# Einsatz hyperspektraler Sensoren zur Überwachung intelligenter LED-Lichtquellen – eine Fallstudie

R. Nestler, R. Jahn, K.-H. Franke, S. Junger, D. Gäbler

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**Zentrum für Bild- und Signal-verarbeitung (ZBS) e.V.**
www.zbs-ilmenau.de

**Technische Universität Ilmenau**
www.tu-ilmenau.de/gdv

**Fraunhofer IIS**

**X-FAB Semiconductor Foundries AG**

**Dr. Rico Nestler**
ZBS e.V. Ilmenau / TU Ilmenau

# Agenda

1. Motivation for monitored LED based lighting systems
2. Multi-channel sensor elements for lighting applications
3. Considerations about feasibility
4. Summary & Outlook

# 1. Motivation for monitored LED based lighting systems

## LED-Lightings

- **Efficiency** and **Costs**
- **Light output** and **( spectral ) diversity**
- **Versatility** for **different lighting tasks**

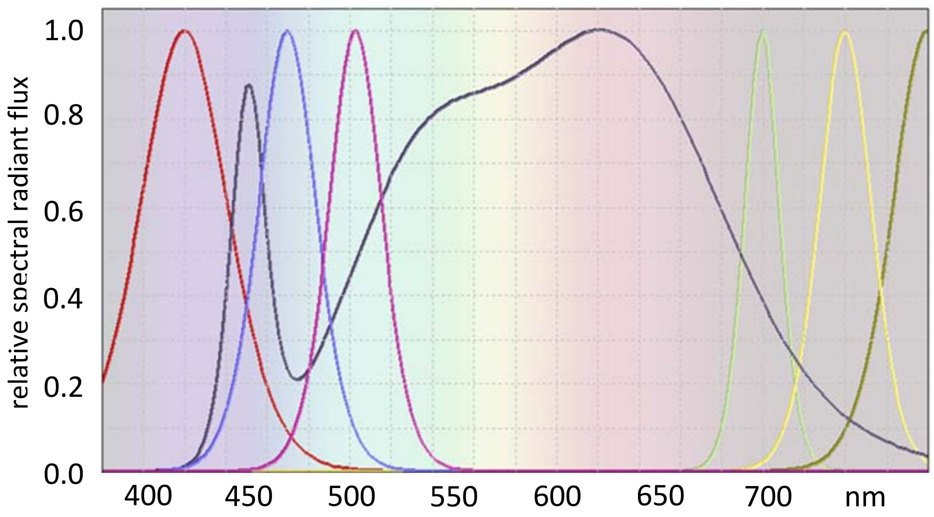

**Customizable light effects**, which result **from specific spectral light compositions**

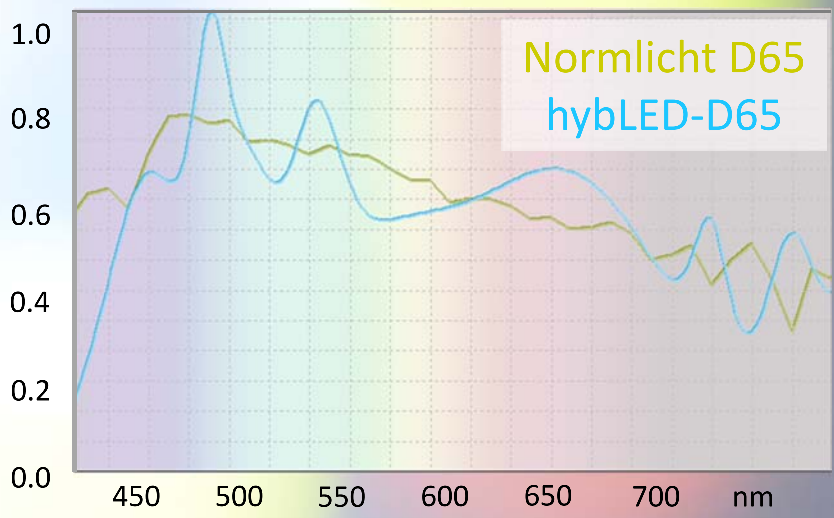
- **physiologically - colorimetric** (affects color quality , visual comfort, CRI),
- **biologically** (affects attention , wellbeing, HCT) or
- **for a specific technical recognition task** (affects contrasts)

# 1. Motivation for monitored LED based lighting systems

## LED-Lightings

- **Color quality** in general lighting or color-critical applications
- **Difficult relation** between **luminous efficiency** and **spectral characteristic**
- **spectral defined** LED lightings: only **hybrid,** but **dynamically**



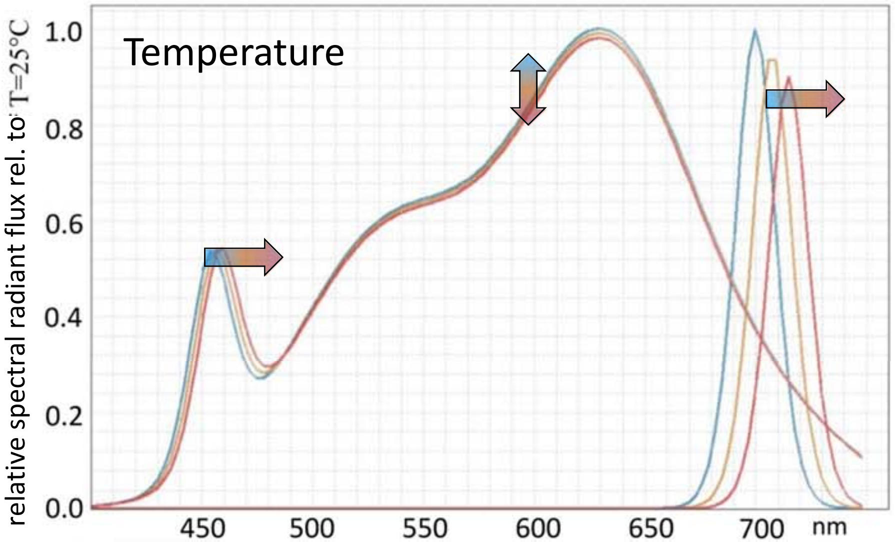



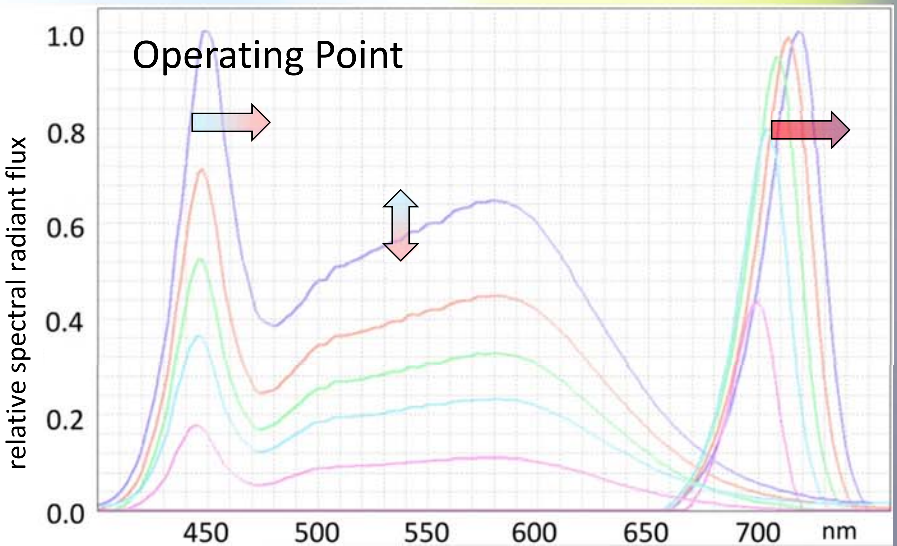
# 1. Motivation for monitored LED based lighting systems

