METRO SUSTAINABILITY 2024

Fiber Optic Sensing platforms for Continuous and Sustainable Soil Water Content Monitoring

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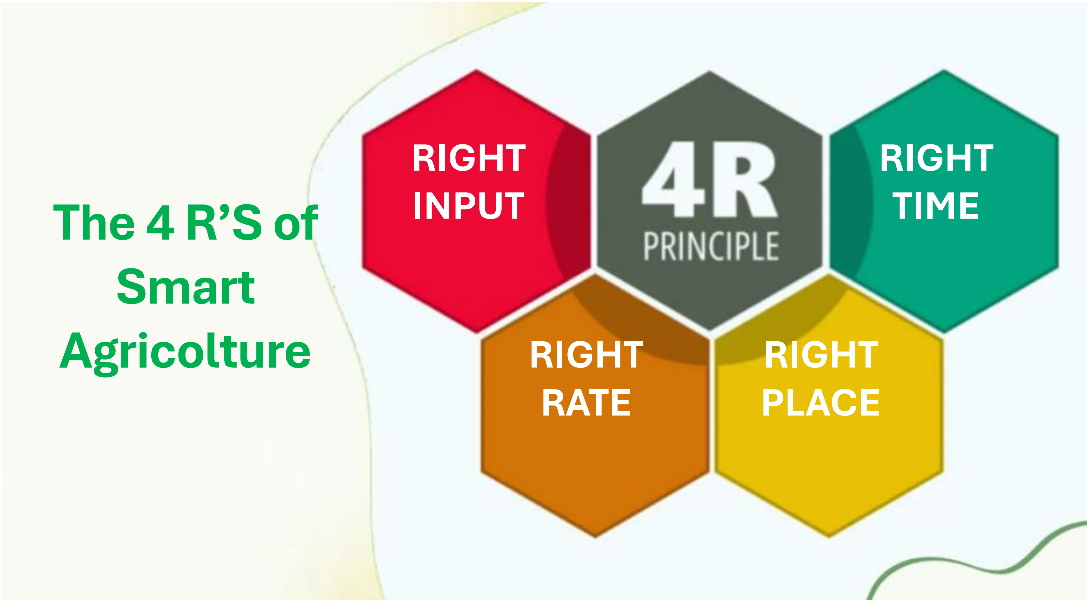
Smart agriculture

- Climate change and global warming have a significant impact on agriculture
- **Smart agriculture** combines information technology and agricultural science to improve the management of traditional practice



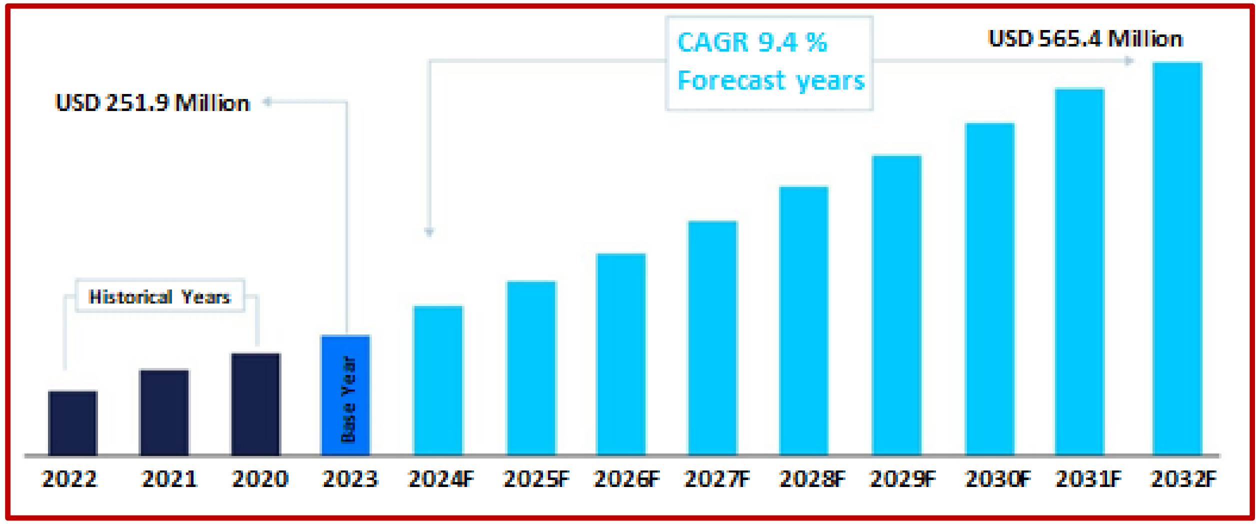
The importance of soil water content monitoring

