Color sensors for smart lighting applications

Fraunhofer Institute for Integrated Circuits IIS

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Overview

1. **Introduction:**

   Why color sensors for smart lighting?

2. **Methodology:**

   Nanostructures as color filters

3. **EU-funded project »LASSIE-FP7«:**

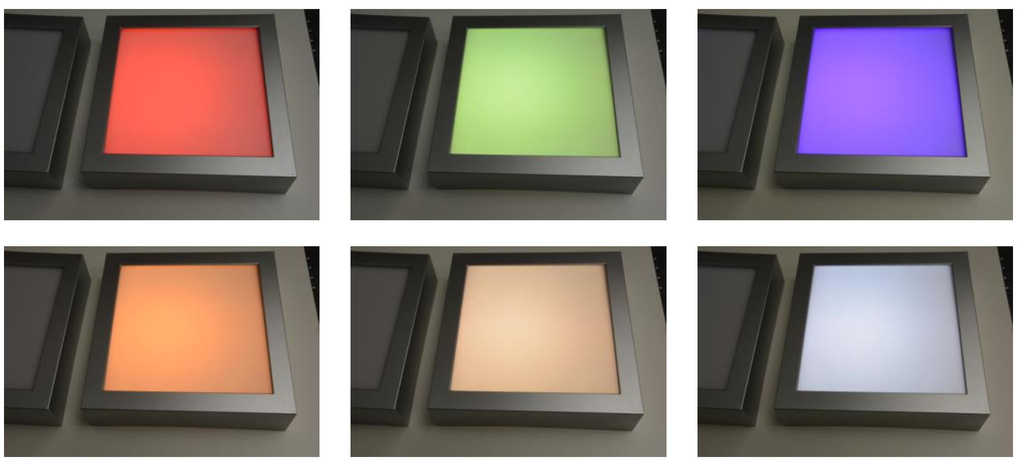
   Realization of color sensors

   Application in a color feedback system

4. **Conclusions**

1. Introduction
Why color sensors for smart lighting?

- »Mixing« of light required for color tuning (»tuneable white«)
- High-quality lighting requires precise color matching over time and from luminaire to luminaire
- Wavelength of LEDs changes with temperature and due to aging
- $\Rightarrow$ How to keep the color of a luminaire constant?



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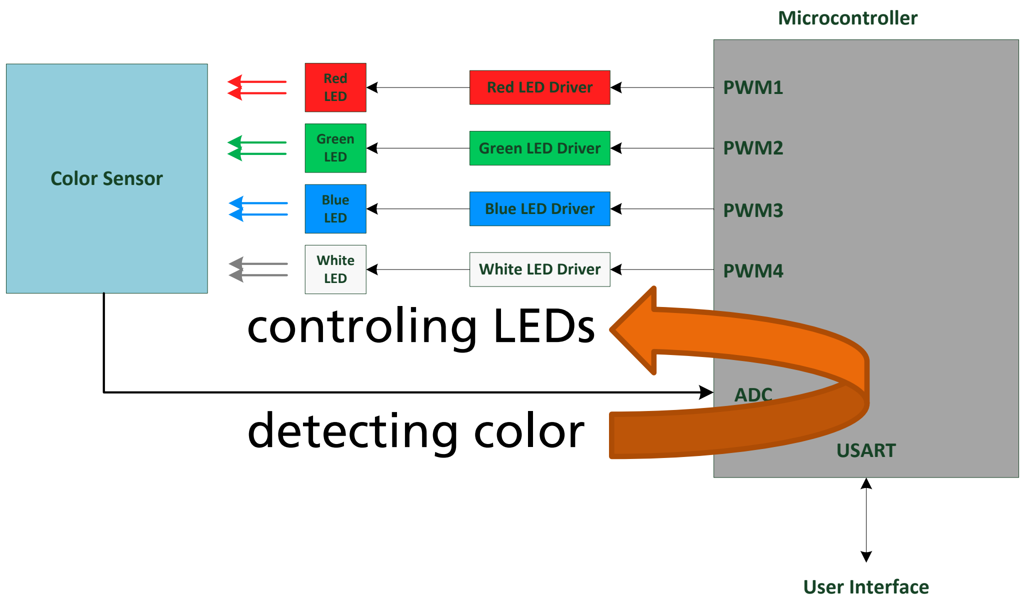
1. Introduction
Why color sensors for smart lighting?

- Color-sensing feedback is more reliable than binning and modeling temperature and aging effects of LEDs



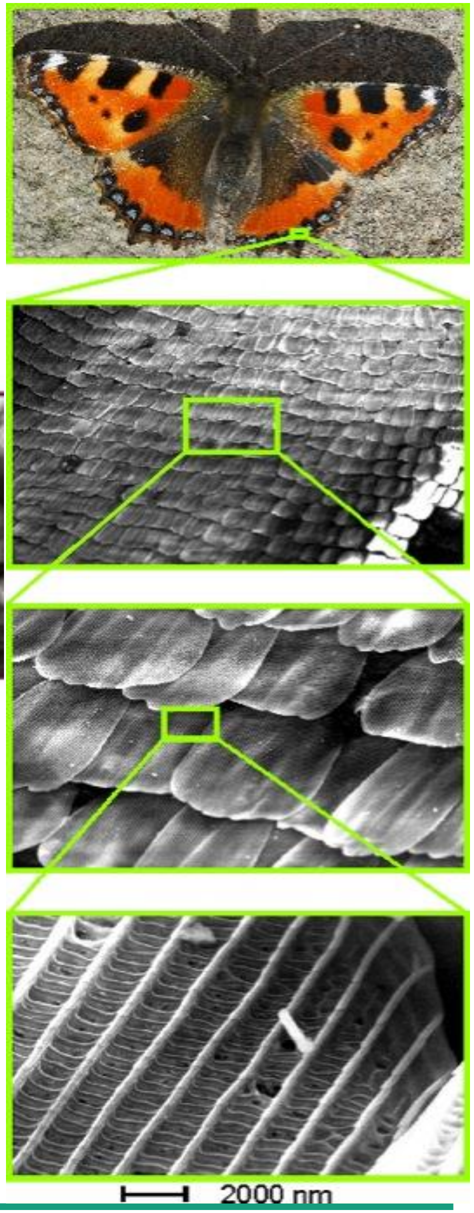
- ⇒ Cost-effective color sensors are needed for high-volume illumination applications

1. Introduction
Technologies for color sensors

- Various filter technologies are well established:
  - Absorption filters, e. g. red, green, blue pigmentfilters (Bayer filter)
  - Dielectric filters (thin film filters, interference filters)
  - In spectrometers: prisms, gratings, tunable filters

- Are there other approaches …
  - … feasible using CMOS semiconductor technolgy?
  - … enabling highly integrated sensors at low cost?