## LED-Lightings

### Drift and aging behavior

- **depends on** LED-type, specimen and operating conditions
- **Radiant flux** / spectral radiant flux
  = *f* **(Time, Temperature, Operating Point)**
- Only in / at operating point approximated intensity drift
- especially **critical for high-power LEDs**



# 1. Motivation for monitored LED based lighting systems

## Why sensory monitored LED-Lightings?

**Stable LED-based light syntheses** require

- **Preselection, pre-aging** and **characterization** of **used LEDs**
- **expensive stabilization and tracking** of electrical **operating points**
- **costly stabilization** of **temperature**

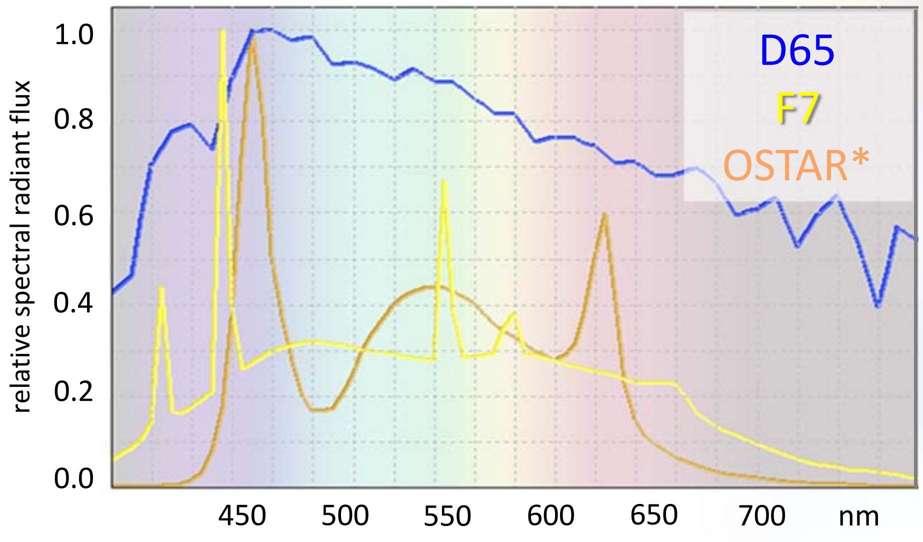
**or**

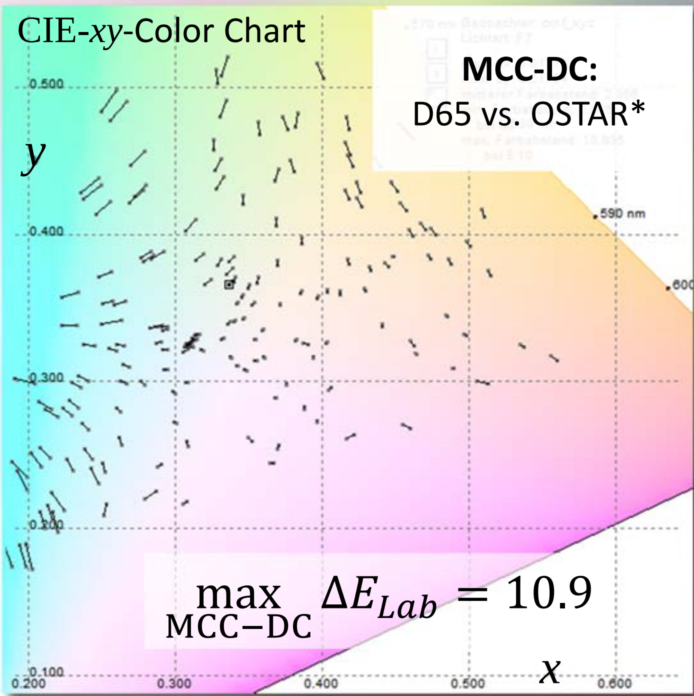
- Continuous **sensor monitoring** and **sensor based adjustment** of light synthesises
  - degrees of freedom of the measurement **greater or equal** the degrees of freedom of the light synthesis
  - **spectral** or **approximately spectral** color stimulus detection

# 2. Multi-channel sensor elements for lighting applications

**Requirements** from the perspective **of the measuring task**

**White points** characterizing **spectral light color stimuli colorimetrically, strong observer - metameric level, unsuitable**

