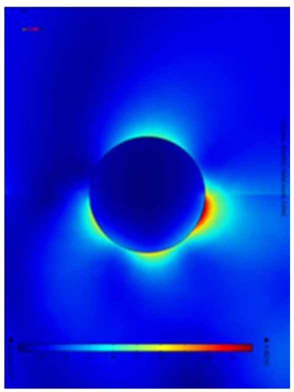


Plasmoniset infrapunailmaisimet

MATINEn tutkimusseminaari, 18.11.2015
Kirsi Tappura, Tekn. Toht., Dos.
VTT, Älykkäät anturijärjestelmät

Plasmoniset infrapunailmaisimet

- Toteuttaja:
  - Teknologian tutkimuskeskus VTT Oy
    - Älykkäät anturijärjestelmät

- MATINEn rahoitus hankkeelle:
  - 69 920 €
- Muut rahoittajat
  - VTT

Outline

Background

Scientific challenge

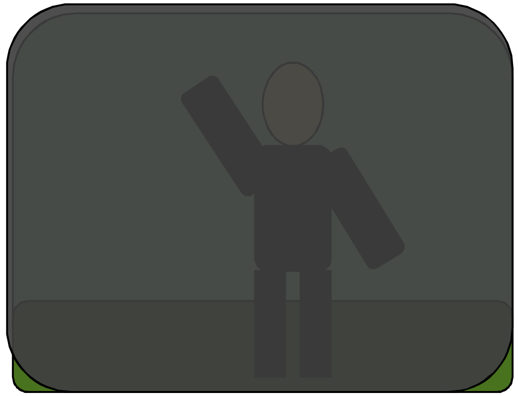
Objectives and tools

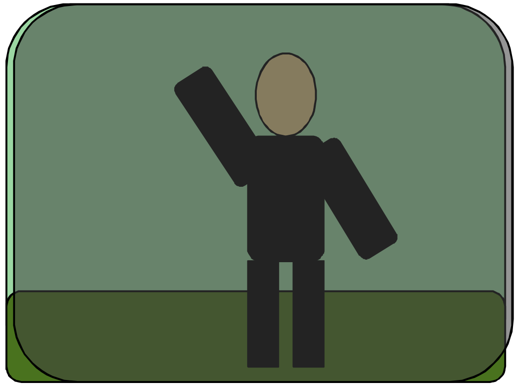
Results

Exploitation potential of the results

Infrared (IR) detectors in military and security applications

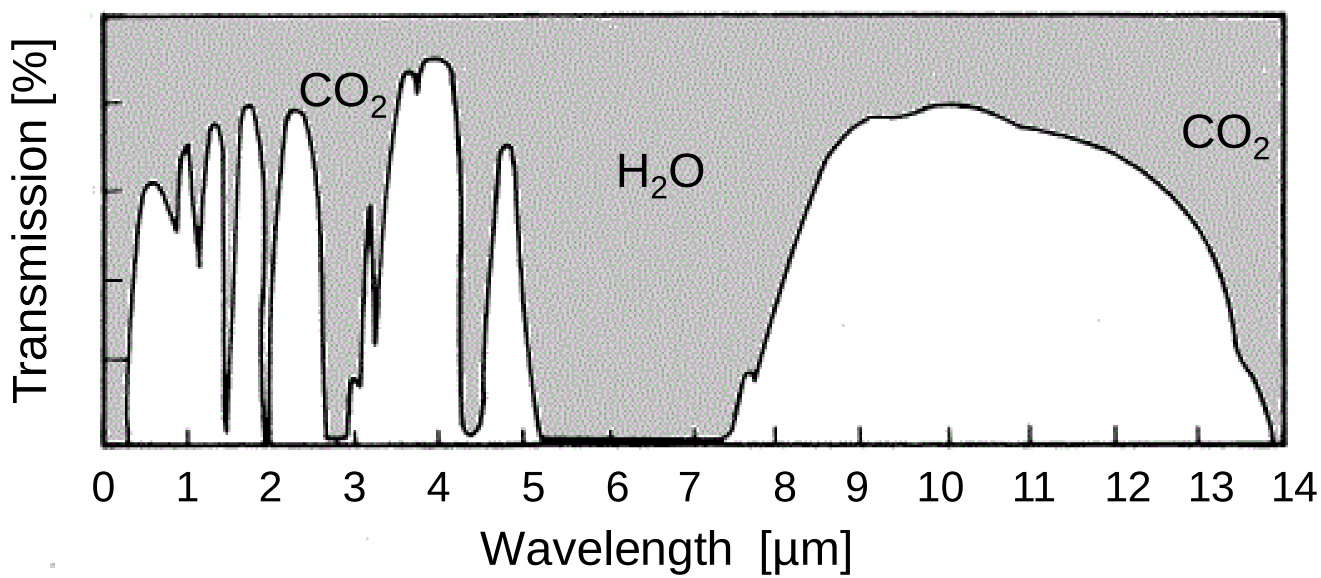
- IR detectors provide the means to detect objects under poor visibility conditions (dark, smoke, fog).
- Infrared radiation is emitted by all objects above absolute zero → possible to see the environment without illumination by passive thermal imaging.
- The characteristic absorption frequencies of many chemical species are within the IR range → remote sensing and stand-off detection of the critical chemical substances





