THALES
Building a future we can all trust

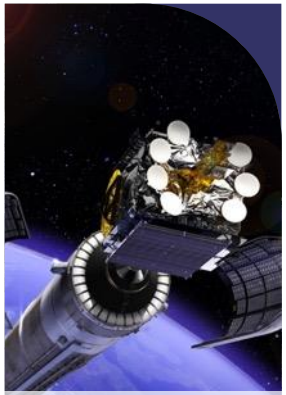
Quantum technologies for sensing, navigation, communications and signal processing

G. Baili, P. Berger, P. Bortolotti, A. Brignon, D. Crété, Th. Debuisschert, D. Dolfi, A. Dot, M. Dupont-Nivet, P. Feneyrou, G. Feugnet, I. Ghorbel, R. Guillamet, F. Gutty, V. Kemlin, J. Kermorvant, Ch. Larat, M. Le Dantec, S. Magaletti, L. Mayer, S. Mesoraca, A. Mizrahi, L. Morvan, F. Nguyen Van Dau, M. Schwarz, D. Tan, J. Trastoy, M. Van Den Bossche, S. Welinski, B. Wirtschafter, J.J. Yu

Thales Research & Technology, Thales SIX, Thales AVS, Thales DMS, Thales Alenia Space, Thales Singapore

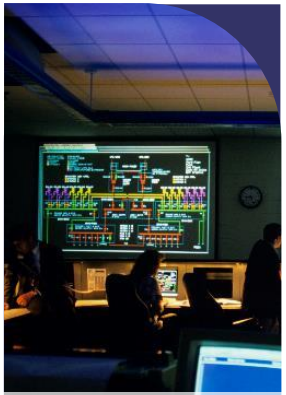
Impact of the second quantum revolution

AEROSPACE



SPACE

DEFENCE



SECURITY

Quantum Sensors

Quantum Communications

Quantum Computing

> **Over next 5-10 years, we expect 2/3 of Thales business to be progressively impacted directly or indirectly by the new quantum devices and systems**

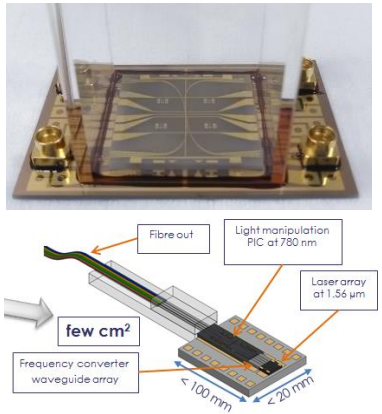
Quantum Technologies for sensing

Objective 1: Positioning, navigation and timing

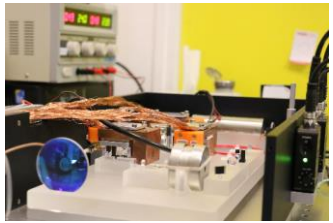
→ to know the **position of any platform with an ultimate precision**, with or without GNSS, through different techniques, potentially hybridized

Technologies addressed by Thales:

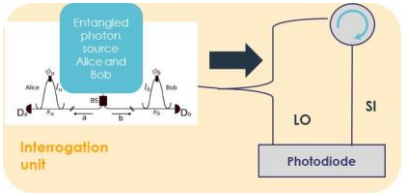
Cold atoms on chip based inertial sensors + PICs

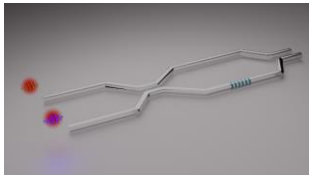


CPT based compact atomic clock

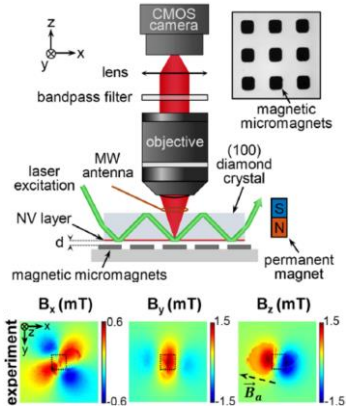


Entangled photons for fiber gyros and sensors





NV Centers in diamonds for gyros and magnetometry



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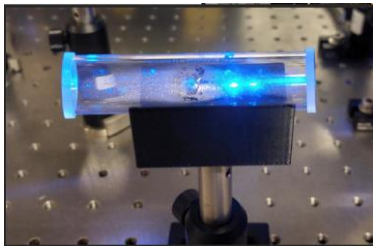
Quantum Technologies for sensing