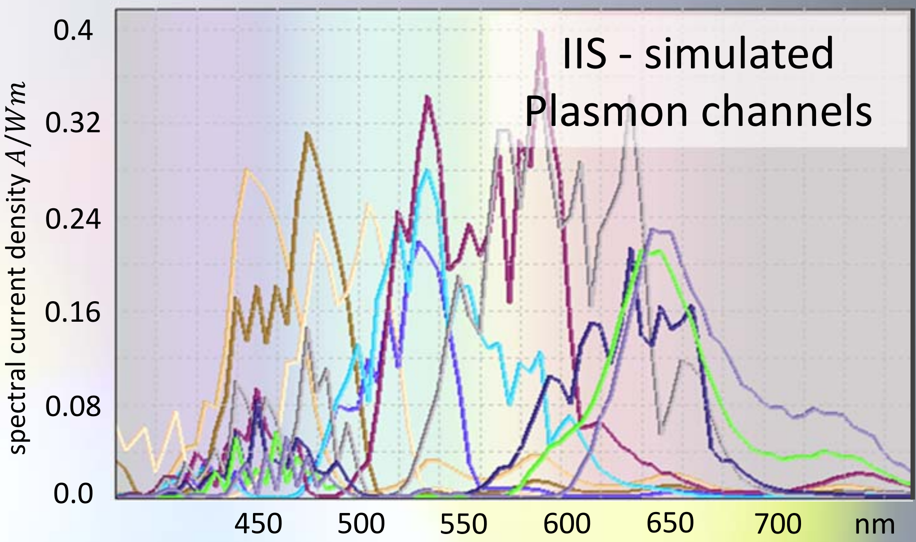


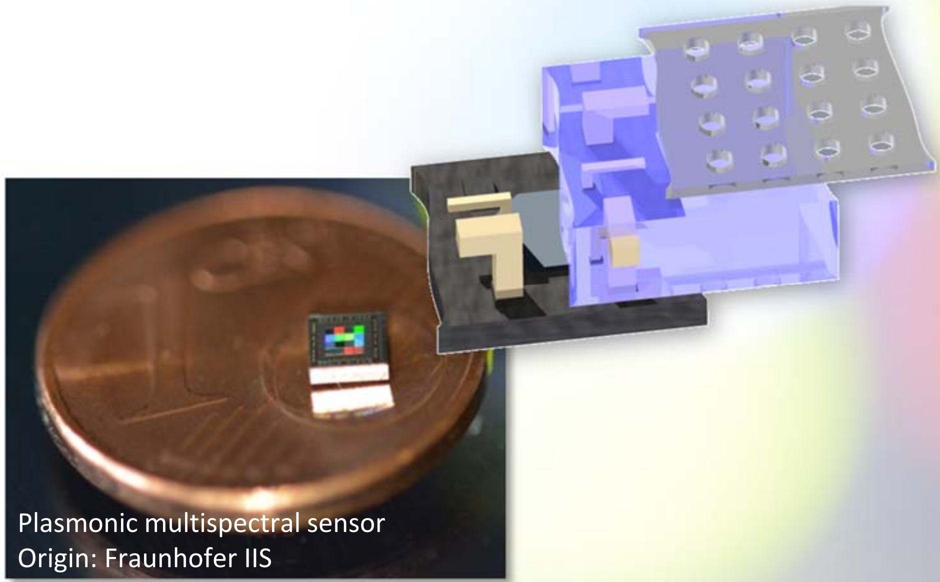




Characterizing of spectral lights by **an approximately spectral measurement, less metameric → „Mehrbereichsansatz"**

# 2. Multi-channel sensor elements for lighting applications

- **Hyperspectral** sensors
  → more than 3 broadbanded channels
- Channel sensitivities **more applicative, energetic or technological oriented** than colorimetric
- spectral or colorimetric measurement **based on spectral estimation**



Plasmonic multispectral sensor
Origin: Fraunhofer IIS

# 2. Multi-channel sensor elements for lighting applications

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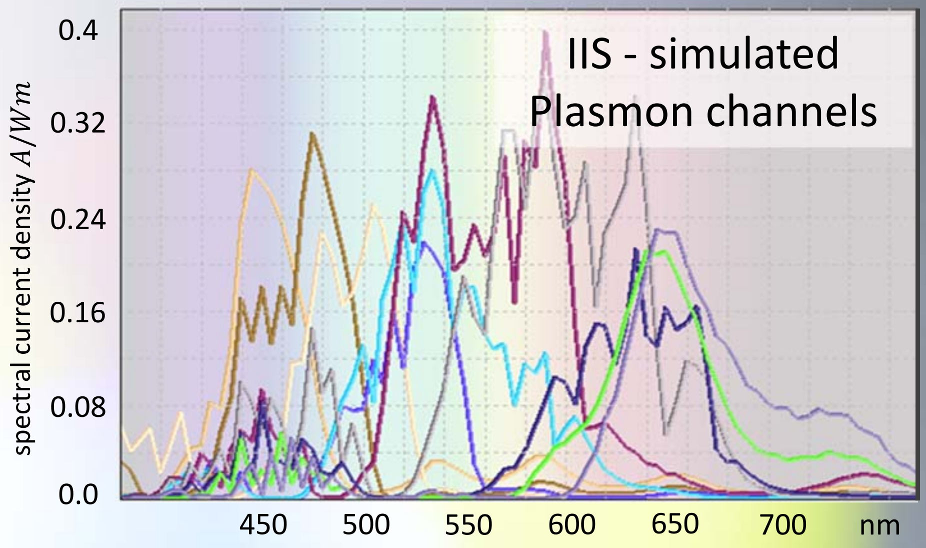



- Spectral estimation is an **inverse, ill-posed problem**
- Color stimuli have to be described **with less degrees of freedom than the spectral domain**.
- **Stabilization (regularization)** with **“knowledge” about the measurement problem:** specific spectral lighting situations or causal lights or parametric models of the lights

## 2. Multi-channel sensor elements for lighting applications

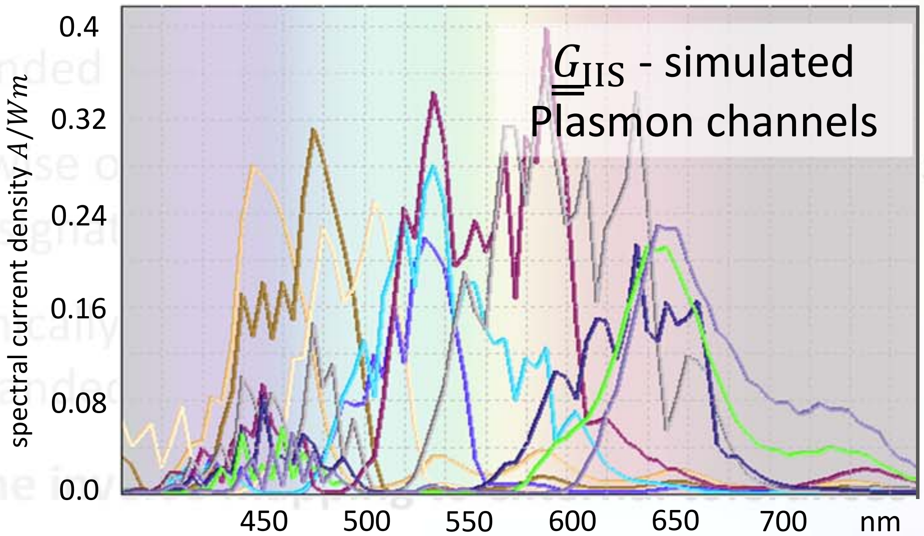
**Requirements** from the perspective **spectral estimation**

- **clear detection of significant changes of spectral color stimuli within sensor responses**
  - broadbanded overlapping channel sensitivities
  - channelwise opposite edges in spectral bands with significant spectral signature changes
  - monotonically ascending / descending sensitivities, where narrowbanded spectral signature changes exist
- **Stability of the inverse mapping to external tolerances**
- **Robustness of the inverse mapping to internal tolerances**
  - best conditioned sensor configuration

# 2. Multi-channel sensor elements for lighting applications

**Requirements** from the perspective **spectral estimation**

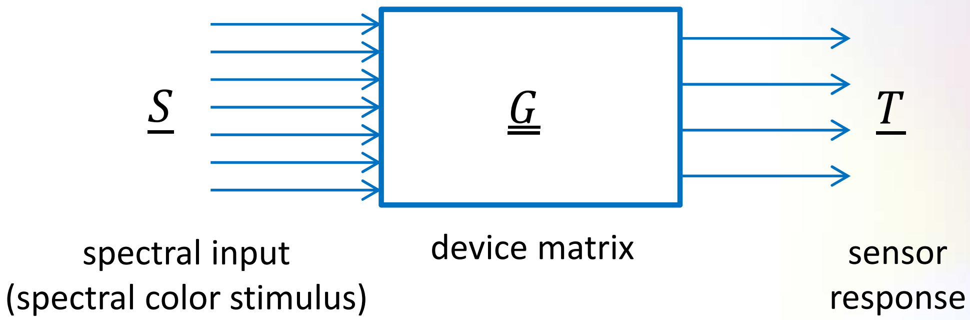
- clear detection of significant changes of spectral color stimuli **within** sensor responses
  - broadbanded
  - channelw... significant spectral signal...
  - monoton... where narrowband...
- Stability of the inv...
- Robustness of the inverse mapping to internal tolerances
  - best conditioned sensor configuration




**Opposite consequences for the design of $\underline{\underline{G}}$ → find a compromise**

# 2. Multi-channel sensor elements for lighting applications

## Condition-based approach for optimal sensor configurations




$$\underline{T} = \underline{\underline{G}} \cdot \underline{S} \qquad r \ll a$$

$\underline{T} \in \mathbb{R}^r$, $\underline{S} \in \mathbb{R}^a$

- **Condition** describes the reaction of output variables, here $\underline{T}$, to changes in the input variables, $\underline{S}$. It also able to determine
  - the **stability** of spectral estimates.
  - the **robustness** of spectral estimates.