Overcoming the impact of climatic changes and the limited availability of water resources on agricultural practices

Mitigating negative environmental, economic, and social impacts due to sudden and heavy floods and landslides

Guaranteeing a good quality of soil and as a consequence sustaining crop and animal productivities

The global soil moisture sensor market is expected to reach USD 565.4 million by 2031 with an Average Growth Rate of 9,4% during the forecast period (2023–2031)



Straits Research , http://www.straitsresearch.com, "Soil Moisture Sensor market"

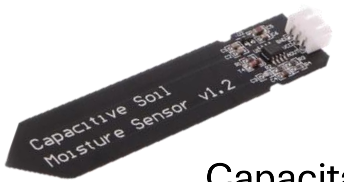
Soil sensor technologies market

Traditional commercial technologies…

Rasheed, M.W., et al. 2022. ***14****(18): p. 11538.*

Frequency Domain Reflectometry

Time Domain Reflectometry



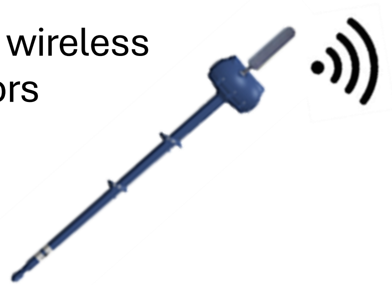
Capacitance

- ✓ Typical accuracy of ± 2-3 %VWC in [0-50] %VWC
- x **Not suited for the supervision of large areas**
- x **Complex cabling**
- x **Complex data loggers**

…and recently emerged approaches

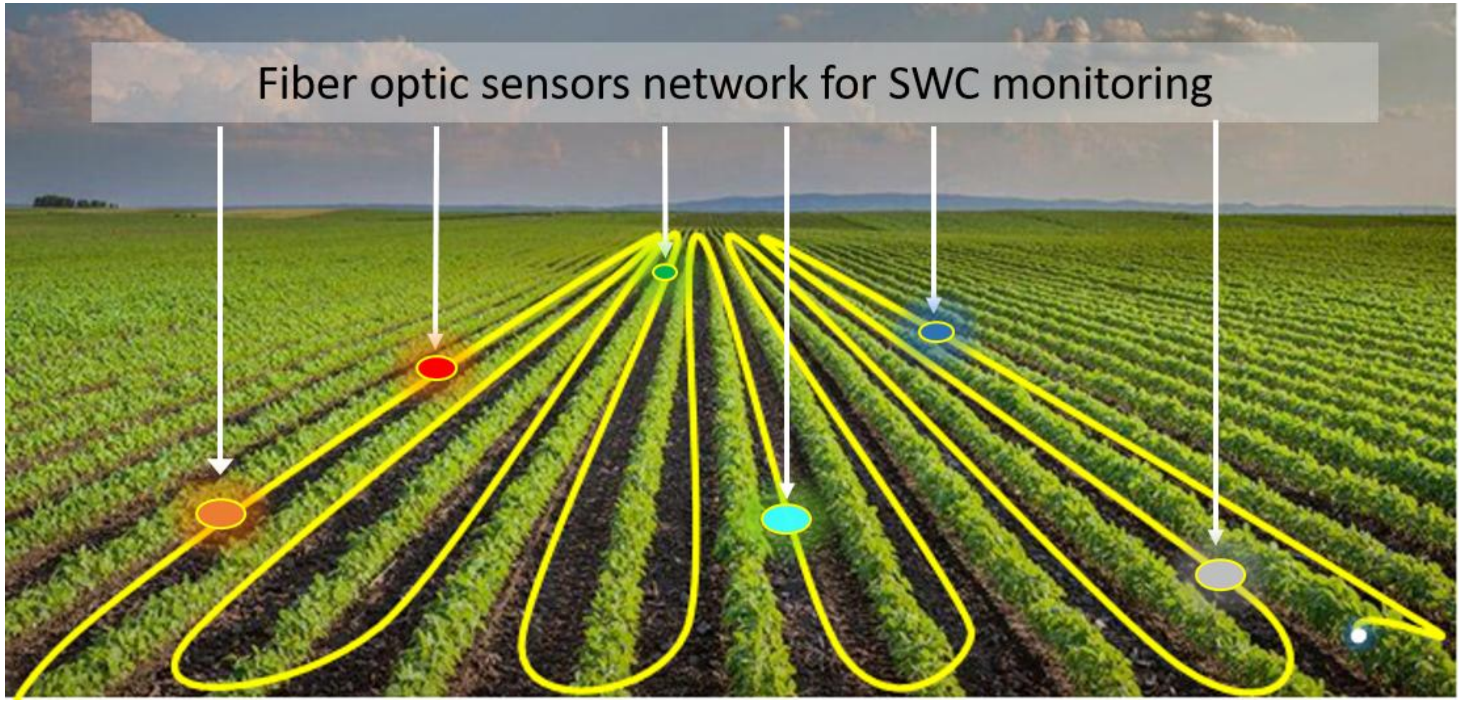
IoT professional station

Stand alone wireless sensors



- ✓ WiFi / 4G connection/Bluetooth
- x **High initial cost**
- x **High maintenance** (batteries recharging or replacement)
- x **Traditional technologies-based**

