FIBER OPTIC TEMPERATURE SENSOR BASED ON IMAGE PROCESSING OF INTERMODAL INTERFERENCE PATTERN

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Starting point in Belgium: pipelines and underground power cables

Pipeline blast

Wind farm power cable failures
Project architecture & milestones

- Provide low-cost thermal and vibration monitoring solution for gas and electricity power underground distribution infrastructure
- Range: 10 km
- Alarming and if possible monitoring and hot spot localization

Target

2010: Kick-off
2014: Proof of concept Local prototyping Patent
2016: Large scale prototyping
Schedule

- Introduction
- Interferometric intermodal technique
- Numerical approach
- Experimental approach
- Extended scope
- Conclusion
Low-cost approach

- Fiber optic network
  - New and existing fiber optic telecommunication network: G.652D type
  - Existing skills of partners

Large geographical distribution

Vibration and temperature

Reuse of existing monitoring network
Fiber Optic Distributed Temperature Sensing (DTS) systems

- Interferometric technique:
  - Cheap lasers and detectors
  - High sensitivity

- Low-cost constraints:
  - High sensitivity sensor but low sample rate (thermal domain)
  - Low coherence light source linked to the range of detection
    - VCSEL for 100 m
    - DFB for several km

< 1 €/m

10 €/m

Interference concept (simplified)

One source

Two sources
Fiber optic Intermodal interference principles

- Fiber optic used at wavelength below cut-off: multimode
- Responsible for modal noise
- This pattern is sensitive to external constraints:
  - Temperature: thermal expansion and refractive index change
  - Mechanical: mode coupling, birefringence, torsion, ...
- Few mode pattern

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Modal equations

\[ \tilde{E} \approx (\tilde{e}_t(x, y) + e_z(x, y) \cdot z) \exp\{i\beta z\} \]

\[ \tilde{H} \approx (\tilde{h}_t(x, y) + h_z(x, y) \cdot z) \exp\{i\beta z\} \]

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ((\lambda_0))</td>
<td>nm</td>
<td>850</td>
</tr>
<tr>
<td>Core refractive index ((n_{co}))</td>
<td>-</td>
<td>1.48</td>
</tr>
<tr>
<td>Cladding refractive index ((n_{cl}))</td>
<td>-</td>
<td>1.46</td>
</tr>
<tr>
<td>Fiber radius (r)</td>
<td>(\mu)m</td>
<td>4.5</td>
</tr>
<tr>
<td>V parameter</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>(l_{max}) (cylindrical symmetry order)</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Maximum number of modes ((V^2/2))</td>
<td>-</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\tilde{e}_t)</th>
<th>(\tilde{h}_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even (HE_{l+1,m})</td>
<td>((\vec{x} \cos(\phi) - \vec{y} \sin(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
<td>(Y.(\vec{x} \sin(\phi) + \vec{y} \cos(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
</tr>
<tr>
<td>Odd (HE_{l+1,m})</td>
<td>((\vec{x} \sin(\phi) + \vec{y} \cos(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
<td>(-Y.(\vec{x} \cos(\phi) - \vec{y} \sin(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
</tr>
<tr>
<td>Even (EH_{l-1,m})</td>
<td>((\vec{x} \cos(\phi) + \vec{y} \sin(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
<td>(-Y.(\vec{x} \sin(\phi) - \vec{y} \cos(\phi)) \frac{J_{l+1}(U,R)}{J_{l}(U)})</td>
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</tr>
</tbody>
</table>
Temperature effect on propagation

- **Poynting vector**

  \[
  I(r, \varphi) = Y[A_{01}^2 \Psi_{01}^2 + 2A_{11}^2 \Psi_{11}^2 \cdot (\sin(\varphi) + \cos(\varphi))^2 + 2A_{01}A_{11} \Psi_{01} \Psi_{11} \cdot (\sin(\varphi) + \cos(\varphi)) \cdot \sin(\Delta \beta z)]
  \]

  \(\sin(\Delta \beta z) = +1\)

  \(\sin(\Delta \beta z) = -1\)

  even and odd HE\(_{11}\) with same phase, TE\(_{01}\) an TM\(_{01}\) with a phase shift of \(\pi/2\), even and odd HE\(_{21}\) with a phase shift of \(\pi/2\)

- **Temperature effect:**
  - Propagation constant of modes + mode coupling
  - Elongation

Interference pattern dynamics vs temperature

Lobes power exchange

\[
I(r, \varphi) = Y [A_{01}^2 \Psi_{01}^2 + 2A_{11}^2 \Psi_{11}^2 (\sin(\varphi) + \cos(\varphi))^2 + 2A_{01} A_{11} \Psi_{01} \Psi_{11} (\sin(\varphi) + \cos(\varphi)) \sin(\Delta \beta z)]
\]

\[
\sin(\Delta \beta z) = +1
\]

\[
\sin(\Delta \beta z) = -1
\]