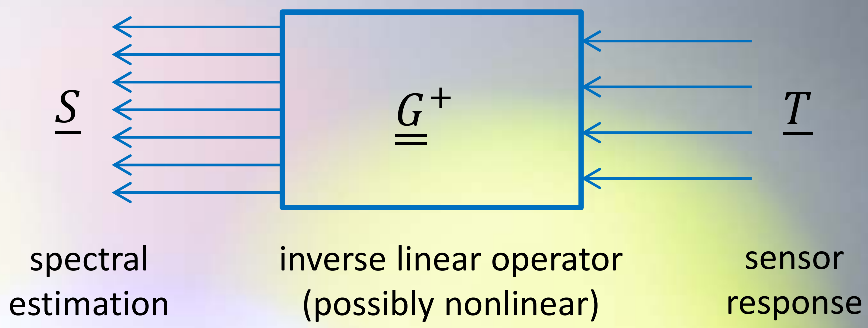
- **Condition number**

$$\kappa(\underline{\underline{G}}) := \frac{\text{maximal relative change of } \underline{T}}{\text{maximal relative change of } \underline{S}}$$

# 2. Multi-channel sensor elements for lighting applications

## Condition-based approach for optimal sensor configurations

- an **appropriate measure** should be able to evaluate the stability of the **inverse problem**




- **modified condition number $\overline{\kappa}$**

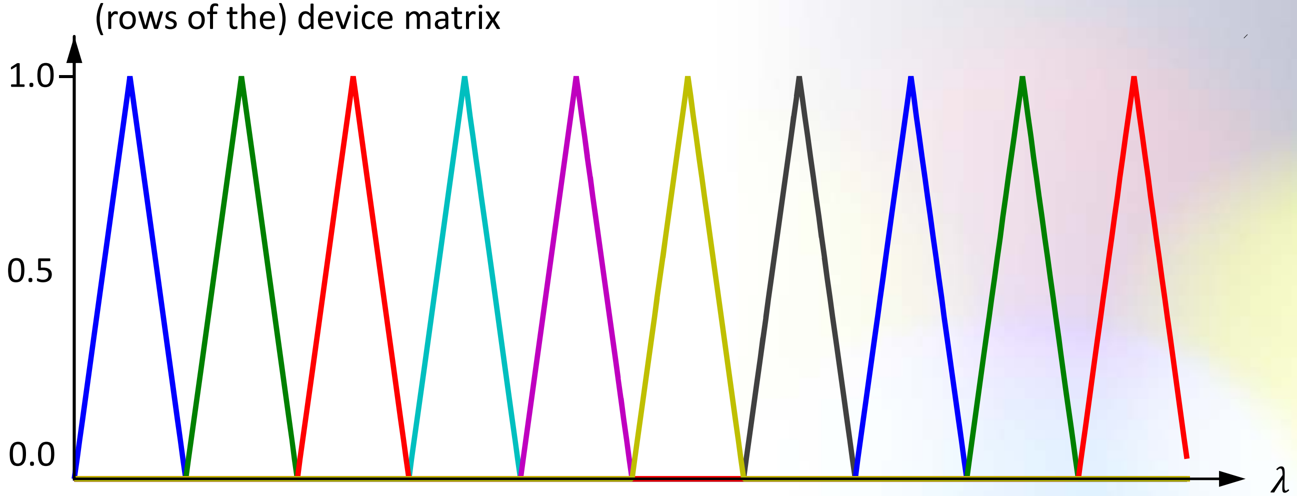
$$\overline{\kappa}(\underline{\underline{G}}) := \frac{\text{maximal singular value } \underline{\underline{G}}}{\text{minimal singular value } \underline{\underline{G}}}$$

- **Characteristics**

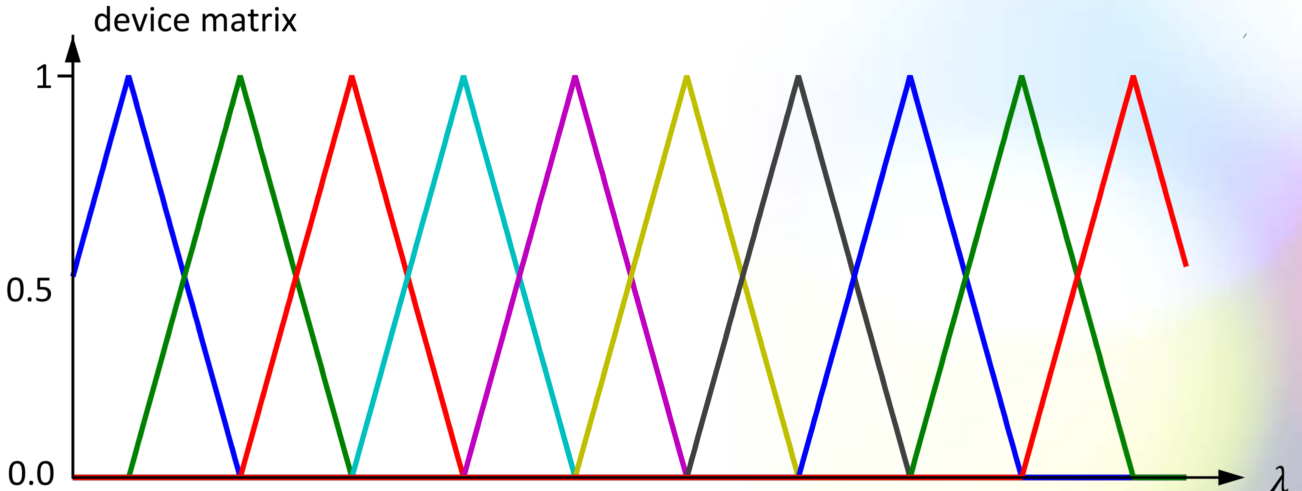
| | |
|---|---|
| $\overline{\kappa}(\underline{\underline{G}}) \geq \kappa(\underline{\underline{G}})$ | worst-case estimation of real condition |
| $\overline{\kappa}(\underline{\underline{G}}) \geq 1$ | minimal if $\underline{\underline{G}}$ is orthogonal, non-overlapping sensitivities |
| $\overline{\kappa}(\underline{\underline{G}}) = \infty$ | maximal if $\underline{\underline{G}}$ has fully linearly dependent sensitivities |
| $\overline{\kappa}(\underline{\underline{G}}) = \overline{\kappa}(\underline{\underline{G}}^+)$ | equivalent for the behavior of the Moore-Penrose-Inverse $\underline{\underline{G}}^+$ |