Fiber Optic Sensors for water content monitoring in soil



- ✓ Multipoint monitoring over large area
- ✓ Wiring complexity reduction
- ✓ Use of one compact interrogation system
- ✓ Easy installation
- ✓ Limited size and weight
- ✓ Resistance to harsh environments

The optical fiber-based technology **as a good candidate to overcome the limitations of the** conventional **sensors**

Leone, M. Results in Optics, 2022: p. 100213.

Optical Fiber-based approaches for SWC monitoring

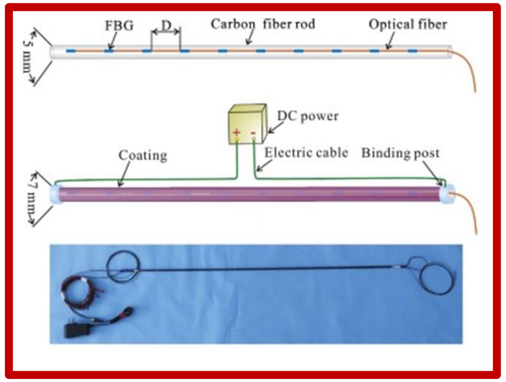
- The **Distributed Temperature Sensing technique** is a fiber optic-based approach largely recognized for in-field soil water content monitoring

The presence of water affects the soil ability to conduct heat → **Water has a higher thermal conductivity compared to air or dry particles, allowing heat to transfer more efficiently through the soil** → **The higher moisture content in soil leads to higher thermal conductivity, enabling heat to move more easily through the soil profile**

In-Field Demonstration

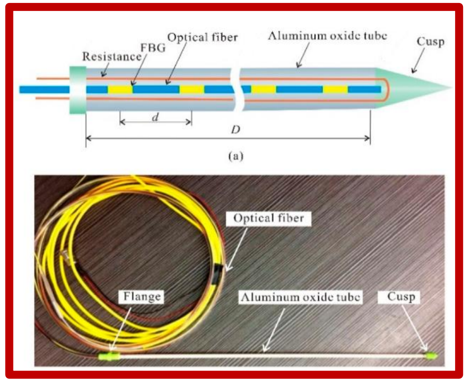
Laboratory demonstration ONLY

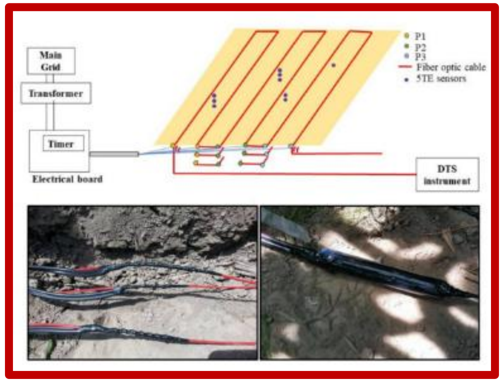
- An electrically generated pulse is applied to heat the soil
- The resultant temperature change is measured through optical fiber technology (fiber itself/FBGs along the fiber) and used to determine the amount of water inside it



Cao, Ding-feng, et al. Engineering geology 242 (2018): 142-149.

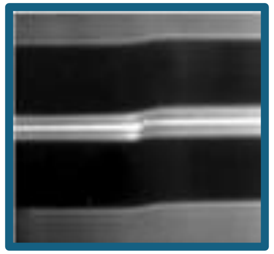
Cao, Dingfeng, et al. Sensors 18.12 (2018): 4431.