2. Methodology
Nanostructures in nature



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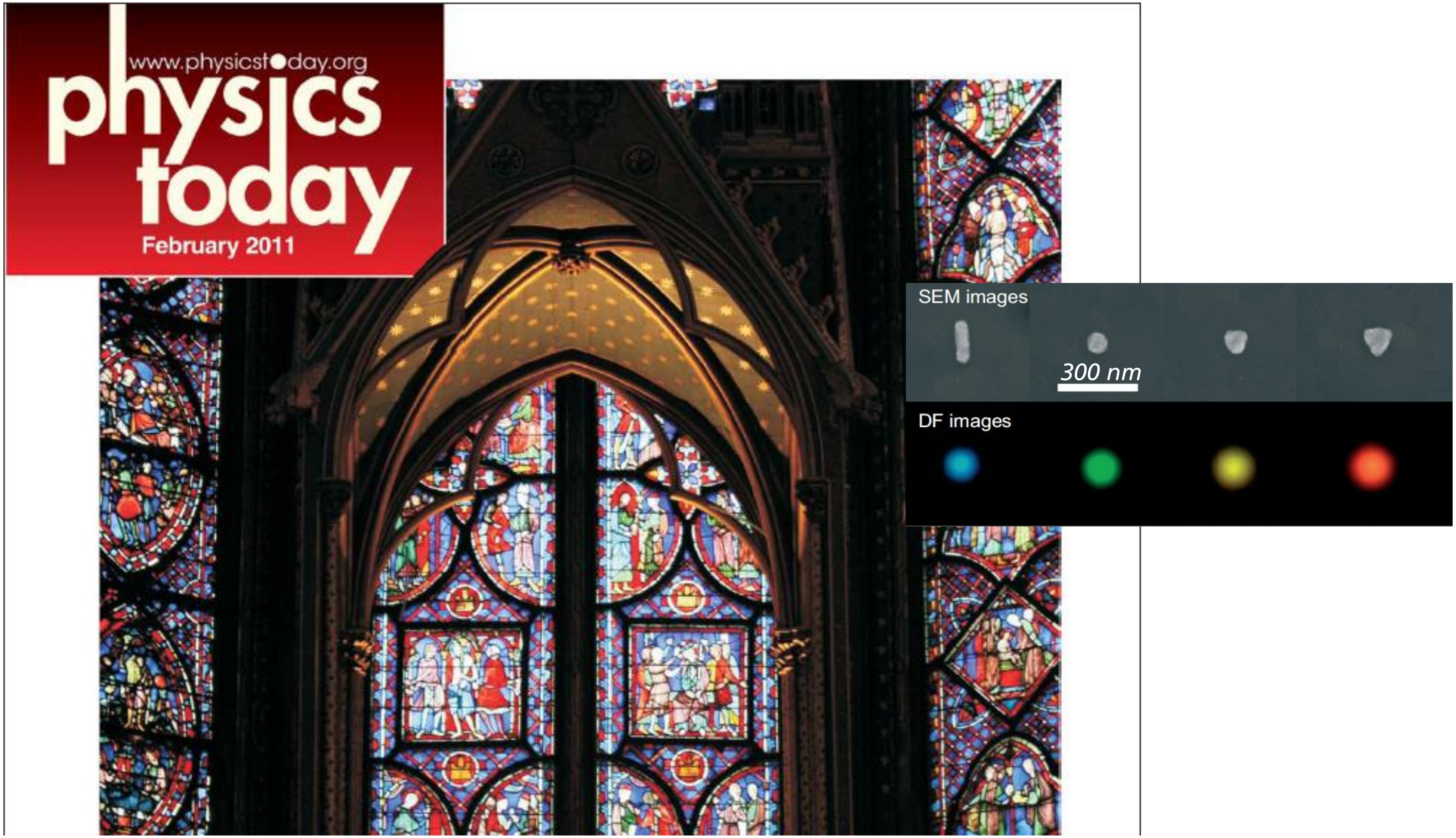
2. Methodology
Nanostructures in art and science



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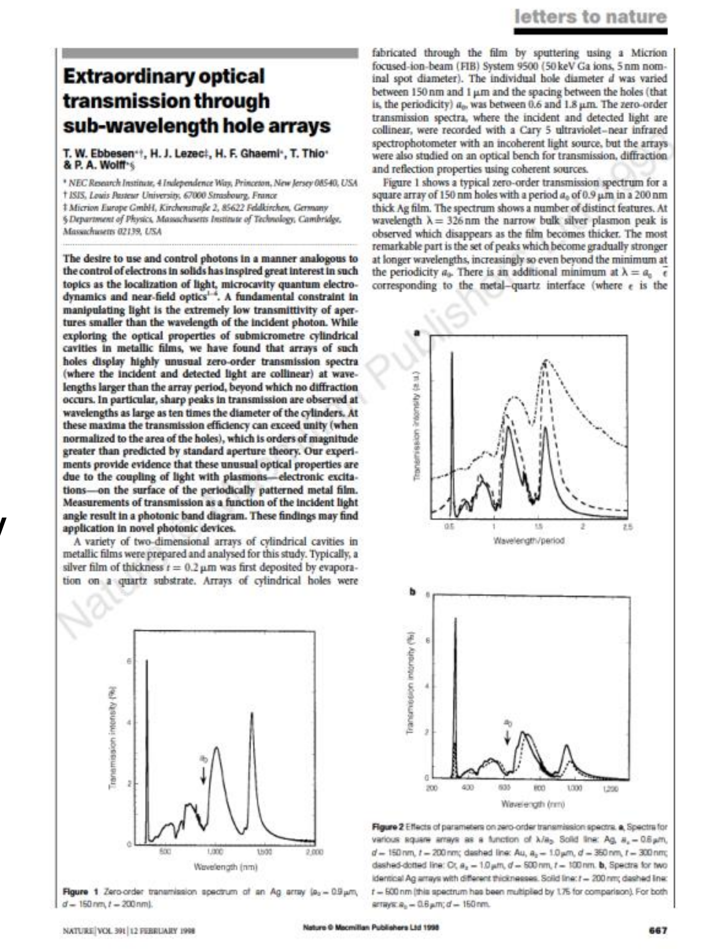
2. Methodology
Surface plasmon resonances