# 2. Multi-channel sensor elements for lighting applications

## Condition-based approach for optimal sensor configurations $r = 10, r \ll a$



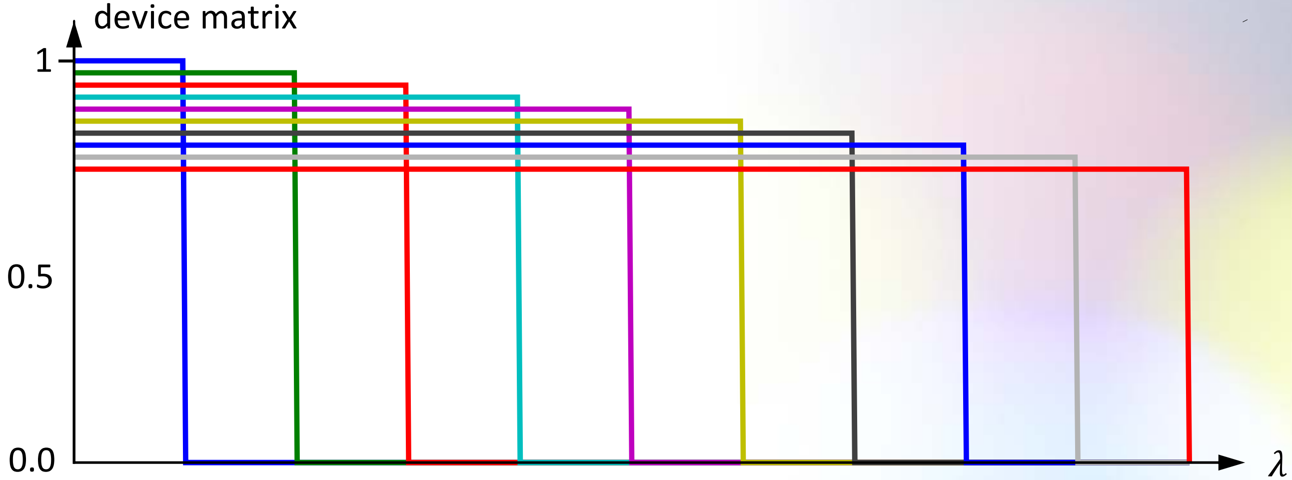

$\overline{\kappa} = 1$



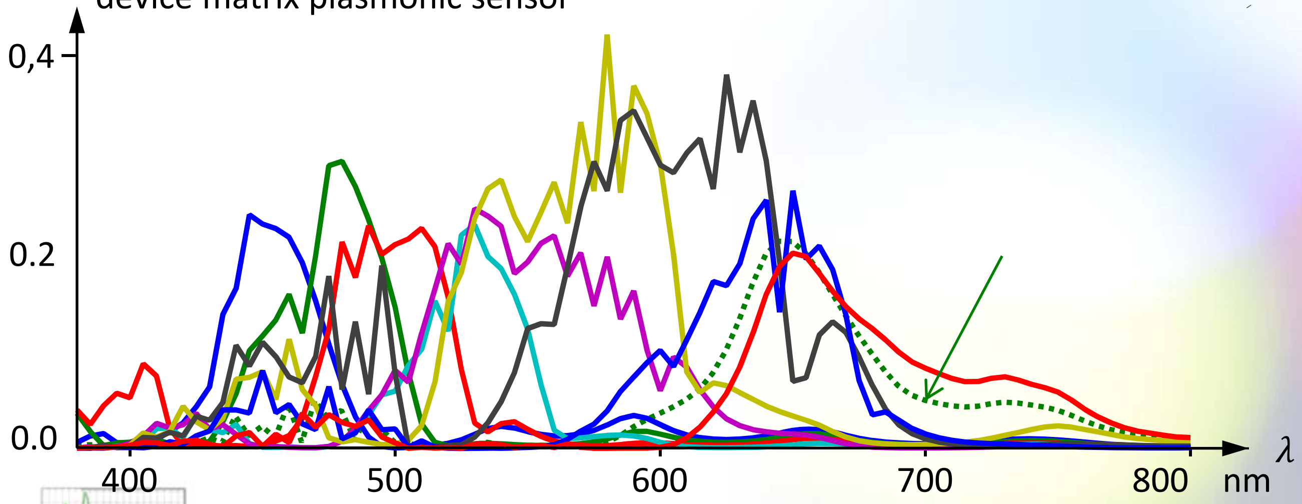

$\overline{\kappa} = 1{,}68819$

# 2. Multi-channel sensor elements for lighting applications

## Condition-based approach for optimal sensor configurations $r = 10, r \ll a$




$\overline{\kappa} = 13{,}2633$

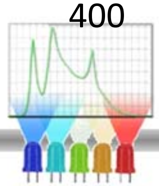



all channels:

$\overline{\kappa} = 28{,}9118$

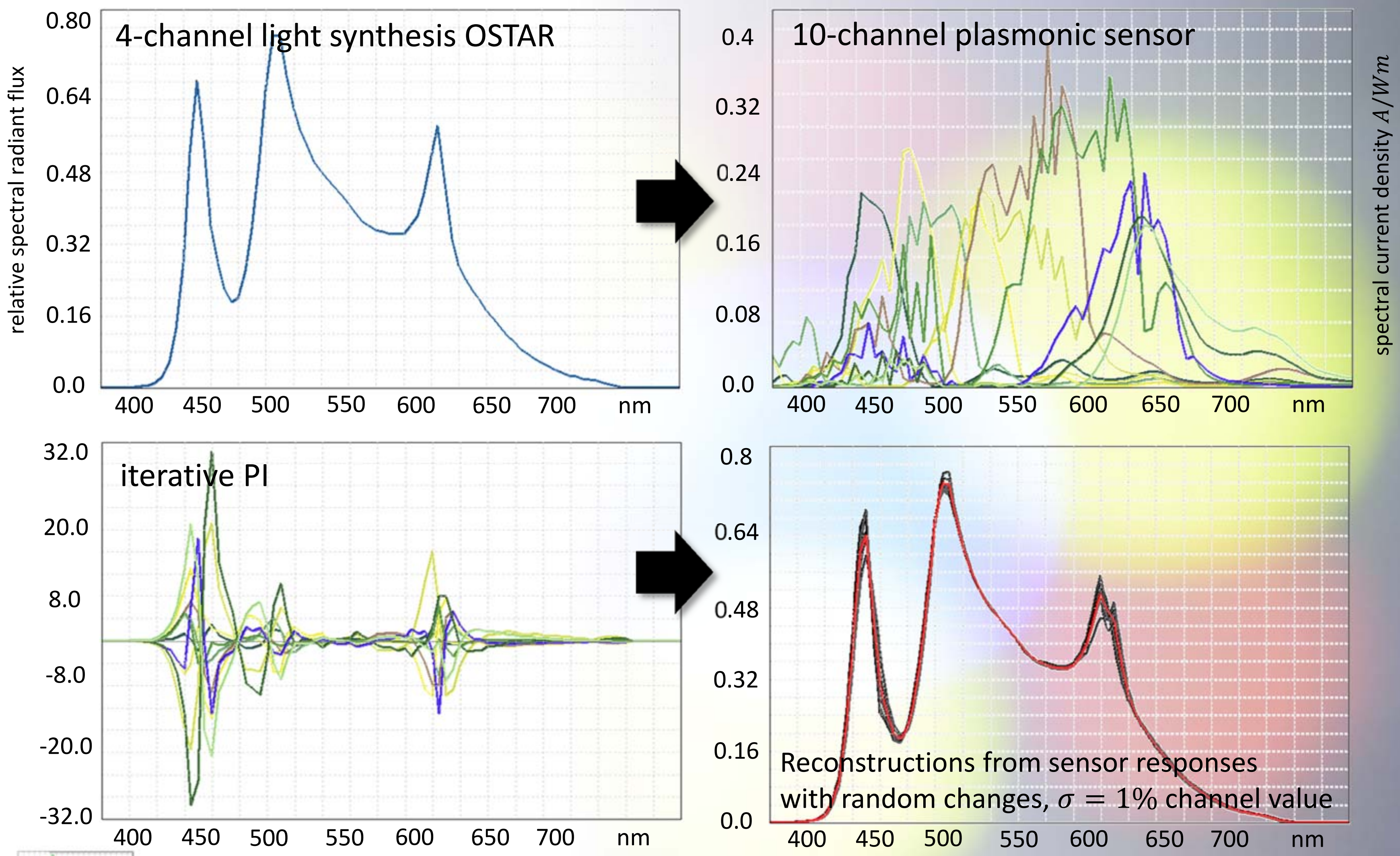
without ········ :