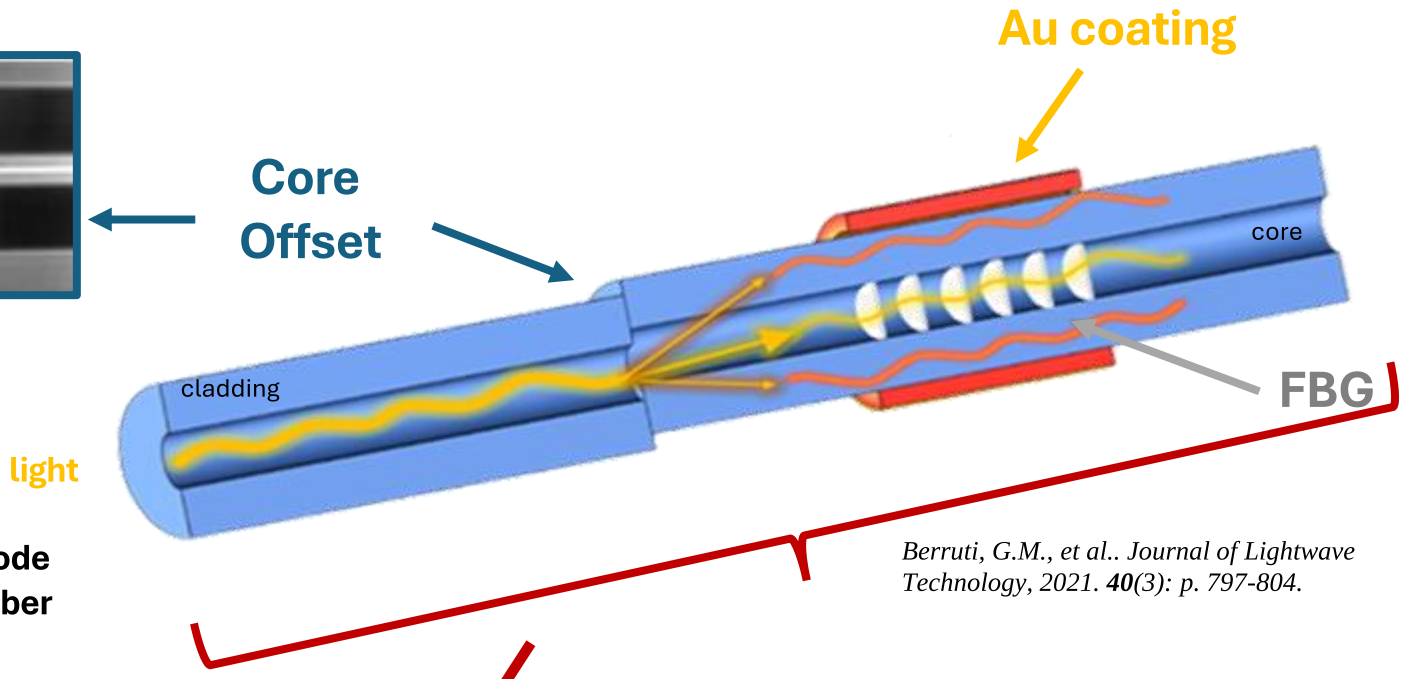




Vidana Gamage, Duminda N., et al. Sensors 18.4 (2018): 1116.

All-Optical Active Sensing Platform for SWC Monitoring



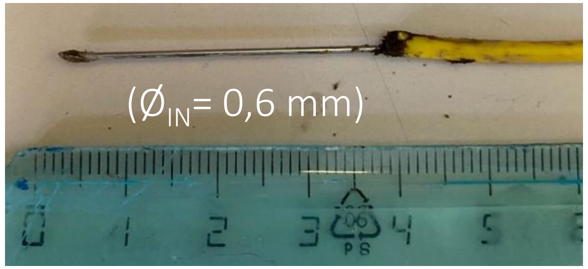


Single Mode Optical fiber

Berruti, G.M., et al.. Journal of Lightwave Technology, 2021. ***40****(3): p. 797-804.*

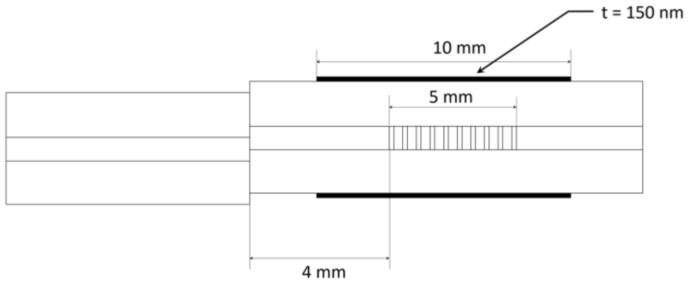
- In-fiber core-to-cladding light coupling component and gold-coated FBG in cascade
- Light travelling in the core is transferred into the cladding through the core offset and is absorbed by the gold (Au) layer
- The resistive heat generation promotes a local temperature variation of the soil in proximity to the device, related to the amount of SWC, monitored through the FBG