- Perforated metal films (»hole arrays«)
  ⇒ resonances of oscillating electrons, »enhanced transmission« (Ebbesen 1998)
- Color and multispectral sensors feasible
- Resonance wavelength can be tailored by geometry at constant layer thickness
  ⇒ ideal for CMOS!



Extraordinary optical transmission through sub-wavelength hole arrays

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The desire to use and control photons in a manner analogous to the control of electrons in solids has inspired great interest in such topics as the localization of light, microcavity quantum electrodynamics and near-field optics[1–4]. A fundamental constraint in manipulating light is the extremely low transmittivity of apertures smaller than the wavelength of the incident photon. While exploring the optical properties of submicrometre cylindrical cavities in metallic films, we have found that arrays of such holes display highly unusual zero-order transmission spectra (where the incident and detected light are collinear) at wavelengths larger than the array period, beyond which no diffraction occurs. In particular, sharp peaks in transmission are observed at wavelengths as large as ten times the diameter of the cylinders. At these maxima the transmission efficiency can exceed unity (when normalized to the area of the holes), which is orders of magnitude greater than predicted by standard aperture theory. Our experiments provide evidence that these unusual optical properties are due to the coupling of light with plasmons—electronic excitations—on the surface of the periodically patterned metal film. Measurements of transmission as a function of the incident light angle result in a photonic band diagram. These findings may find application in novel photonic devices.

A variety of two-dimensional arrays of cylindrical cavities in metallic films were prepared and analysed for this study. Typically, a silver film of thickness $t = 0.2\,\mu m$ was first deposited by evaporation on a quartz substrate. Arrays of cylindrical holes were fabricated through the film by sputtering using a Micrion focused-ion-beam (FIB) System 9500 (50 keV Ga ions, 5 nm nominal spot diameter). The individual hole diameter d was varied between 150 nm and 1 μm and the spacing between the holes (that is, the periodicity) a_0, was between 0.6 and 1.8 μm. The zero-order transmission spectra, where the incident and detected light are collinear, were recorded with a Cary 5 ultraviolet–near infrared spectrophotometer with an incoherent light source, but the arrays were also studied on an optical bench for transmission, diffraction and reflection properties using coherent sources.

Figure 1 shows a typical zero-order transmission spectrum for a square array of 150 nm holes with a period a_0 of 0.9 μm in a 200 nm thick Ag film. The spectrum shows a number of distinct features. At wavelength $\lambda = 326$ nm the narrow bulk silver plasmon peak is observed which disappears as the film becomes thicker. The most remarkable part is the set of peaks which become gradually stronger at longer wavelengths, increasingly so even beyond the minimum at the periodicity a_0. There is an additional minimum at $\lambda = a_0\sqrt{\epsilon}$ corresponding to the metal–quartz interface (where ϵ is the

Figure 1 Zero-order transmission spectrum of an Ag array ($a_0 = 0.9\,\mu m$, $d = 150$ nm, $t = 200$ nm).

Figure 2 Effects of parameters on zero-order transmission spectra. **a**, Spectra for various square arrays as a function of λ/a_0. Solid line: Ag, $a_0 = 0.6\,\mu m$, $d = 150$ nm, $t = 200$ nm; dashed line: Au, $a_0 = 1.0\,\mu m$, $d = 350$ nm, $t = 300$ nm; dashed-dotted line: Cr, $a_0 = 1.0\,\mu m$, $d = 500$ nm, $t = 100$ nm. **b**, Spectra for two identical Ag arrays with different thicknesses. Solid line: $t = 200$ nm; dashed line: $t = 500$ nm (this spectrum has been multiplied by 1.75 for comparison). For both arrays: $a_0 = 0.6\,\mu m$; $d = 150$ nm.