The most important wavelength bands

- are the so called atmospheric windows (e.g. 3-5 µm and 8-12 µm) where the absorption by H_2O, CO_2 etc. is low and, thus, the transparency high.



Development of infrared detectors/systems

Thermal detectors

1940 — **PbS**, PbSe

1. gen. scan to image

1950 — Ge:X, InSb

HgCdTe

2. gen. focal plane arrays + readout-IC to image

1960 — PbSnTe, Si:X

Si:X/CCD, PtSi/CCD

1970 — HgCdTe/CCD

HgCdTe/SPRITE

InGaAs

1980 — QWIP

3. gen. FPA + ROIC to image

Bolometer FPAs, 2-colour **HgCdTe FPAs**, Pyroel. FPAs

1990 — Multi-state det., 2-color QWIP FPAs, Type-II superlattice, QDIP

MEMS FPAs, 4-color FPAs, 2-color type-II FPAs, nBn det.

2000 — 2-color megapixel FPAs, 147 megapixel FPAs

4. gen. FPA + ROIC to image

2010 — Trapping detectors

2020

Adapted from Martyniuk et al. 2014

The needs and the scientific challenge

- In general, there is a continuous demand for higher performance:
  - higher **sensitivity**, better thermal **resolution** (higher signal-to-noise ratio), fast response, increase in **pixel density**, multispectral imaging, and **cost reduction** especially in the IR imaging **array systems**.
  - need to develop **high-performance sensors with less cooling**
- Thus, in spite of the widely available commercial photonic and thermal detectors, there is still a need especially for IR imaging array systems that combine:
  - a reasonable price,
  - convenient operation, and
  - excellent performance.

Objectives of the project

- **To investigate the feasibility to improve the functionality of IR detectors by inclusion of plasmonic nanostructures.**

→ **to find novel solutions for**

  - enhancing photocurrents or photoresponsivity (signal/noise ratio) and sensitivity
  - engineering the spectral response

The problem is approached mainly by theoretical and computational means.

- **2015**:
  - Detector types selected to be as transferrable as possible
  - Plasmonic structures for enhanced scattering into the detector
  - Plasmonic structures to exploit the local field enhancements
- **2016**:
  - Influence of plasmonic structures on the detector characteristics

Plasmons

- Plasmon: a harmonic oscillation of a free electron gas at a certain carrier density dependent frequency in metal-like materials
- An electromagnetic field coupling to a plasmon → hybirid excitation → resonance → plasmon polariton
- Such coupling occurs at the a metal-dielectric interface → surface plasmon polariton (SPP)
- In a **propagating** surface plasmon polariton (**PSPP**) the electromagnetic field is confined in 1D or 2D.
- **In the localized** surface plasmon polaritons (**LSPP**) the electromagnetic field is confined in 3D, e.g. in nanoparticles.
- At a resonance the lifetime of photons is increased → The local amplitude of the electromagnetic field is enhanced.
- The resonance frequency of LSPP defined by the material properties, dimensions and shapes of the nanostructures, as well as by the properties of the environment

$$\omega_p = \sqrt{\frac{ne^2}{m\epsilon_0}}$$

$$\omega_{sp} = \omega_p / \sqrt{2}$$

$$\omega_{lsp} = \omega_p / \sqrt{3}$$

Known ways to enhance the absorption of electromagentic radiation in material by plasmonics

- Enhancing scattering cross-section:
  - reduce the reflection losses (“antireflection coating”)
  - enhance the optical path of photons in the active layer such that their probability for absorption is enhanced
- Light trapping
- Enhancing the electromagnetic near-field → confined absorption in the desired volume
- Spectrally redistribute the electromagnetic radiation
  - localized surface plasmon polaritons may decay into energetic, “hot” electrons
  - by enhancing the efficiency of up-converters or down-converters if such elements are incorporated in the absorber material (losses a disadvantage)

→ Plasmonics gives more freedom to optimize/improve IR detector designs (thickness, speed, carrier collection efficiency, etc.)