..integrated in standard
40 mm long stainless steel needle



Optimized fabrication parameters

1. Enhanced heating efficiency
2. Final thermal mass minimization

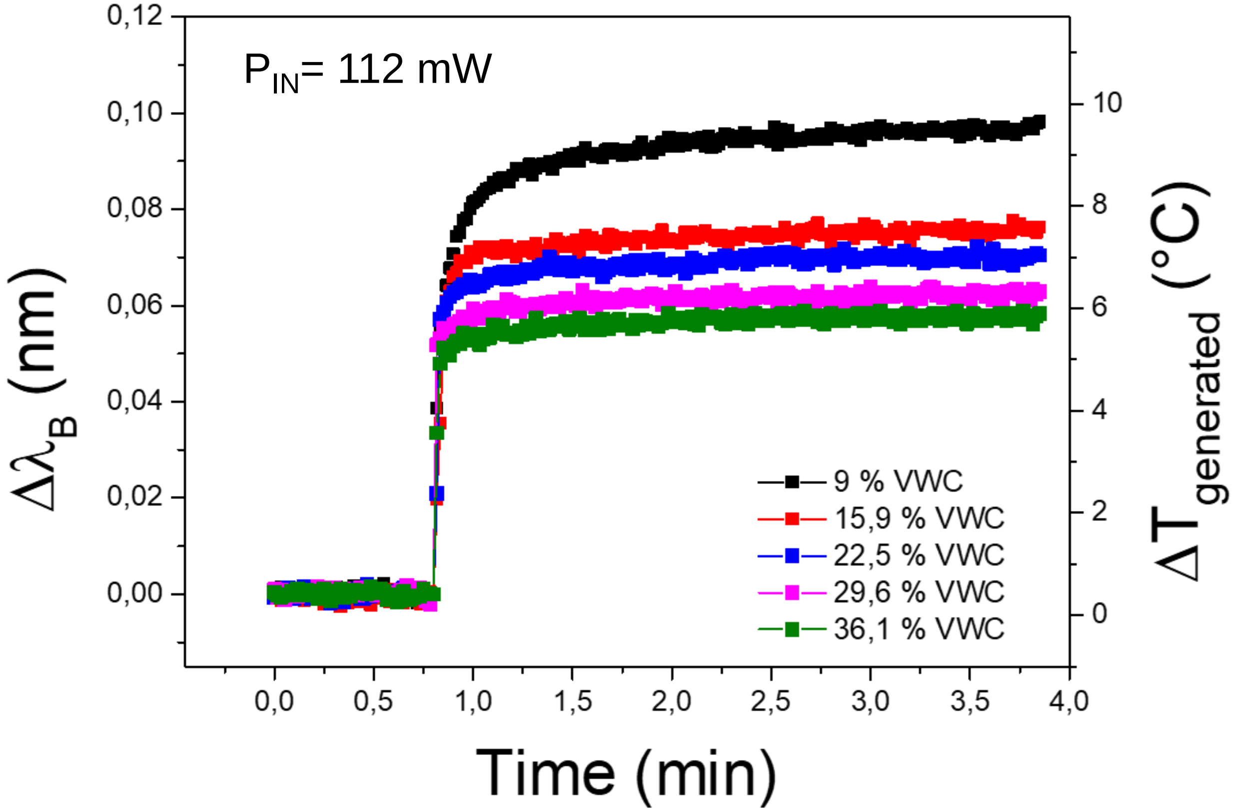


Real time monitoring of the soil water content through the use of the FBG integrated in the Au coated region

Berruti, G. M. , et al. Optics and Lasers in Engineering 178 (2024): 108209.