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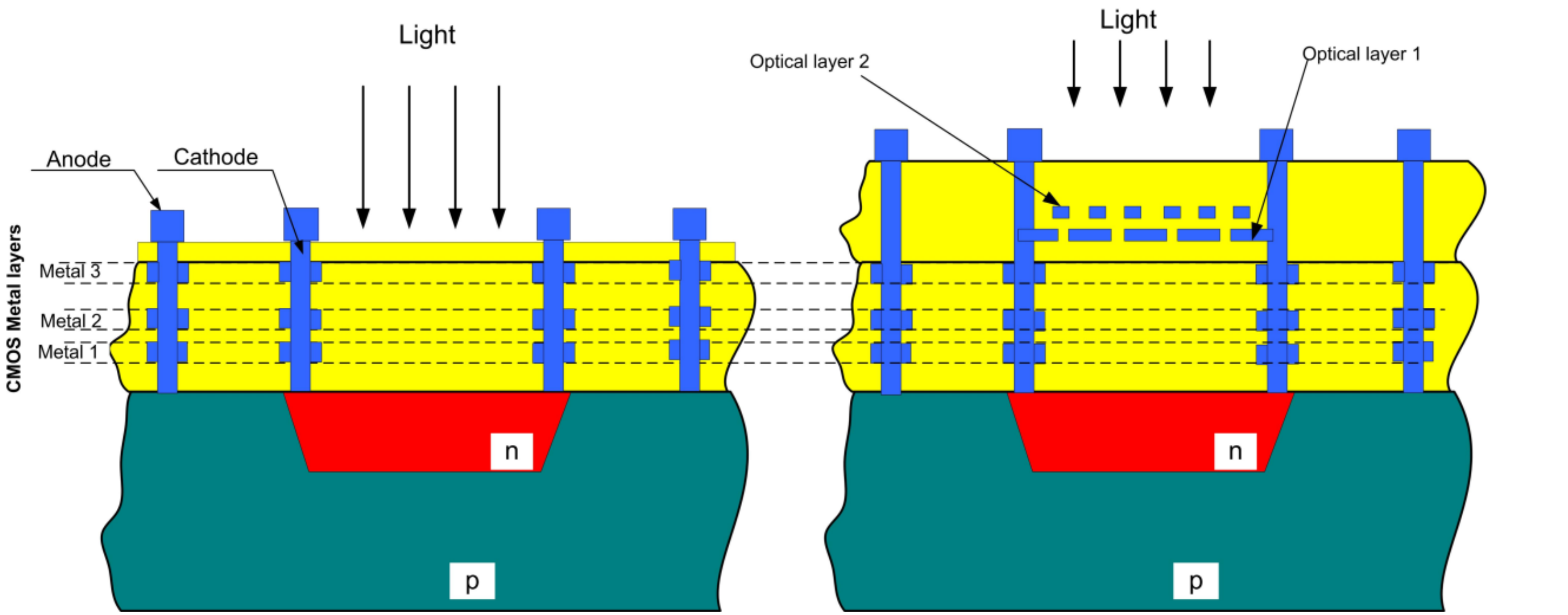
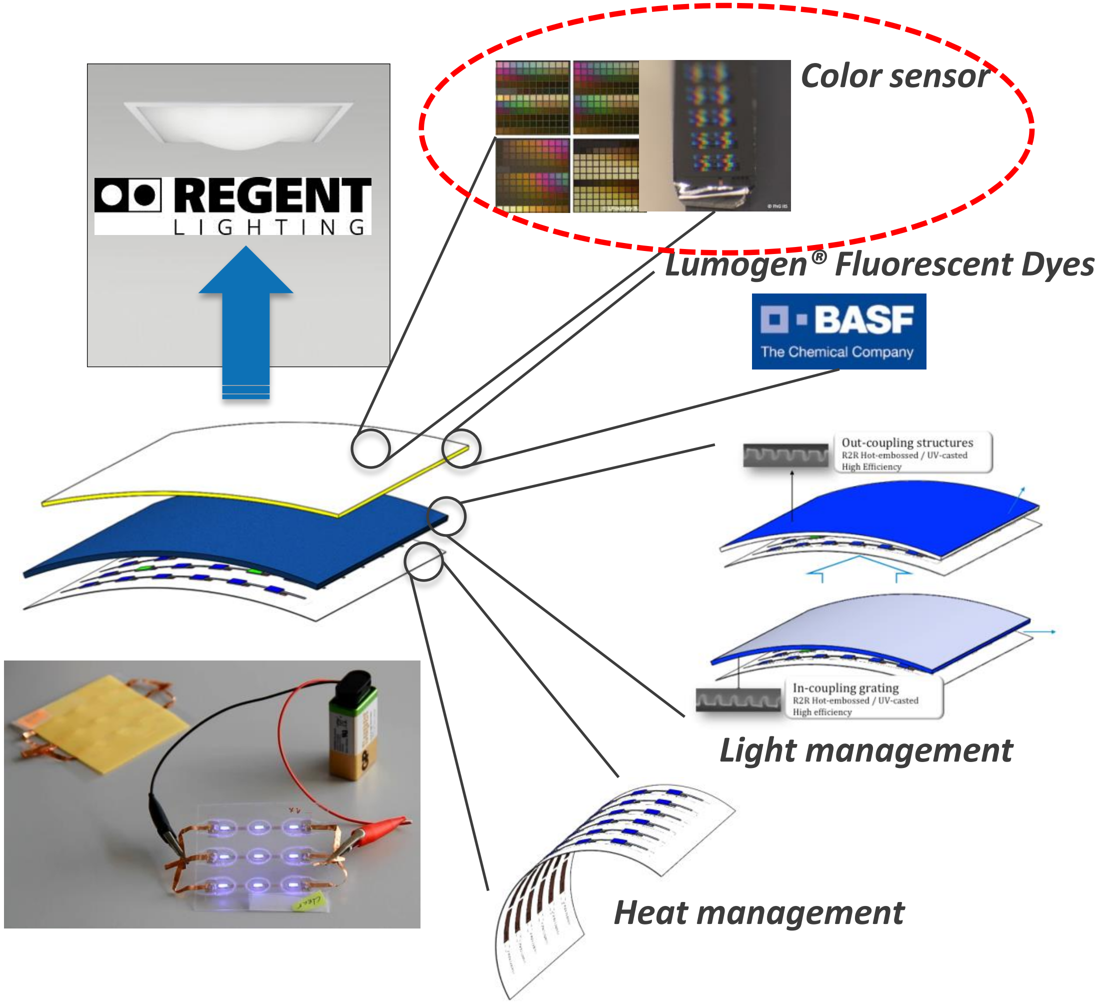
2. Methodology
Nanostructures as spectral filters