Detector materials in the plasmonic model systems studied

Absorbers:

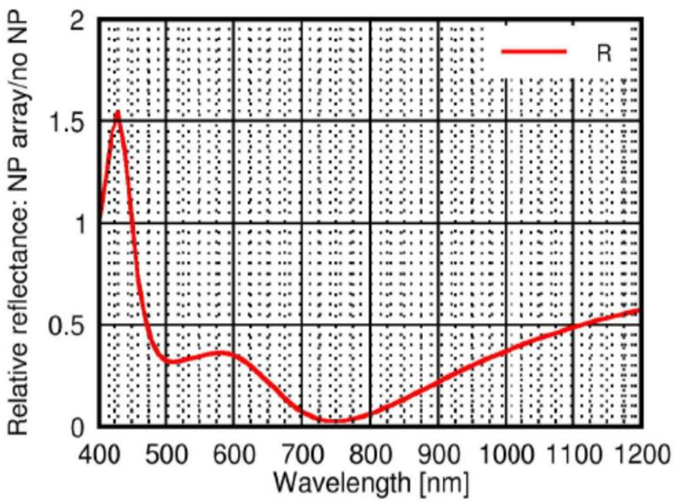
- Si (near IR)
  - E_g = 1.1 eV --> wavelength up to ~ 1.13 µm
- PbS (short-to-mid IR)
  - E_g = 0.37eV → wavelengths up to ~ 3.35 µm
- $Hg_{1-x}Cd_xTe$ (long-wave IR)
  - E_g ~ 0.083eV for x = 0.2 (77 K) → wavelengths up to ~ 15 µm

Materials for plasmonic structures:

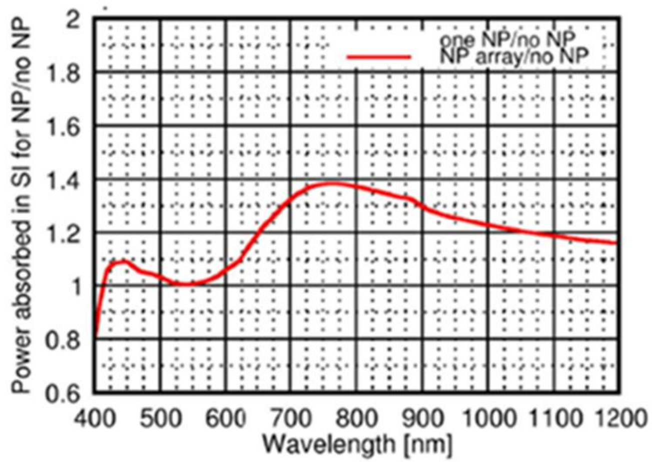
- Metals
- semiconductors with appropriate doping

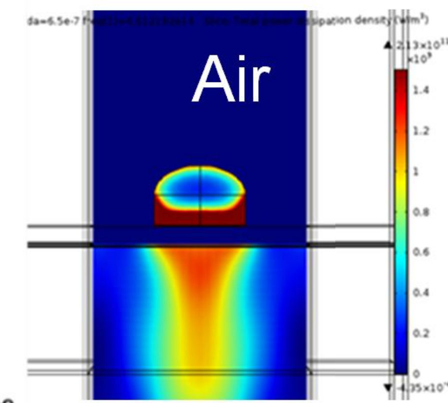
Plasmonic nanostructures for visible and near-IR regions