$\overline{\kappa} = 13{,}0406$



# 2. Multi-channel sensor elements for lighting applications

## Stability due to condition-optimal sensor configuration



# 2. Multi-channel sensor elements for lighting applications

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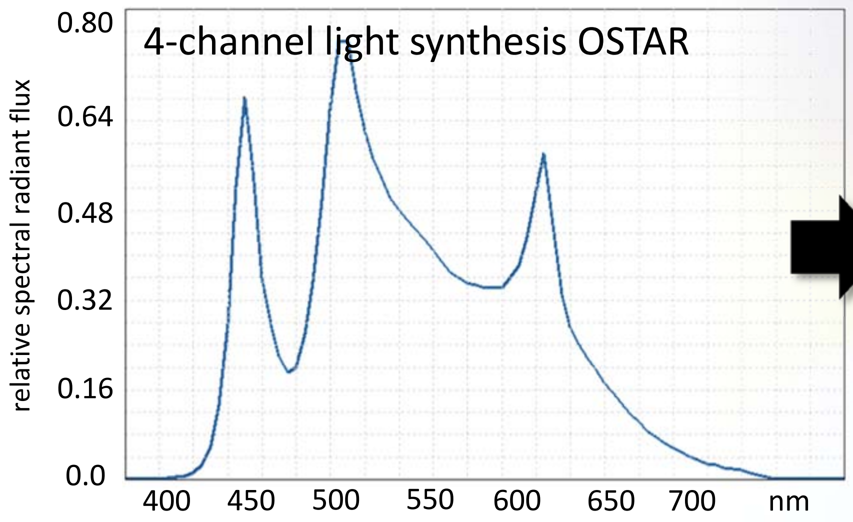
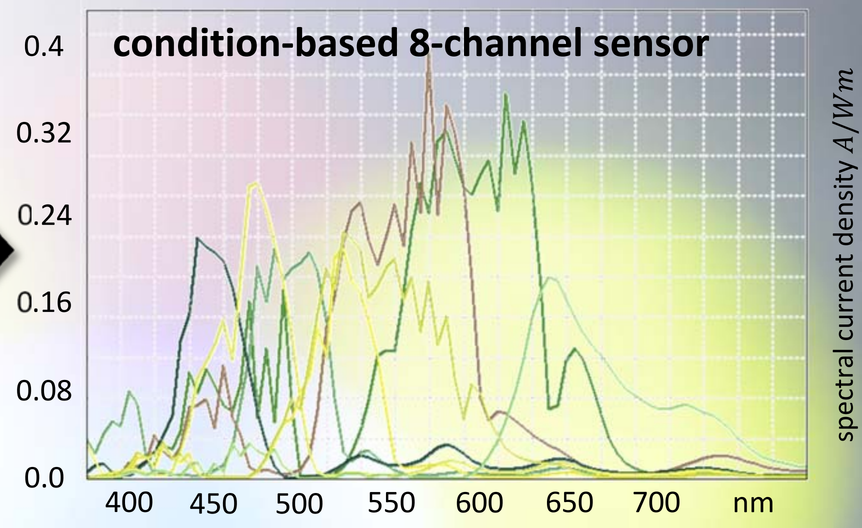
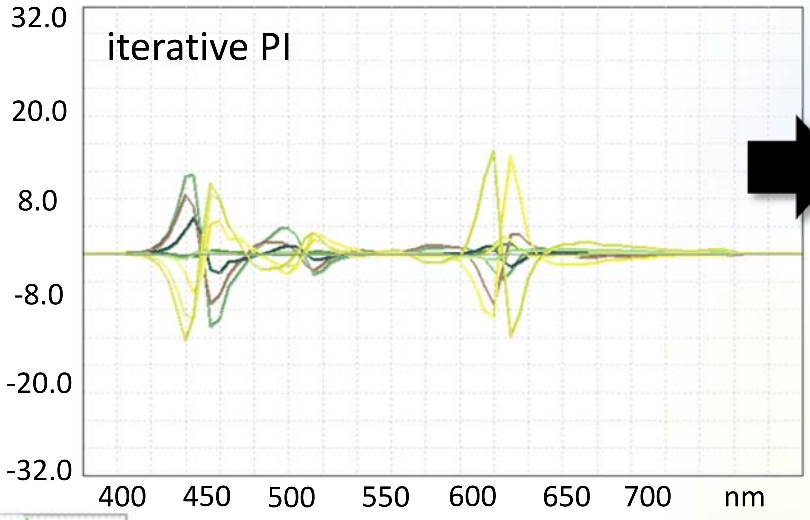
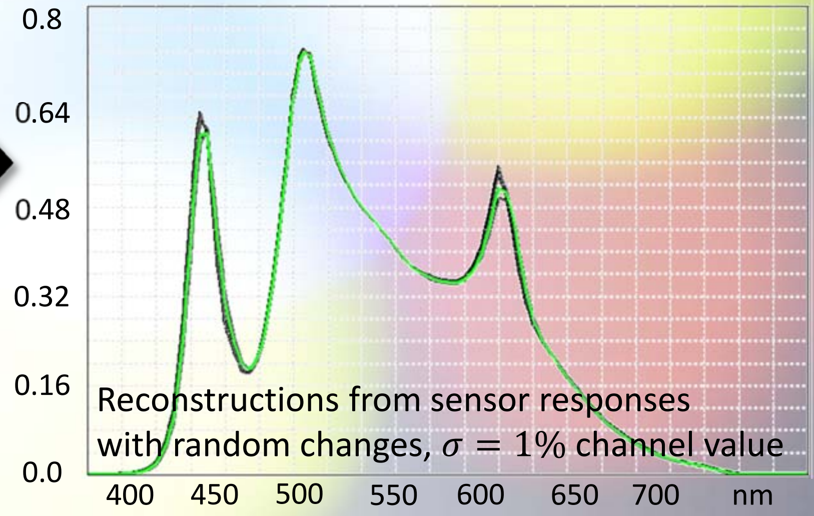