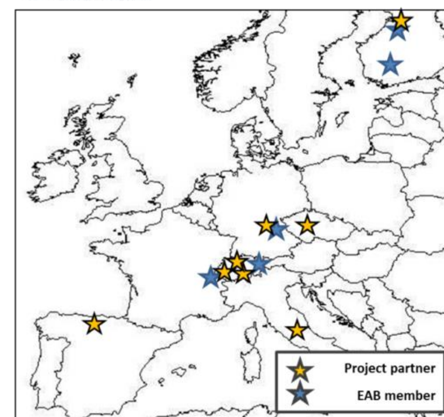


Conventional CMOS photodiode

Photodiode with added metal layers as on-chip optical filters

3. EU-funded project »LASSIE-FP7«
Large Area Solid State Intelligent Efficient luminaires

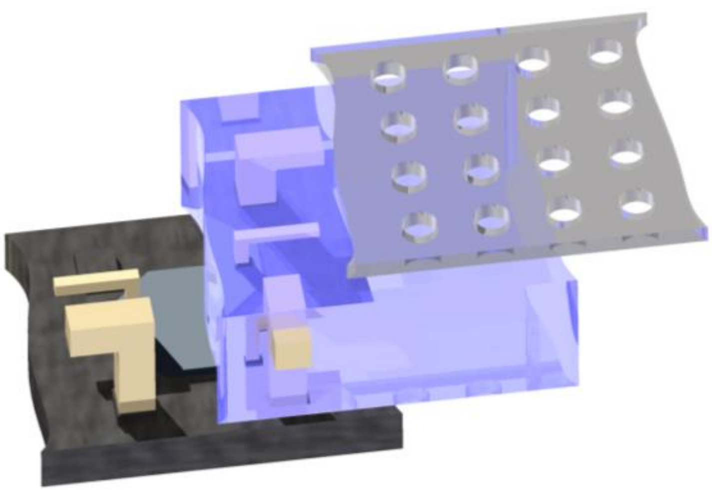


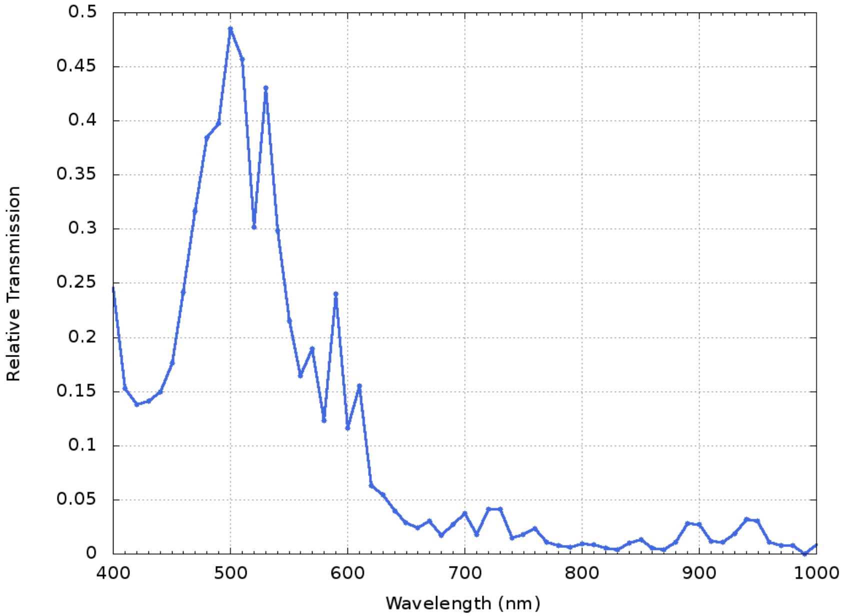


Property of the LASSIE-FP7 Consortium

3. »LASSIE-FP7«
CMOS nanostructures as color filter

- Hole arrays with a typical period of 200 – 400 nm and »enhanced transmission« due to plasmon resonances are used
- Filter wavelength is tailored by varying the geometry





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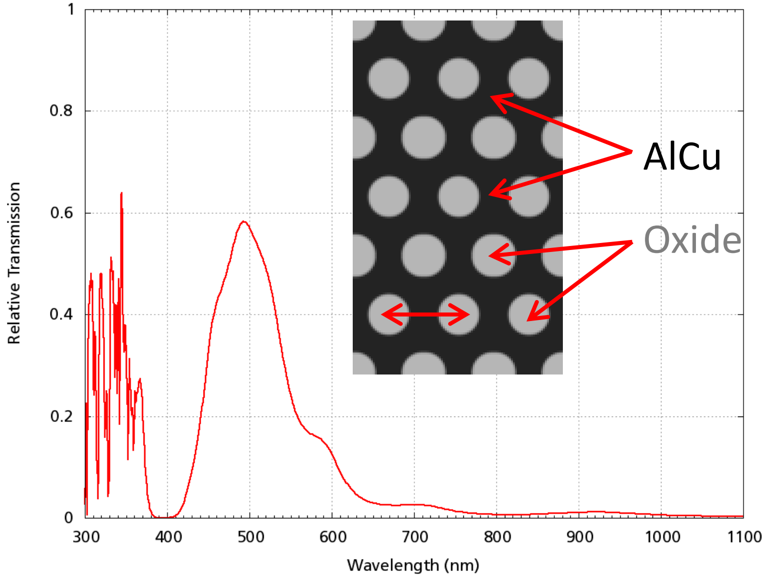
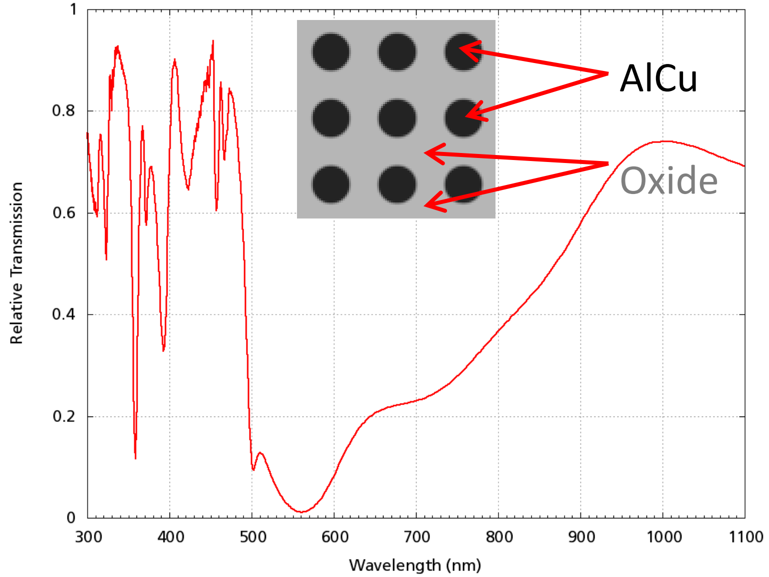
3. »LASSIE-FP7«
Simulation of metallic nanostructures

Simulation: green filter (band pass)