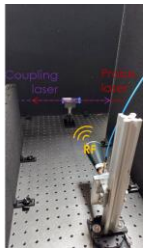
Objective 2: Quantum radio frequency sensing

→ to improve RF sensing **sensitivity, probability of intercept, dynamic range and frequency coverage/agility**, of at least one order of magnitude

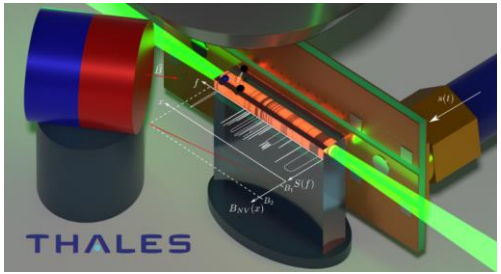
Technologies addressed by Thales:

Rydberg atoms

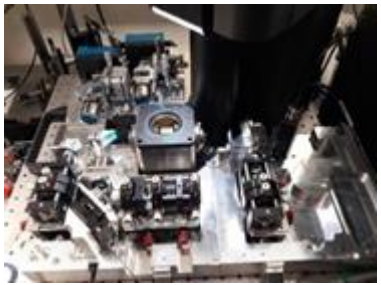




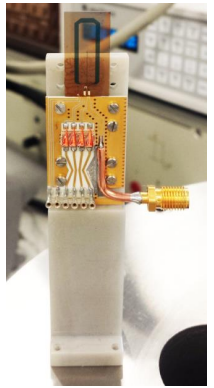
NV Centers for RF signal processing



RF signal analysis based on Spectral Hole Burning



SQIFs



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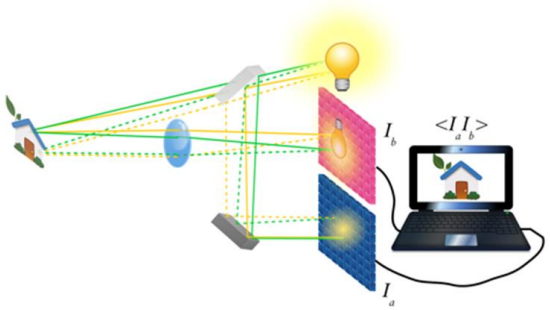
Quantum Technologies for sensing

Objective 3 : Quantum optronics sensing

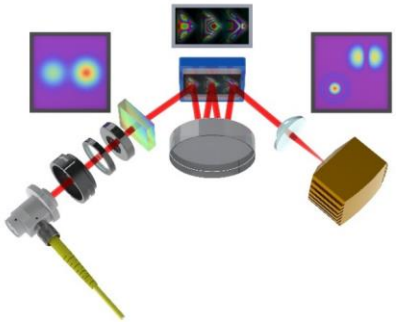
→ to improve **optronic systems resolution and sensitivity, down to photon counting level**, for longer range detection/identification/classification, including in severe atmospheres

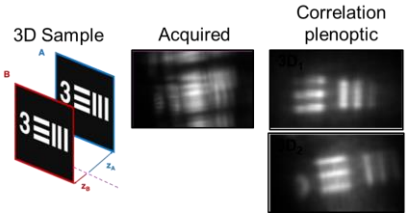
Technologies addressed by Thales:

Active systems based on non-classical illumination



Passive systems based on Quantum Technologies



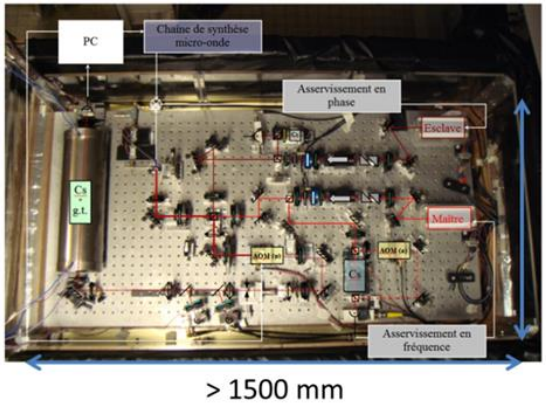


Univ. Aldo Moro, Bari

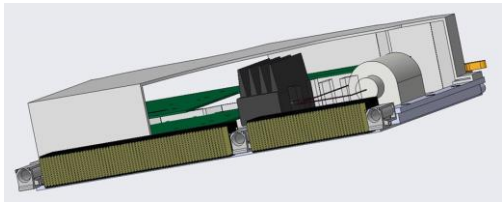
CPT Cs clock based on the use of a dual frequency laser

CPT Cs clock : Coherent Population Trapping Cesium clock

Demonstration at SYRTE



Compact Cs CPT clock at TRT: bench



(ojective V< 1L)

towards further integration

Applications

- navigation, GNSS
- communication networks synchronization
- radar and E.W multistatic systems

Differentiators

- **One day stability x 10**
- **Volume ÷ 10**

Compared to Cs optically pumped atomic clocks in current development

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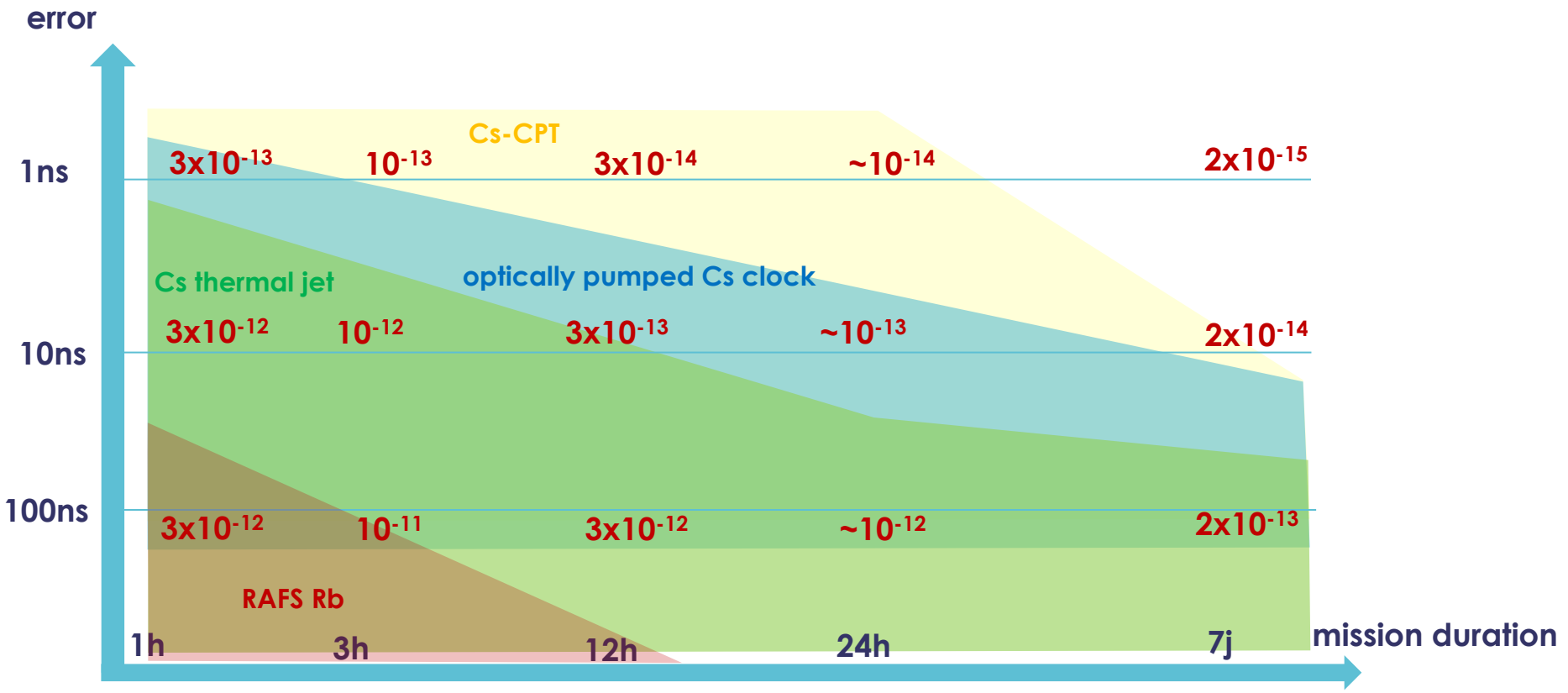
Atomic clocks: performance classes