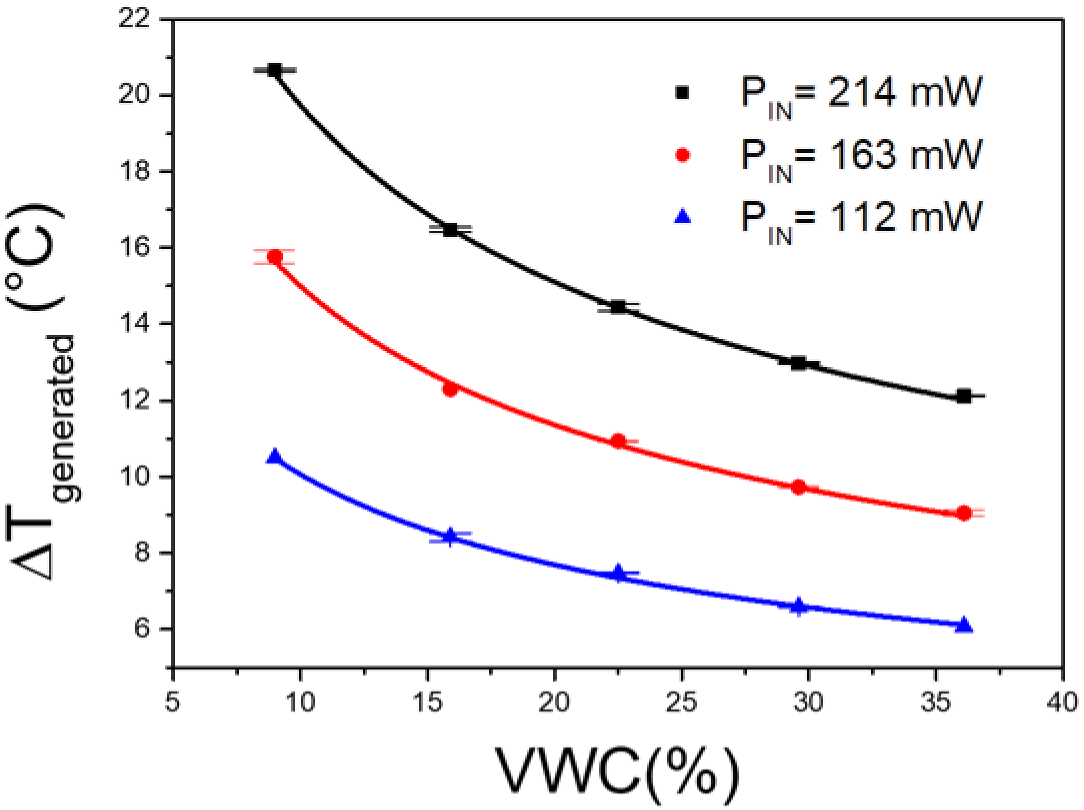
Sensor characterization

Typical sensor response



- ΔT generated decreases when the soil water content increases
  - Response time of ≤ 10 seconds

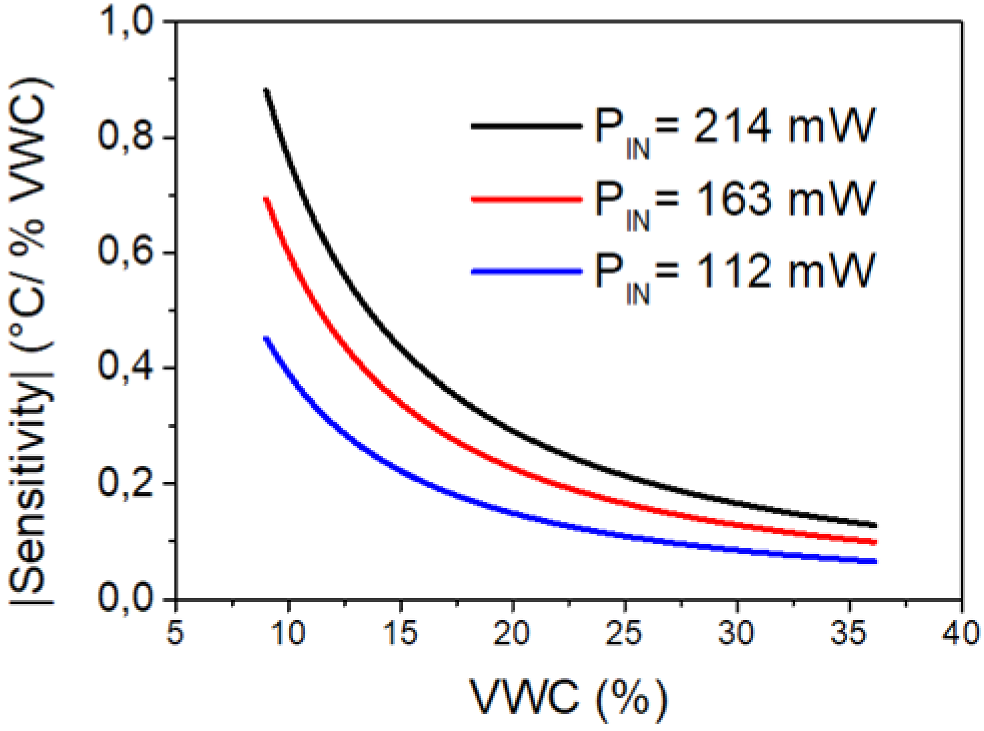
Calibration curves for incremental P_{IN}