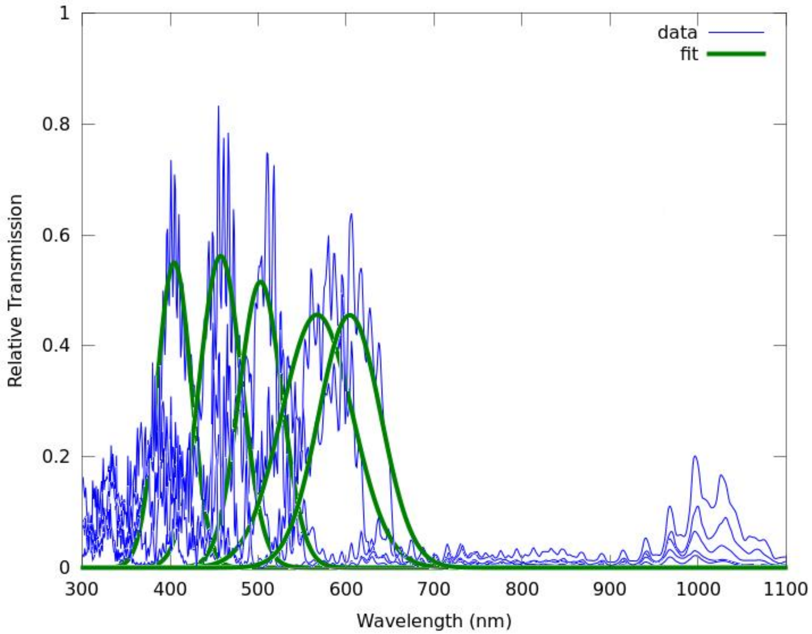
Spectral transmission of a hole array
(period 280 nm)

Simulation: blue filter (low pass)



Spectral transmission of an island array
(period 320 nm)

3. »LASSIE-FP7«
Simulation of metallic nanostructures



Spectral filters covering the wavelength range from 400 – 600 nm

- Example for a filter set of color/multispectral sensor
- Typically, 8-16 spectral channels are used
- More robust than color sensors with 3 channels, more spectral information

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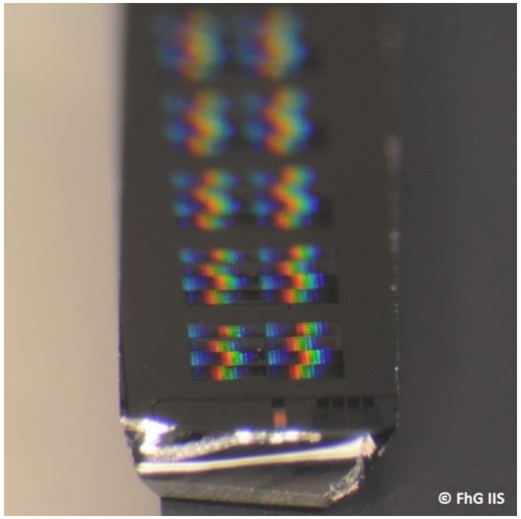
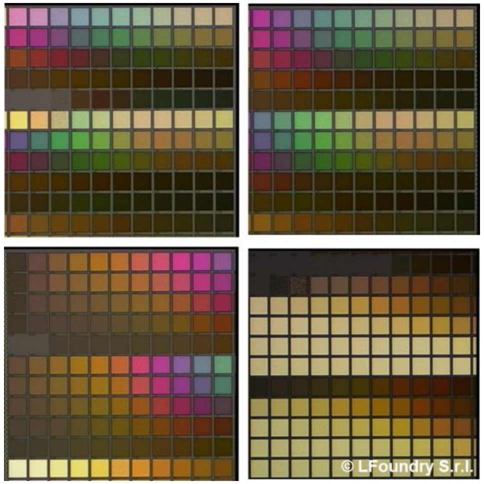
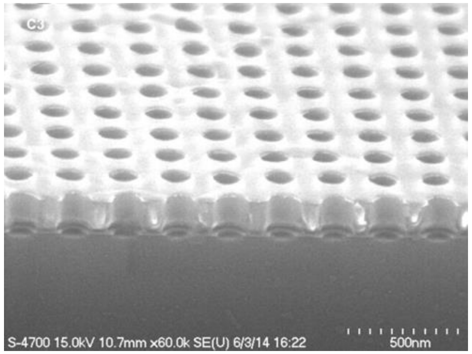
3. »LASSIE-FP7«
Fabrication of CMOS color sensor



LFoundry chip

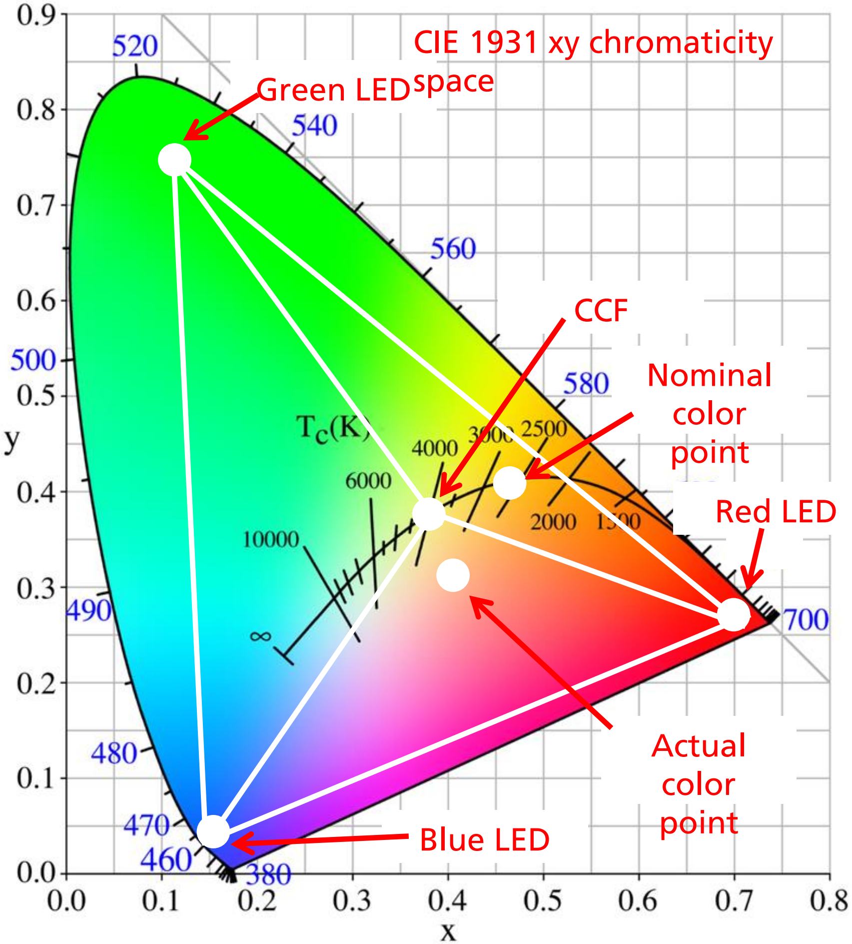


Optical images from MPW



SEM image of nanostructure

3. »LASSIE-FP7«
Color tuning concept



- Colour conversion film optimised for 4000 K (main application)
- Red + green + blue LED for colour tuning
- Target tuning range: CCT 2700 – 6500 K
- Feedback control algorithm tunes from actual to nominal colour point iteratively