Plasmonic silver nanoparticles (NP) on silicon



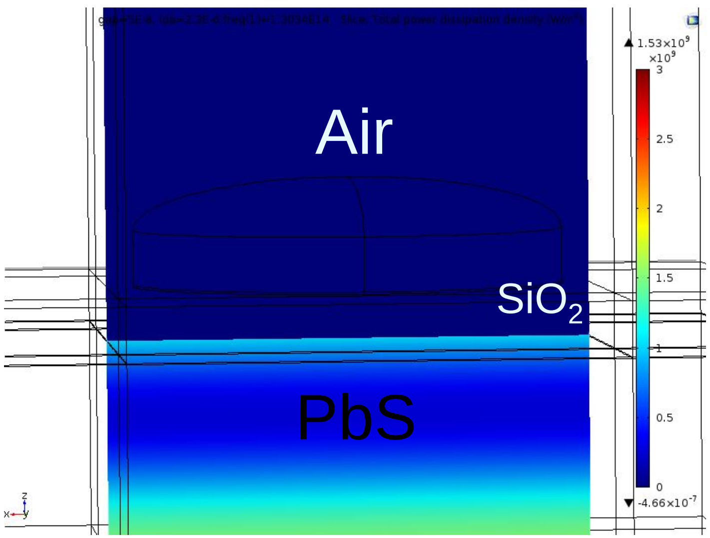
Absorption enhancement



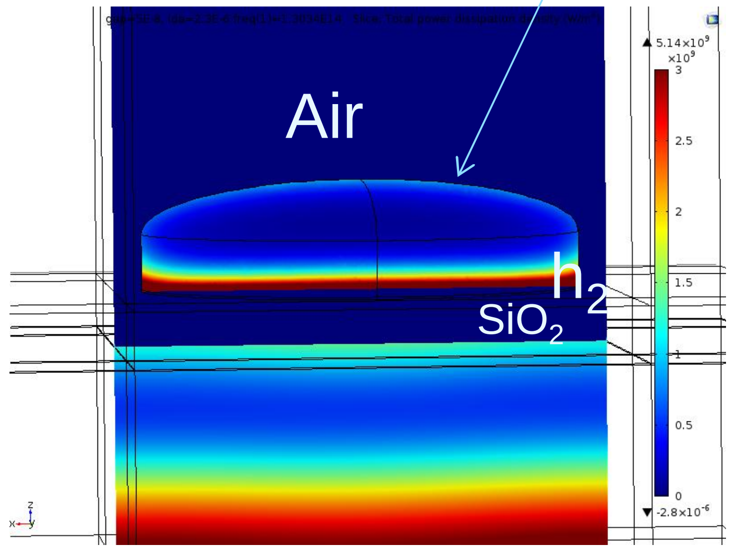


Absorption in PbS near 2 µm

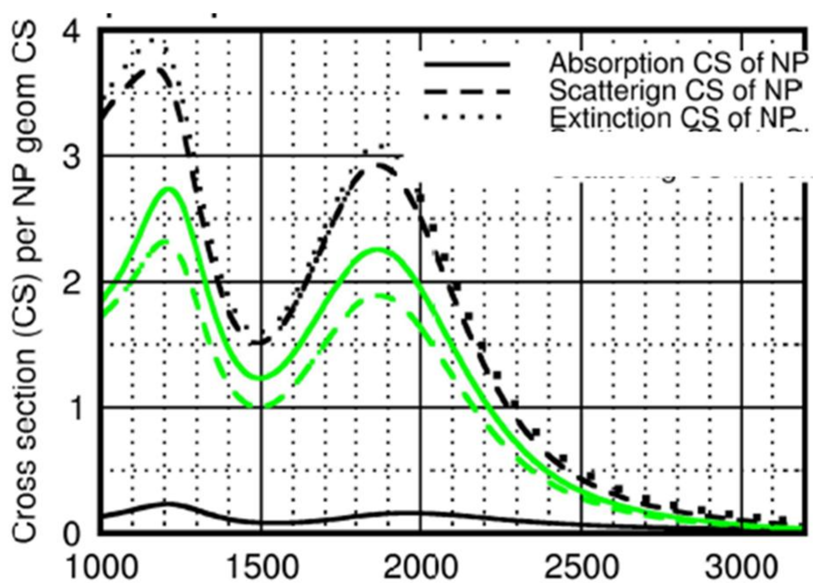