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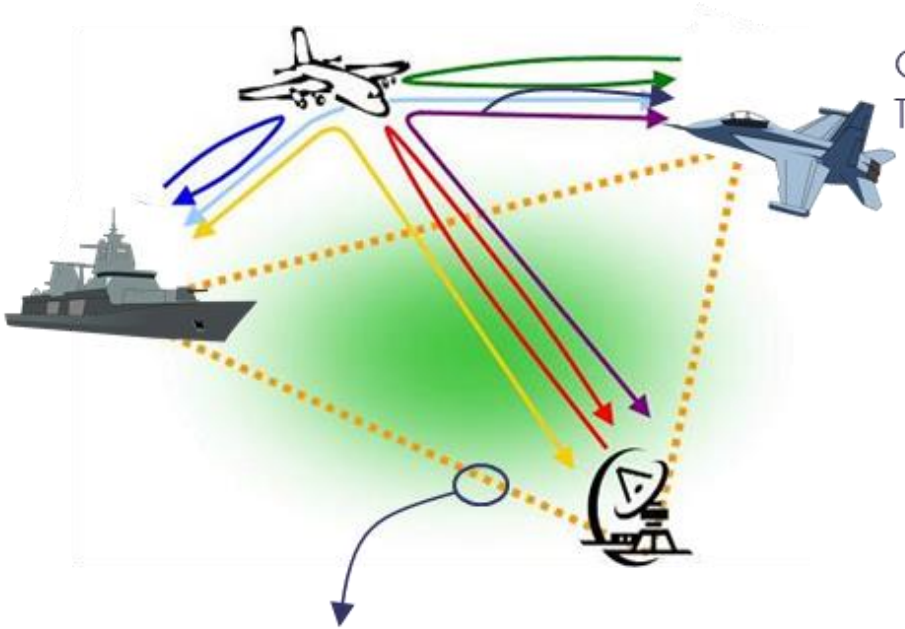
Time/frequency distribution for platform synchronization/multistatic sensing



- Multi-static radar : coherent/incoherent data fusion
- Radio emitter localization
- Require both **time synchro. and relative position**

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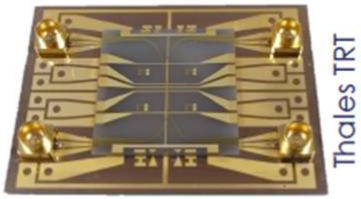
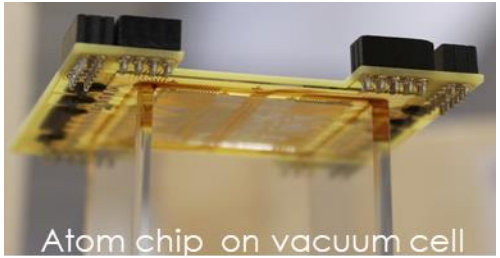
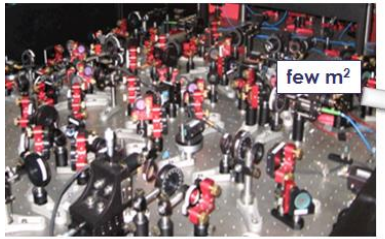
Cold atoms for inertial measurement units