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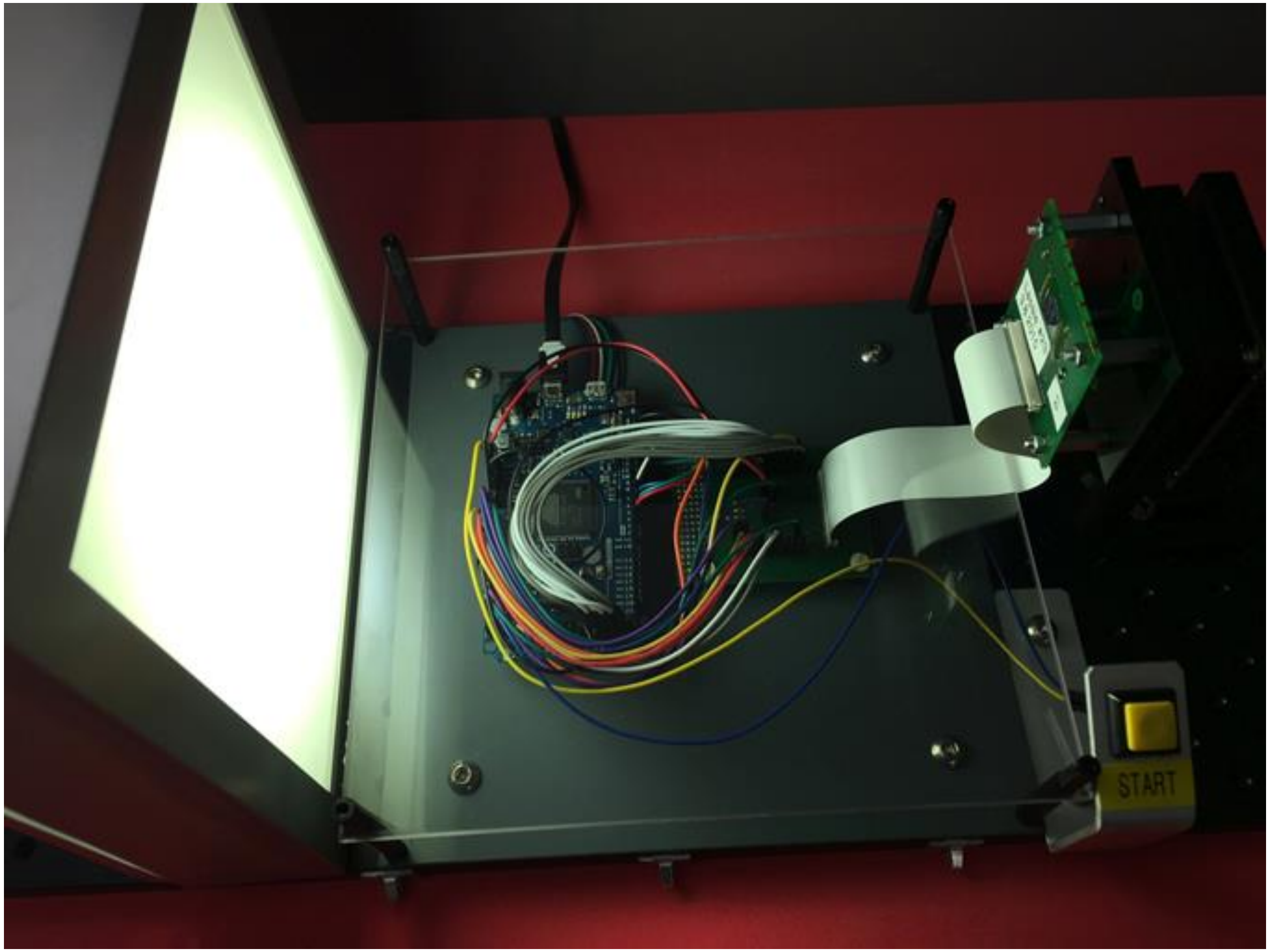
3. »LASSIE-FP7«
Color feedback demo



