Sensitivity
  - Sensor realization
  - Stability

- **Polarization state modulation**
  - External treatment
  - "Simplicity" of the sensor
  - Sensitivity
**EO modulation techniques**

### Phase modulation

- **EO crystal: [\( r \)]**
- **Photodiode**
- **Linear zone**
  - √ Wellproven (modulator)
  - √ Compatible with integrated optics
  - X Control of the reference path
  - X Sensitivity

### Amplitude modulation

- **EO crystal in cavity: [\( r \)]**
- **Photodiode**
- √ sensor size
- √ Sensitivity
- X Sensor realization
- X Stability

### Polarization state modulation

- **EO crystal: [\( r \)]**
- **Polarization treatment**
- **Photodiode**
- √ External treatment
- √ “Simplicity” of the sensor
- X Sensitivity
The EO probe

- Crystal size can be chosen depending on the application
- 2 probe sheaths: measurement in air or water-based liquids
- **Transverse** or **longitudinal** probe

Crystal size can be chosen depending on the application

2 probe sheaths: measurement in air or water-based liquids

Transverse or longitudinal probe
The EO probe

- Crystal size can be chosen depending on the application
- 2 probe sheaths: measurement in **air** or **water-based liquids**
- **Transverse** or **longitudinal** probe

- **Dielectric sensor**
- **Millimeter sized**
- **Pigtailed probe (~100 m)**
- **Adaptative coating**
EO probe description and performances

**Linearity**

Response of the probe versus $|\vec{E}|$

$\rightarrow$ depends on the EO coefficients, on the permittivity and on optoelectronic treatment
**EO probe performances (1)**

### Linearity

Response of the probe versus $|\vec{E}|$

$\rightarrow$ depends on the EO coefficients, on the permittivity and on optoelectronic treatment

![Linearity Graph](image)

### Vectorial selectivity

Response of the probe versus $\gamma \vec{E}$

$\rightarrow$ EO intrinsically rejects the transverse component

![Vectorial Selectivity Graph](image)
EO probe performances (1)

**Linearity**

Response of the probe versus $|\vec{E}|$

$\rightarrow$ depends on the EO coefficients, on the permittivity and on optoelectronic treatment

![Graph showing linearity](image)

$P$ (dBm) vs Electric field (V/m)

- Dynamics $> 120$ dB
- $|\vec{E}|_{min} < 1$ V.m$^{-1}$.Hz$^{-1/2}$

**Vectorial selectivity**

Response of the probe versus $\gamma_{\vec{E}}$

$\rightarrow$ EO intrinsically rejects the transverse component

![Graph showing vectorial selectivity](image)

- Accuracy $< 0.5$ dB
- Selectivity $> 65$ dB
EO probe performances (2)

Bandwidth of the EO system

Frequency response depends on:

- Temporal response of the EO effect
- Frequency cut-off of the optoelectronic unit
- Photon lifetime within the crystal

![Normalized EO signal vs Frequency (Hz)](image_url)
EO probe performances (2)

Bandwidth of the EO system

Frequency response depends on:

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![Graph showing frequency response and normalized EO signal vs. frequency](image-url)
EO probe performances (2)

Bandwidth of the EO system

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Spectral response > 8 decades of frequency
Pulsed measurement

Comparative measurement of ns pulse:

EO probe $\leftrightarrow$ D-Dot in a GTEM cell
Pulsed measurement

Comparative measurement of ns pulse:

EO probe ↔ D-Dot in a GTEM cell

Pulsed measurement

Comparative measurement of ns pulse:

EO probe $\leftrightarrow$ D-Dot in a GTEM cell

- EO measurement without any post-treatment
- Arbitrary positionning of the EO probe
- EO bandwidth $\rightarrow$ 20 GHz $\gg$ D-Dot bandwidth

Antenna

Vectorial mapping in the near field region:
→ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – fundamental mode
Antenna

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Antenna

Vectorial mapping in the near field region:
→ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – **cross polarization**
Antenna

Vectorial mapping in the near field region:
→ Pattern in the vicinity of the antenna aperture (frequency domain-900 MHz) – **longitudinal field**

- No need of a "big" anechoic chamber
- Comprehensive reconstruction of the E-field **vector**
Simultaneous measurement of $E/T$

Bioelectromagnetism

Determination of the **Specific Absorption Rate**: $SAR = \frac{\sigma E_{\text{rms}}^2}{\rho} = C \frac{\partial T}{\partial t}$

**Measurement conditions**
- CW exposure 1.8 GHz
- *In situ* analysis of $E$ et $T$
- Biological media: $\varepsilon_r = 77$
Simultaneous measurement of $E/T$

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**Response versus $E$**

Response in the media and in air:

![Graph showing response versus E with curves demonstrating signal intensity vs. power delivered by synthesizer (dBm)]
Simultaneous measurement of $E/T$

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Response versus $E$
Response in the media and in air:

Temperature response
Comparative analysis:
EO probe ↔ Luxtron probe
Simultaneous measurement of $E/T$

Bioelectromagnetism

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- Biological media: $\varepsilon_r = 77$

Response versus $E$

Response in the media and in air:

$$|\vec{E}|_{min,BIO} < 200 \text{ mV.m}^{-1}\text{.Hz}^{-1/2}$$

Resolution in $T < 30 \text{ mK}$

Temperature response

Comparative analysis:

EO probe $\leftrightarrow$ Luxtron probe
Specific Absorbtion Rate

Determination of the SAR: 3D mapping inside a phantom head:

Max. measured SAR\(\text{max}\) = 360 W/kg

Measurement threshold as weak as 10 \(\mu\)W/kg
Specific Absorbtion Rate

Determination of the SAR: 3D mapping inside a phantom head:

\[
E\text{-field within the phantom (}\varepsilon_r = 44.2 + i19.1)\n\]
Specific Absorbtion Rate

Determination of the SAR: 3D mapping inside a phantom head:

E-field within the phantom ($\varepsilon_r = 44.2 + i19.1$)

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Magnetic Resonance Imaging

→ Very complex EM environment

- EM field:
  - DC B-field (3 T, 4.5 T and more),
  - Pulsed RF B & E fields (127 MHz, 200 MHz and more)

- Biological media under test:
  - $\mu_r \approx 1 \rightarrow$ no artefact on B gradient
  - heterogeneous in shape
  - heterogeneous in dielectric constant
  - $\varepsilon_r = 20 \sim 60$ and $\sigma = 0.1 \sim 1$ S/m
Magnetic Resonance Imaging

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Measurement of the E-field to analyse the radiation pattern of the birdcage & the exposure of the biological media (SAR)
MR images and SAR

→ Mapping of the rms field in a pre-clinical 4.7 T MRI*
MR images and SAR

→ Mapping of the rms field in a pre-clinical 4.7 T MRI*

MR images and SAR

→ Mapping of the rms field in a pre-clinical 4.7 T MRI*

*Very good agreement between measurements and simulations
MR images and SAR

MR image using a patch antenna with optical decoupling:
→ local modification of static B field
→ **Strong image distortion** induced by an ultra small non antimagnetic component!
MR images and SAR

MR image using a patch antenna with optical decoupling:
→ local modification of RF E field
→ **Strong modification of the local SAR**
MR images and SAR

MR image using a patch antenna with optical decoupling:
→ local modification of RF E field
→ **Strong modification of the local SAR**

- Devices, components, connections, and cables have to be qualified for a use in MRI system
MR images and SAR
E-field measurement inside biological media
→ Fully artifact-free images (RBW = 100 kHz)

Lab MRI 200 MHZ (birdcage ant., flash seq.)
Clinicnal MRI 127 MHz (wrist ant., gradient echo seq.)
MR images and SAR
E-field measurement inside biological media
→ Fully artifact-free images (RBW = 100 kHz)

In vivo analysis Clinical MRI 127 MHz (pelvis ant., gradient echo seq.)
MR images and SAR
E-field measurement inside biological media
→ Fully **artifact-free** images (RBW = 100 kHz)

*Image modified only due to the insertion of the probe (no distortion of the field)*
MR images and SAR

SAR assessment

Pre-clinical MRI 4.7T

Lab MRI 200 MHZ (birdcage ant.)

Clinical MRI 3T

Clinical MRI 127 MHz (wrist ant.)

The exposure depends dramatically on the complex permittivity AND on the shape of the imaged media.
MR images and SAR

SAR assessment

Lab MRI 200 MHZ (birdcage ant.)

Clinical MRI 127 MHz (wrist ant.)

- In-situ & real time monitoring of the SAR
- The exposure depends dramatically on the complex permittivity AND on the shape of the imaged media
Hyperthermia in MRI

→ **Applying RF field** (Sine 115 MHz) to locally increase the temperature and hence, **improving the efficiency of chemotherapy**

**Spiral antenna (Ø 15 cm)**
- Placed **outside the body** to heat tumor **inside the body** (44 °C)
- Feeding source CW: 100 W, 115 MHz
- \( \lambda_{air} \approx 2.5 \text{ m}, \lambda_{body} \approx 30 \text{ cm} \)

4D mapping of the *in-situ* rms E-field deduced from \( E_i, \varphi_i \)
Intense electric field

Single shot measurement of $E_x$ and $E_y$ within a discharge:

Intense electric field

Single shot measurement of $E_x$ and $E_y$ within a discharge:

Plasma oscillation

Intense electric field

Single shot measurement of $E_x$ and $E_y$ within a discharge:

Plasma oscillation

- E-Field up to more than 3 MV/m
- Alternate characterization impossible

Intense electric field

Disturbance on the potential difference inducing the discharge (measured with a home-made resistive divider):

Intense electric field

Disturbance on the potential difference inducing the discharge (measured with a home-made resistive divider):

- Very weak induced perturbation on the field
- No disturbance on the field applicator

Plasmas

- 4\textsuperscript{th} state of matter
- constitute more than 99.9 % of the universe (both in volume and mass)
- used in a lot of applications: surface treatment of liquid/solid, medicine, agriculture, combustion, propulsion, nanofabrication . . .
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- used in a lot of applications: surface treatment of liquid/solid, medicine, agriculture, combustion, propulsion, nanofabrication . . .
**Plasma analysis**

**Dielectric Barrier Discharges (DBD):**

- Voltage source: 50 Hz, [0-25] kV, 1 mA
- Implementation fully suitable for:
  - DBD (in the [15-25] kV range)
  - E-field measurement with the EO probe
Plasma analysis

Dielectric Barrier Discharges (DBD):

Probe 1 (DBD analysis)

Probe 2 (needle)

10 kV

20 kV

$\times 2$

$\times 5$
Plasma analysis
Dielectric Barrier Discharges (DBD):

- Non-linearity between voltage and field
- Phase shift of 90° induced by the charged species
Plasma analysis

Ar plasmajet and target: The Ar Plasma jet is fed by a voltage signal at 1 MHz, i.e., the single shot vectorial field pattern is obtained in 1 μs.
Plasma analysis

Ar plasmajet and target: The Ar Plasma jet is fed by a voltage signal at 1 MHz, i.e. the single shot vectorial field pattern is obtained in 1 µs.

The plasma behaviour is be affected by the target (have to be taken into account).
High Voltage and energy

→ 25kV composite insulator: Radial E field mapping at 50 Hz
(meas. in time domain, dynamic range > 50 dB)
High Voltage and energy

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High Voltage and energy

→ 25kV composite insulator: Radial E field mapping at 50 Hz
(meas. in time domain, dynamic range > 50 dB)

E-field analysis instead of visual/electrical inspection

Other similar cases: pollution, salt fog, icing, bird poop, ...
High Voltage and energy

EM perturbations on train busbar:
Pantograph lowering → Electric arcs
High Voltage and energy
EM perturbations on train busbar:
Pantograph lowering $\rightarrow$ Electric arcs

- Few hundreds discharges (only a few tens were expected)
- Increasing E-field vs time
- Early ageing of pantographs and transformers
Reaching TeraHertz Frequencies

Working in the equivalent time domain (repetitive pulses only-no jittered signal):

emitter/receiver=cubic crystal (ZnTe <111>)

Amplified laser fs
800 nm
45 fs @ 1kHz
5 W

probe beam

pump beam

THz beam

HWP

emitter

receiver

QWP

Delay line

Magnitude (dB)

Frequency (THz)

Time (ps)

E Field (a.u.)
Reaching TeraHertz Frequencies

Linear polarization state of the THz beam generated with a linearly polarized laser beam

Elliptical polarization state of the THz beam generated with a circularly polarized laser beam
Reaching TeraHertz Frequencies

Linear polarization state of the THz beam generated with a **linearly polarized** laser beam

Elliptical polarization state of the THz beam generated with a **circularly polarized** laser beam

- Measurement of ps pulses
- Vectorial measurement up to 10 THz
Outline

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Conclusion

Performances of the EO technique:

✓ Fully dielectric sensor
✓ Millimeter sized
✓ Spatial resolution better than 1 mm$^3$
✓ Minimum detectable field lower than 100 mV.m$^{-1}$.Hz$^{-1/2}$
✓ Achievable dynamics of more than 120 dB
✓ Frequency bandwidth up to 100 GHz in real time (40 GHz for commercial product)
✓ Vectorial selectivity better than 50 dB
✓ Optical remote up to 100 meters
Conclusion

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✔ Spatial resolution better than 1 mm³
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Performances of the EO technique:

- Fully dielectric sensor
- Millimeter sized
- Spatial resolution better than 1 mm$^3$
- Minimum detectable field lower than 100 mV.m$^{-1}$.Hz$^{-1/2}$
- Achievable dynamics of more than 120 dB
- Frequency bandwidth up to 100 GHz in real time (40 GHz for commercial product)
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Conclusion

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Applications of the field measurement with EO probe:

- Antenna
- MRI
- Plasma
- Energy
- SAR
- EMC
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- Aerospace (characterization of Tx antenna)
- Interaction between pulsed laser and plasmas
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THANK YOU FOR YOUR ATTENTION