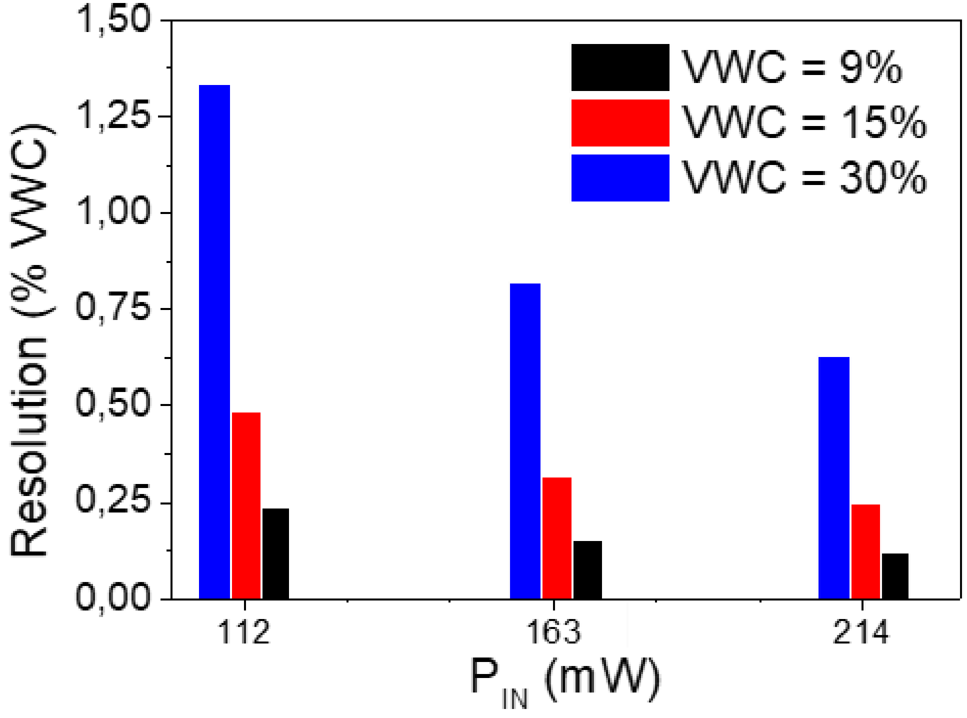


- Non-linear response vs incremental decreases when the
  - The higher P_{IN}, the higher $\Delta T_{generated}$

Berruti, G. M. , et al. Optics and Lasers in Engineering 178 (2024): 108209.

Sensing performance



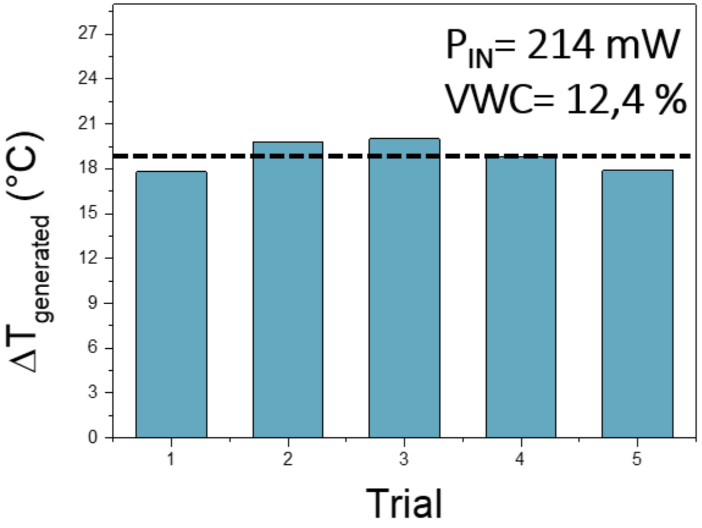


- Sensitivity decreases for higher soil water content values and increases at higher P_{IN}
- Resolution of 0,12 %VWC for P_{IN}= 214 mW

Berruti, G. M. , et al. Optics and Lasers in Engineering 178 (2024): 108209.

Repeatability and energetic efficiency

Repeatability analysis



18,8 ± 1,0 °C

↓

11,8 ± 1,5 %VWC

- 5 extractions/insertions/activations in soil
- Repeatability of ± **1,5 %VWC** (due to change of soil compaction)