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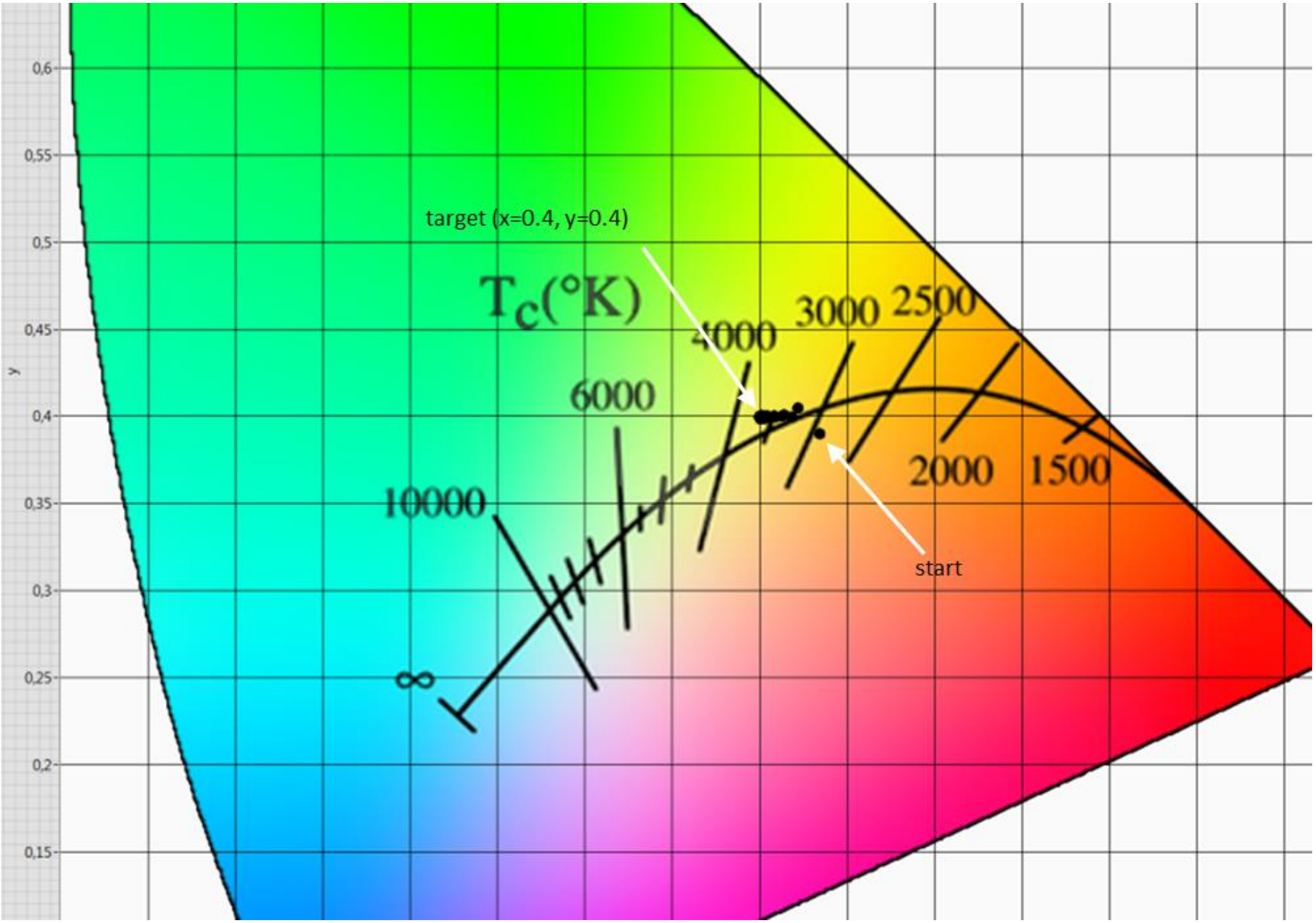
3. »LASSIE-FP7«
Color feedback demo



3. »LASSIE-FP7«
Color feedback demo

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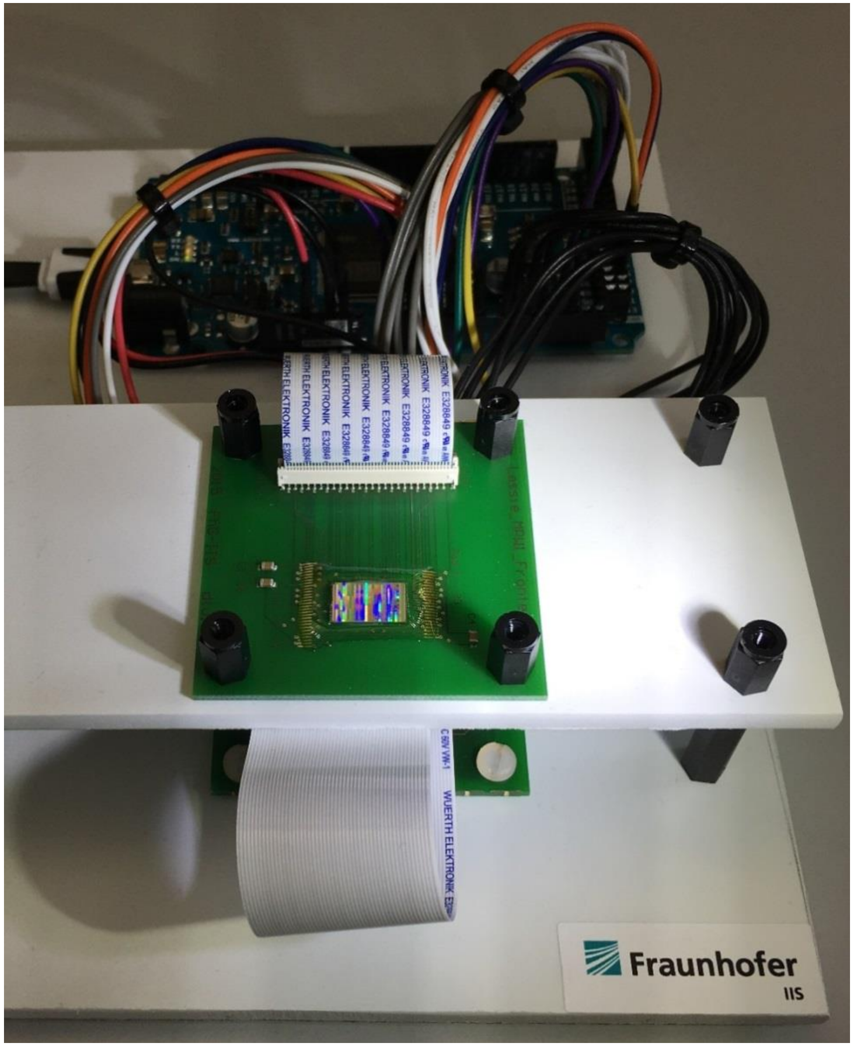
3. »LASSIE-FP7«
Color sensor demo at the LASSIE booth

- Multispectral sensor
- Microcontroller board for sensor configuration and data acquisition
- Live sensor data at different colored illumination conditions



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4. Conclusions

- High-quality LED lighting systems benefit from color feedback sensors
- Photodiodes with on-chip colour and multispectral filters can be fabricated in high volume at low cost using a CMOS process
- Implementation of color feedback loop in order to stabilize the chromaticity point of LED luminaires demonstrated in »LASSIE-FP7«