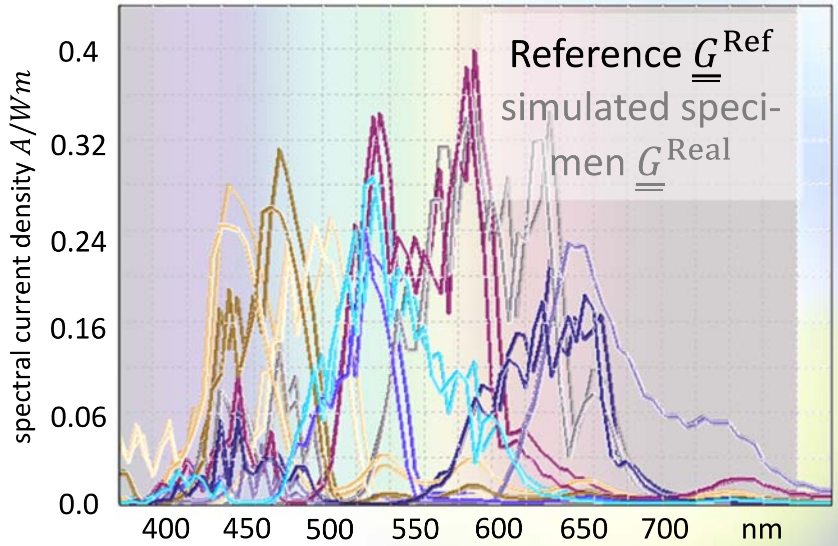



# 3. Considerations about feasibility

The feasibility is mainly influenced of **internal** tolerances of the measuring problem

- **Technologically** related **manufacturing tolerances**
- **Field behavior** $\underline{\underline{G}}^{\mathrm{Real}}(t,T)$
  - **primary tolerances** of the channel sensitivities $\underline{\underline{G}}^{\mathrm{Real}} \neq \underline{\underline{G}}^{\mathrm{Ref}}$
- **Possibilities to deal with it**
  - **secondary tolerances** of the target sensor response $\underline{T}^{\mathrm{Real}} \neq \underline{T}^{\mathrm{Ref}}$

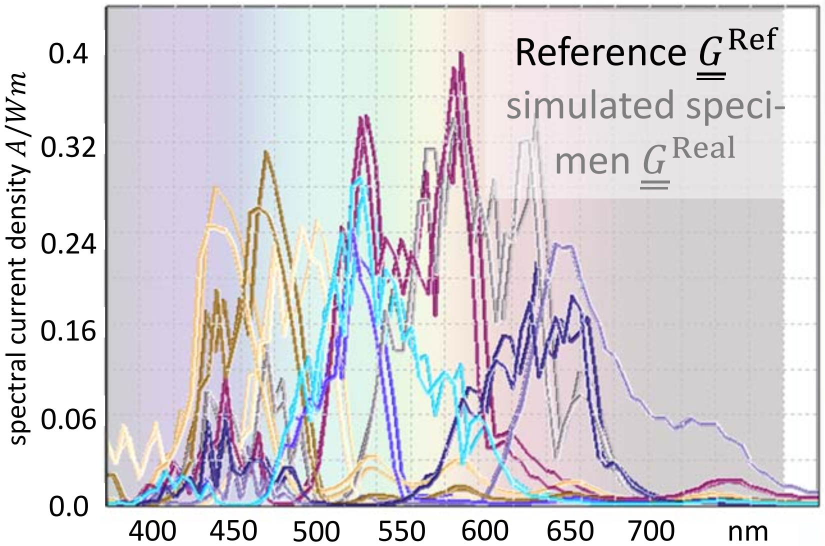


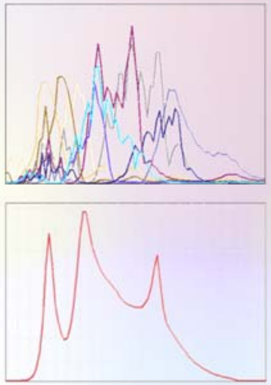
# 3. Considerations about feasibility

- **Inverse problems are strong sensitive** against **inner and outer tolerances**
- **observable (secondary) tolerances** are **strong color stimulus dependent** (mod. condition number)
- **condition-based** device configuration
- **additional regularization** with global constraints to the “Inverse” or to the shape characteristics of spectral reconstructions
- **Calibration at secondary level**, z.B. $\underline{T}^{\mathrm{Ref}} \overset{!}{\approx} \underline{\tilde{T}} = \underline{\underline{A}} \cdot \underline{T}^{\mathrm{Real}}$
  - **only with references to the measuring task**
  - calibration approach directly influenced by the **condition of sensor device**

# 3. Considerations about feasibility

## Effect of secondary level sensor calibration



Sensor response $\underline{T}^{\mathrm{Real}}$

[2.38738, 1.02671, 1.02712, 2.35167, 0.670116, 0.871947, 0.980327, 0.936658, 1.80248]

Calibration-step

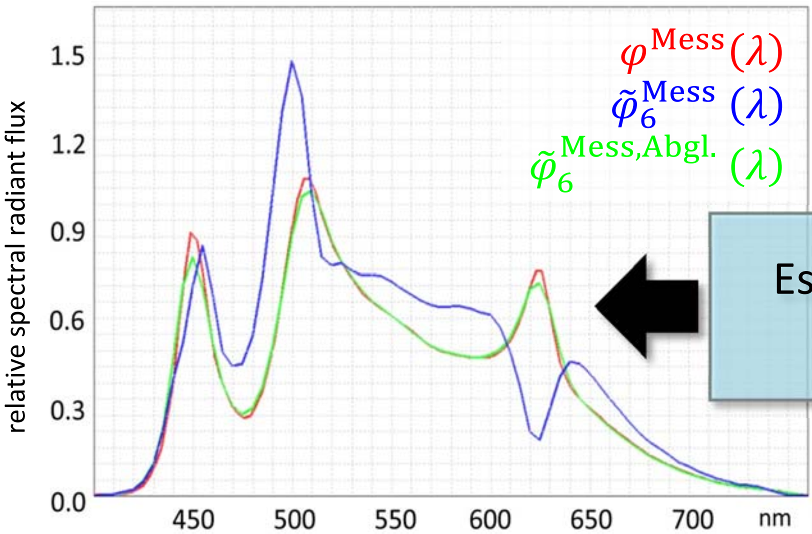
Sensor response **with** calibration $\underline{\tilde{T}}$