No plasmonics



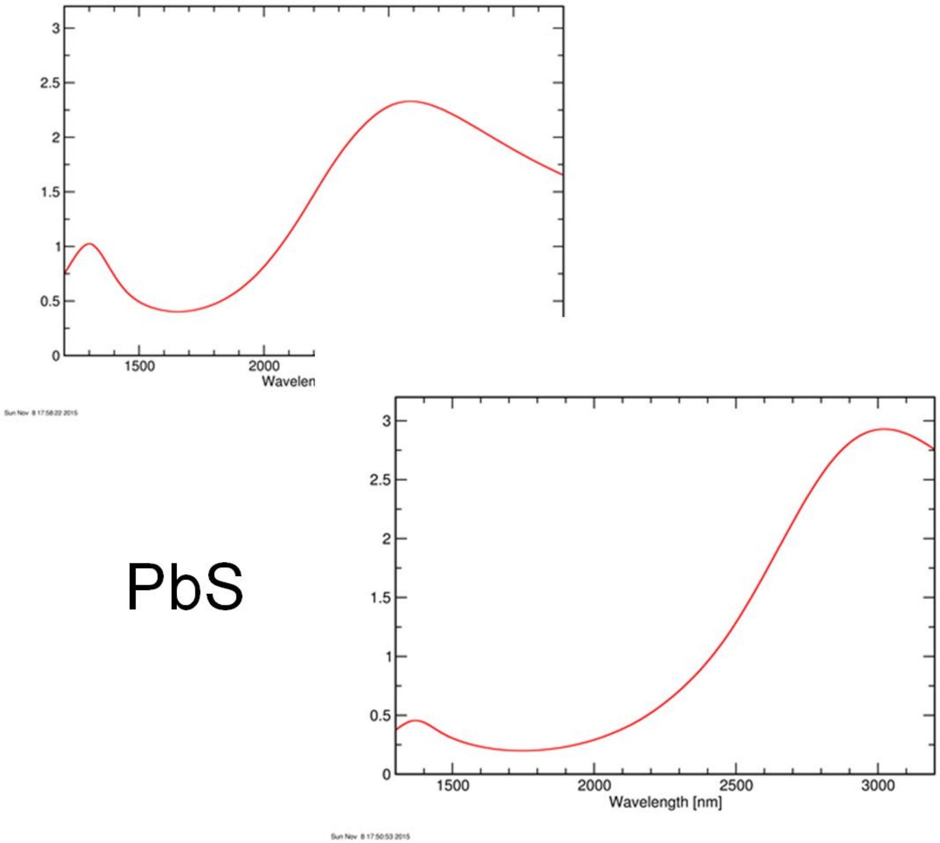
Plasmonic nanoparticle on the absorber



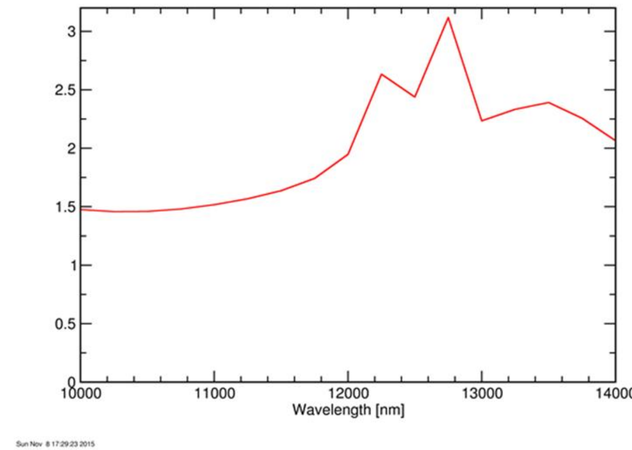
Scattering, absorption and extinction cross sections for a single nanoparticle on PbS (an example)