Energy consumption per single measurement

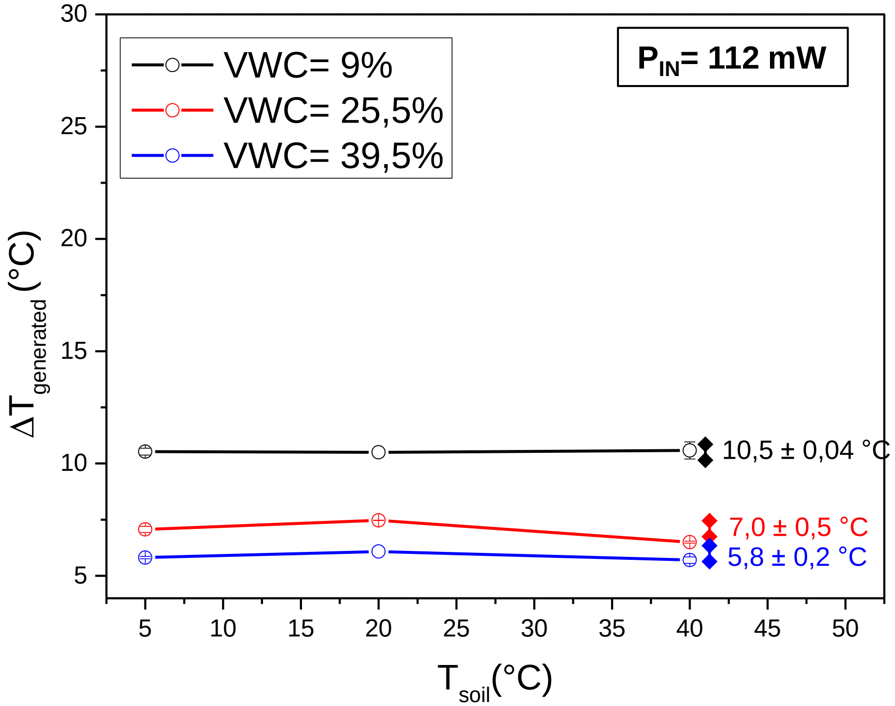
$$E_{consumption} = t_{settling} \cdot P_{IN}$$

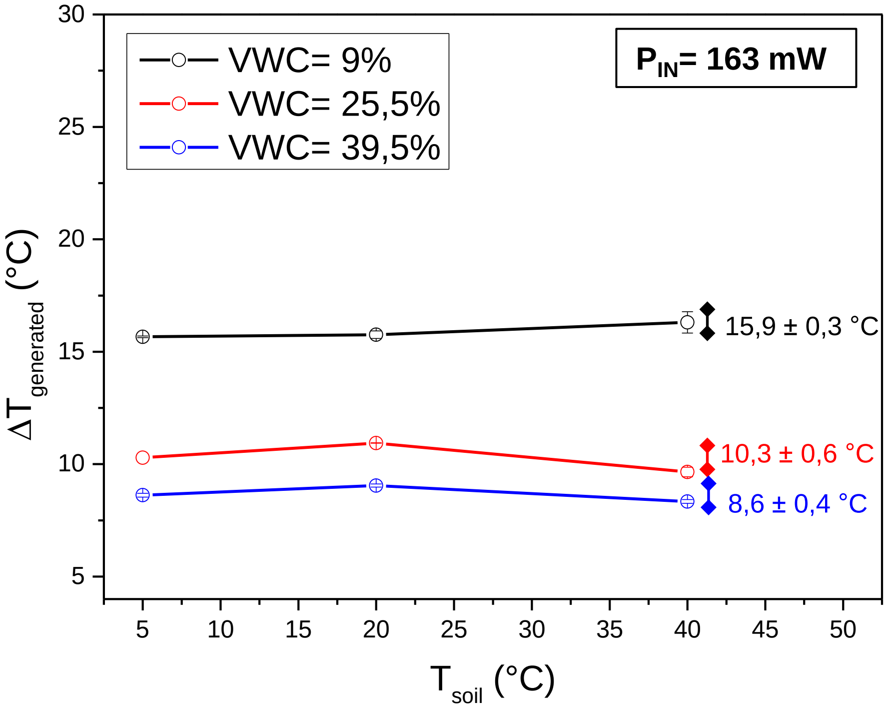
	$t_{settling}$ [s]	$E_{consumption}$ [Wh]
P_{IN} = 112 mW	21	$0,6 \cdot 10^{-3}$
P_{IN} = 163 mW	23	$1,0 \cdot 10^{-3}$
P_{IN} = 214 mW	30	$1,8 \cdot 10^{-3}$

The choice of P_{IN} as a result of a trade-off between required performance (e.g.sensitivity) and the final system energetic efficiency

Berruti, G. M. , et al. Optics and Lasers in Engineering 178 (2024): 108209.

Temperature cross-sensitivity





- Soil temperature between 5 ° C and 40 ° C
- Under the same conditions, **$\Delta T_{generated}$ is practically independent upon the soil temperature**
- Unavoidable variations around the mean value (lower than ±1 ° C) **in line with the repeatability** error due to the extractions and insertions of the probe within the soil sample

Berruti, G. M. , et al. Optics and Lasers in Engineering 178 (2024): 108209.

Conclusions

- **Climate crisis** and the **limited availability of water resources** represent **the most important challenges** that technology must face in order to provide efficient **soil moisture monitoring** solutions
- We have provided the experimental demonstration of an advanced **all-optical self-heated sensing platform for continuous and sustainable SWC monitoring.**
- **The proposed platform provides highly stable, fast, robust and energy efficient measurements**, with **sensing performance comparable to the most common and widely used techniques for SWC monitoring.**

Thank you for your attention