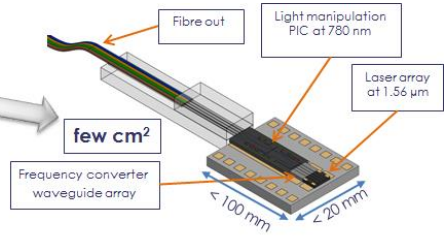
Atom chip (target) : $\frac{\delta g}{g} \sim 1 \cdot 10^{-6} @ 1\,s$



1-3 liters targeted





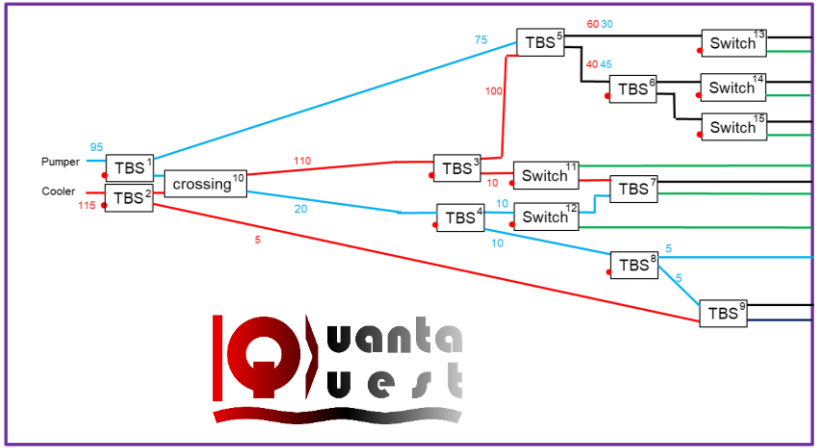


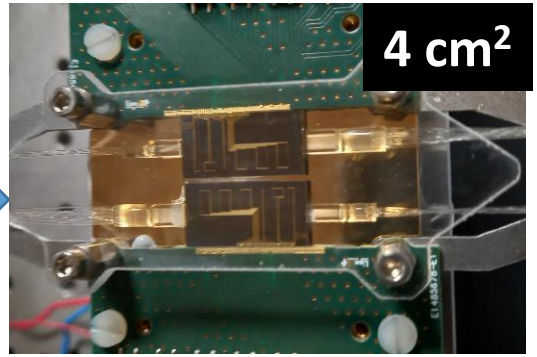
Applications

- atomic clock (navigation, GNSS reference, telecom networks synchronization)
- gyroscopes, accelerometers, gravimeters, : ***towards an ultra-compact multifunction inertial measurement unit***

Differentiators

- low-energy and high precision device
- compact
- integration of advanced function on the same chip + sensors multiplexing





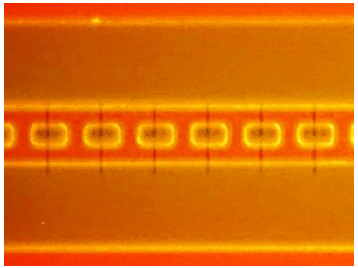
Kylia (Astrid NIARCOS)

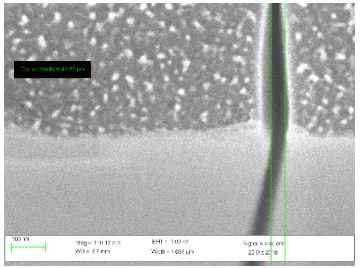
SQIFs based electromagnetic sensors

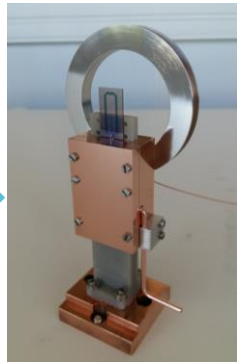
SQIF : Superconducting Quantum Interference Filter

Extremely sensitive / large bandwidth electromagnetic sensing *(from VLF to millimeter waves)*

- based on arrays of SQUIDs
  - SQUID = Superconducting Quantum Interference Device







T=60-70K

Applications (SIX, DMS, LAS)

- Antennas VLF, LF, HF
- Airborne HF detection and direction finding
- Radio-communications
- Magnetic Anomaly Detection (MAD)