[2.48964, 1.19561, 1.04848, 2.54391, 0.688352, 0.992164, 1.08094, 0.976844, 1.84832]

Reference sensor response $\underline{T}^{\mathrm{Ref}}$

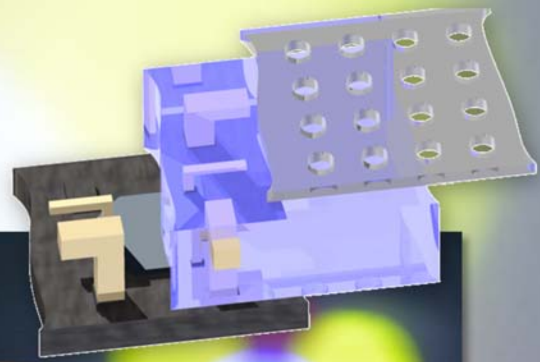
[2.49090, 1.19561, 1.04751, 2.54704, 0.687925, 0.991941, 1.08174, 0.977130, 1.84916]

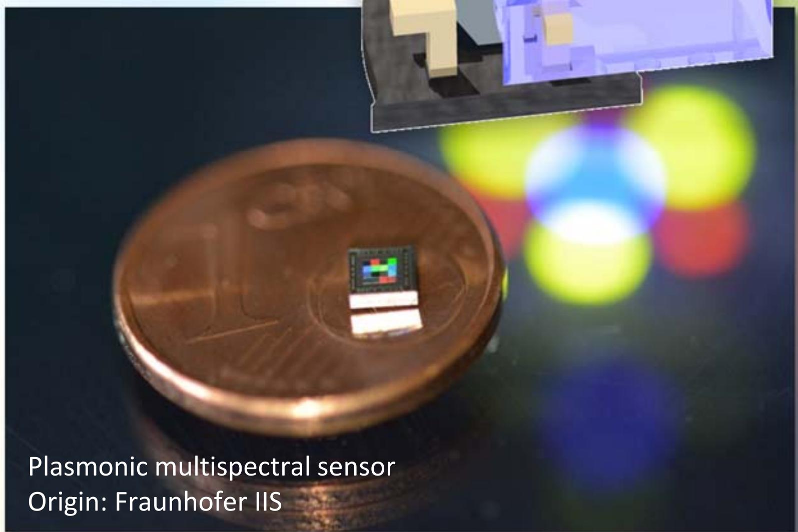
Estimation-step



# 4. Summary & Outlook
## Project FEEDLED

1. **Components for innovative, self-monitoring lighting solutions with new sensors, integrated measurement data processing, new optical light mixing principles**
   - economically and technically efficient
   - scalable for different requirements
2. **Sensor monitoring** of spectral light characteristics
3. Compensation of aging and drift of all lighting components through **integrated sensory control**

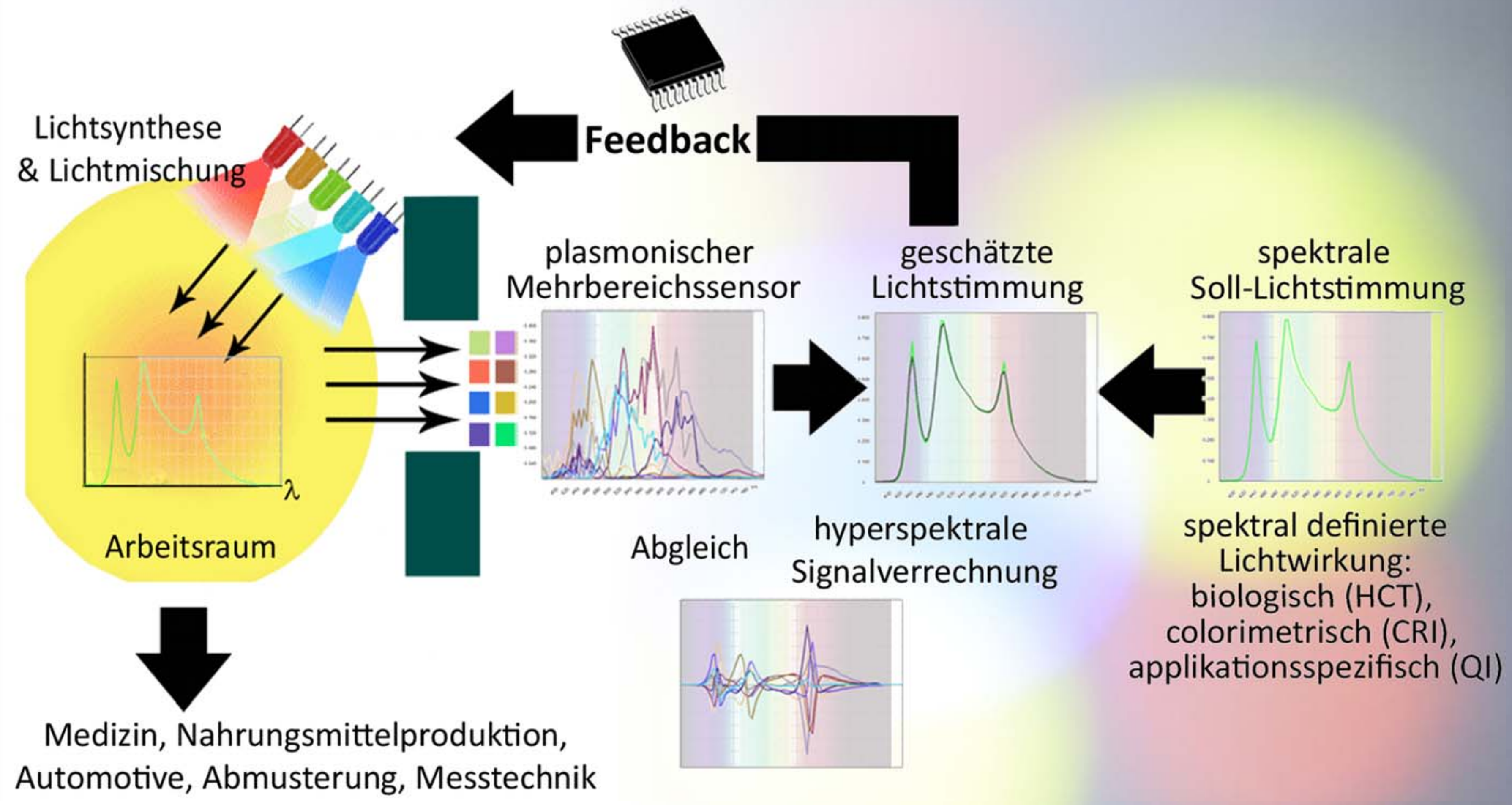




Plasmonic multispectral sensor
Origin: Fraunhofer IIS

# 4. Summary & Outlook

## FEEDLED-Approach



# 4. Summary & Outlook

## Thank you for your attention!

The shown results are part of a currently running joint project "Feedback" system for intelligent LED -based lightings (FEEDLED)", which is anchored in the BMBF "Smart Lighting"-funding program.

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GEFÖRDERT VOM

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