Examples of plasmon-induced absorption enhancement in the absorber materials



PbS



HgCdTe

Summary of the main results

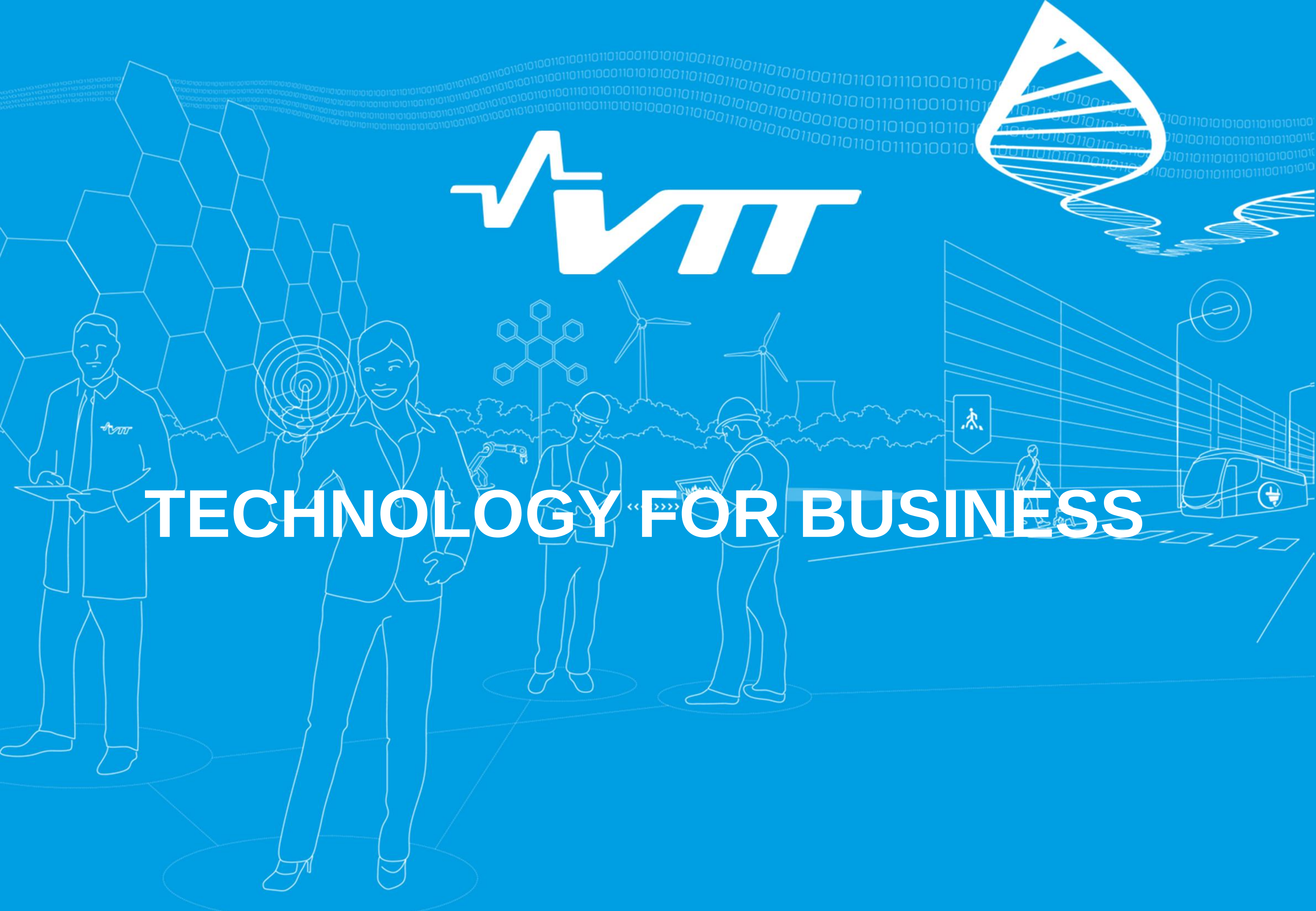
- Over three-fold absorption enhancements have been computationally demonstrated for PbS and HgCdTe detectors near the 3 µm and 12 µm wavelength regions, respectively. Even higher enhancements have been obtained at narrow bands in Si detectors in the near-IR regions.
- The enhancements are due to the interplay of the plasmonic and detector structures (lateral structures, layers, materials, etc.), enhanced scattering of light into the absorber, as well as the enhanced electromagnetic field in the absorber.
- Shown to be able to enhance selected wavelength and suppress others → the spectral features can be tuned

Exploitation of the results

- Research plan for year 2016: to study the influence of plasmonic structures on selected detector characteristics
- The results are already so far very promising suggesting that plasmonics nanostructures may be used in the development of future high-performance IR detectors with enhanced functionalities.
- The suggested methods also provide high potential for cost reduction in high-performance IR imaging systems.
- Considering the fast development of high-throughput nanofabrication techniques

  → plasmonic nanostructures in relatively low-cost devices seems feasible in the near future (note: IR vs. visible)

  → can be introduced into a standard IR detector/imaging camera fabrication process without significant additional efforts


TECHNOLOGY FOR BUSINESS