Lobes rotation

\[
I(r, \varphi) = Y [A_{01}^2 \Psi_{01}^2 + A_{11}^2 \Psi_{11}^2 + 2 \sqrt{2} A_{01} A_{11} \Psi_{01} \Psi_{11} \cos(\frac{\pi}{4} + \varphi - \Delta \beta z)]
\]

even and odd \(HE_{11}\) with same phase, \(TE_{01}\) an \(TM_{01}\) with a phase shift of \(\pi/2\), even and odd \(HE_{21}\) with a phase shift of \(\pi/2\)

Image processing: need for one/two spots interference pattern

- Multiple modes: Velocity field approach
- Optical flow
  - Horn Schunck Algorithm
- Few mode: Pattern recognition tracking
- Block pattern matching and tracking
  - Gravity center tracking
Resulting pattern (gravity center tracking)
All modes and few modes: need for spatial filtering to select modes

All modes (30)

Few modes (HE11, TE01 and TM01, HE21, HE31, EH11, HE12)
Heating and cooling
Numerical approach: results (1)
Numerical approach: results (2)
Linear dependency between temperature deviation and total path length of the gravity center of the few-mode and few-lobe interference pattern

- **Low-cost technique**: $< 1 \, \text{€/m}$
  - Detector: Commercial CMOS camera sensor (down to -60 dBm sensitivity threshold level)
  - Laser: VCSEL for 100 m, DFB for 10 km
  - Reuse of G.652 @ 850 nm:
    - Spatial filtering for mode selection and few spots interference pattern

- **Image processing**:
  - Pattern recognition / Gravity center
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Experimental approach

- Lab:
  - water tank
- On-site 1:
  - 7 km underground cable between Leuze and Ligne
- On-site 2:
  - Electrical junctions
Experimental setup (1): lab

- VCSEL source @ 850nm
- 200 m FUT
- FUT from 12°C upto 20°C
Image processing : vectorization

- **Step 1:**
  - Neighborhood points selection:
    - Prevent from speckle hopping/Vibration filtering

- **Step 2:**
  - Successive points processing:
    - Scan every following points
    - Compute distance to successive segment
      - If close enough: don’t take care of the point
      - If far enough: insert point into final traject
**Impact on interference pattern**

- Oscillation superimposed
- Acceleration of the gravity center when FUT & HnC both heating or cooling
- Deceleration when FUT heating and HnC cooling
- Deceleration when FUT cooling and HnC heating
- Enable heating/cooling discrimination

**Heating/Cooling section**
Setup ORES 2012-2013

- G.652 24 fibers cable laid between Leuze and Ligne substations
- 850 nm and 1MHz laser source
- Spatial mode filtering via connectors spacing
Functional blocks

Industrial Suitcase #1
- Industrial automata: GENIP
- GPRS interface
- Laser source driving
- Local temperature measurements
- Remote FPGA settings tuning
- FTP archiving – Site monitoring

Modbus Interface + Temperature Sensor

Install a longer image

Industrial Suitcase #2
- Switch
- FPGA
- CAM
- Local Display
- VGA2USB
- USB

Laser source and driver OEM

Fiber access

230 V Power Supply

Ethernet for IEC 61850

Ethernet for VPN

Modbus Interface + Flowmeter sensor

Cable access
Setup
Currents

- 10 days
- I1, I2, I3 qh measurements

Graph showing currents over time (days) from 15/09/2013 to 27/09/2013.
Heating results

- Heat index is computed:
  - Sum of the square of the current variation for all the cables:

\[ HI = \sum_{j=1}^{3} \frac{dI_j^2}{dt} \]
Failure scenario: soil drying

- Soil drying:

Source: SOILVISION
Failure scenario

- Soil drying:

Source: SOILVISION
Failure scenario: simulation

- Simulated soil drying: 40 °C in 10 days over 250 m
- Detected after 2 days
Experimental setup (3)

- Electrical joints
- $95^2$ cable @ (20V/0-600A)
- 5 m of G.652D wrapped around the joint
Thermal Study

- IR camera:
  - For a defaulting junction: DJ

@ 200 [A]

@ 400 [A]
Optical Study

Functional block

Figure inspired by [2]

Electrical joint study during 12 hours

- Linearity

![Graph showing temperature over time for different current levels (100 A, 200 A, 300 A, 400 A). The graph includes a linear fit equation with R² = 0.99.](image)
Conclusion (part 2)

- Good agreement between theory and practice
- Sensitivity:
  - Between 2 and 3 pixel/K.m for G.652 and a 200*200 projection area of the speckle
- Linearity:
  - Confirmed in a specified image sampling rate range
- Drift:
  - Harnessed on several days
  - Need for algorithm upgrade for months and years
- Vibration filtering qualitative
- Power black-out: need for recalibration
  - UPS but very small consumption (10 mA)
- Distance range:
  - Tested over 7 km return: 14 km
Pipeline monitoring

Absence of gas leak

Presence of gas leak

Source: OMNISENS
Scope extension to fire safety and leak detection

- Fire safety for ducts, pipes and cables
- Fire safety for transformers and electrical cabinet
- Overheating protection for IT servers
Conclusions (part 2)

- Provide low-cost thermal and vibration monitoring solution for gas and electricity power underground distribution infrastructure in Belgium as a start point
  - Range: 10 km
  - Localization !!!