

Near-infrared spectral sensing: The invisible colours of light

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* Conflict of interest statement: Some of the authors are shareholders of MantiSpectra bv

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Eindhoven University of Technology

Engineering university (physics, chemistry, electrical engineering, ...)



- English is official language
- Ranks 1-2nd worldwide in industrial collaborations
- High-tech hotspot in Europe
- Thousands of graduates/PhD hired yearly

Plan for this talk

- Spectroscopy and spectral sensing
- A simple hardware for spectral sensing
- What can we do with a spectral sensor?

Spectral sensing

We all use colour information to measure materials...





https://www.aao.org/eye-health/anatomy/cones

- About 6 millions cone cells
- 3 types: "red", "green", "blue"

Spectral sensing

We all use colour information to measure materials...



How does it work?

www.wikipedia.com

- Information from three cone types is combined as "colour"
- We "learn" (by experience) what a given colour means

What do we see? Diffuse reflection

Diffuse reflection: Light scattered multiple times by inhomogeneities comes out of sample in all directions



What our eyes see is mostly diffuse reflection

Origin of colour information

Diffuse reflection is affected by absorption of light in the material \Rightarrow Its spectrum carries information on the absorption spectrum



https://omlc.org/news/may99/rd/index.html S. Weng et al., https://doi.org/10.1080/10942912.2020.1716793

\Rightarrow Origin of colour!

What produces the absorption?

Molecular bonds can vibrate at specific frequencies



Electromagnetic waves at those frequencies (or multiples) can excite vibrations \Rightarrow Transfer energy to material \Rightarrow Are absorbed

8 www.phys.org https://en.m.wikipedia.org/wiki/File:Animated-mass-spring.gif



Near-infrared spectroscopy



Can we do better than the human eye?

The human eye measures only three wavelength bands. A **mantis shrimp** can measure up to 12 wavelength bands!



Gary Cranitch, Queensland Museum

Can we do better than the human eye?

A **spectrometer** can measure >1000 wavelengths



Spectroscopy: A 200 years-old technology **TU/e**

11 www.edmundoptics.eu www.metrohm.com

The future: *Embedded* spectroscopy

- Spectroscopy as part of any production system and consumer appliance
- Only possible at <10\$ cost levels
- Requires scalable semiconductor fabrication technology



12 deutz-fahr.com; shutterstock.com; coolblue.nl



Approaches for NIR integrated spectrometers

How to integrate a NIR spectrometer on a semiconductor chip?

Ex. Waveguide-based grating + detector array:



13 X. Ma et al., DOI: <u>10.1109/JPHOT.2013.2250944</u>

BUT: This approach requires to couple light in a waveguide! ⇒ Not suitable for diffuse reflectance

"Optical invariant": The product of image size and angular aperture cannot be changed by an optical system

Our approach: A spectral chip

An array of detectors with integrated filters:

- Each detector measures a different part of spectrum
- Efficient coupling from free space



Resonant-cavity-enhanced detector structure



Fabrication process: III-V on silicon

Integrating bottom mirror in III-V detector:

- Bonding III-V wafer with Ag on Si
- Process n-inch III-V on n-inch Si





Responsivity detector array



Hakkel et al., Nature Communications 2022van Klinken et al., APL Photonics 2023

- One pixel \rightarrow 2-3 peaks
- Tuning 900-1650 nm
- Linewidth \approx 60 nm FWHM
- Responsivity ~0.12-0.3 A/W
 Envelope:



Questions?



Part 2: What can we do with a spectral sensor?



From *spectrometry*...



From spectrometry to spectral sensing



The sensing module

Spectral chip





Chip carrier + electronic readout



- Light source
- Amplif.+ADC
- Connectivity

Sensing module



Applications











Measurement of moisture in rice grains

Arborio



Measurement of moisture in rice grains



Partial Least Squares (PLS) regression

Ou et al., Sensors 22, 7627 (2022)

Classification of plastics



Test set prediction: Accuracy = 100 %



Ou et al., Sensors 22, 7627 (2022)

Measurement of fat and protein in milk

And more!

Classification of coffee

Classification of illicit drugs

Kranenburg et al., Talanta 245, 123441 (2022)

What else can you measure?

The spectrum is often used to code other information

TU/e

bbc.com

What else can you measure?

The spectrum is often used to code other information

- Spectral transduction: Stable against power fluctuations, is not affected by propagation
- Need to measure spectral shifts at the sub-nm level
- For this we need a spectrometer, right?

30 Image adapted from Imas et al., Sensors 20, 6289 (2020)

Our approach: Multispectral read-out

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"Multispectral readout" of optical resonances

Our approach: Multispectral read-out

Wavelength measurement

- Minimum imprecision = 5 pm
- More precise than OSA + fitting
- \Rightarrow Suitable for reading out (bio)sensors

Conclusions

Spectral sensors are not spectrometers, but they can *replace* spectrometers for:

- Near-infrared spectroscopy
- High-resolution optical sensing