Differentiators

- **Large reduction of antennas size**
- Stealth

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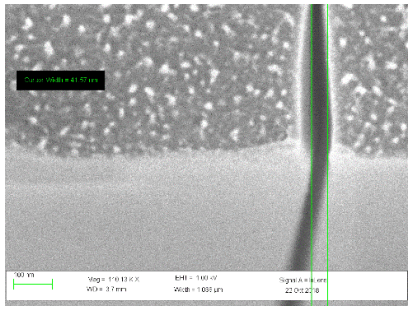
SQIF based electromagnetic sensors

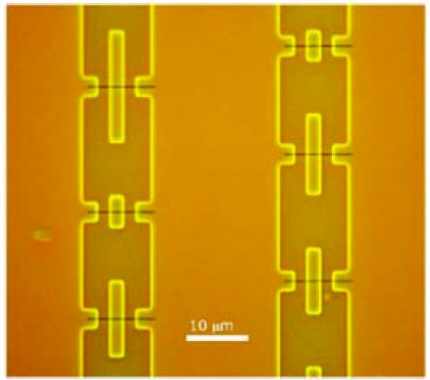
Coll. Thales R&T, Thales SIX, Thales DMS, ESPCI, C2N

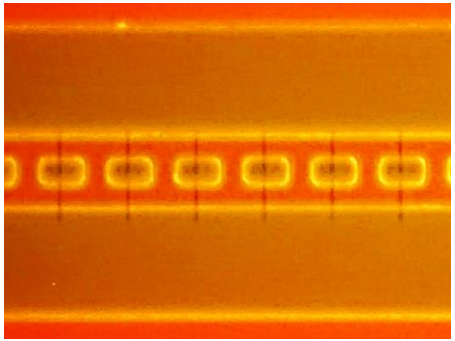
Extremely sensitive / large bandwidth electromagnetic sensing *(from VLF to millimeter waves)*

- based on arrays of SQUIDs
- Josephson Junctions in high Tc superconductors

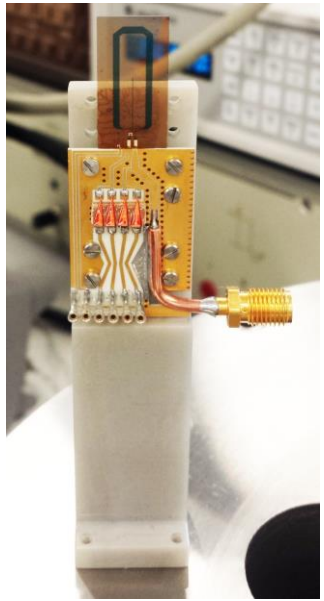


40 nm slit opened in the photoresist before irradiation of the YBCO layer





examples of SQIFs 1D and 2D arrays of typ. few 10^3 SQUIDs



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Superconductor based mux/demux and filters in a compact cryocooler for naval applications

* artist's view

➔towards a SQIFbased sensor in a compact cryocooler for underwater or airborne drones

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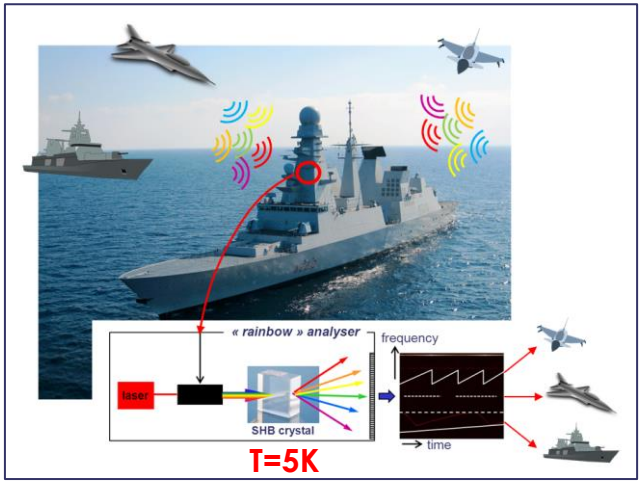
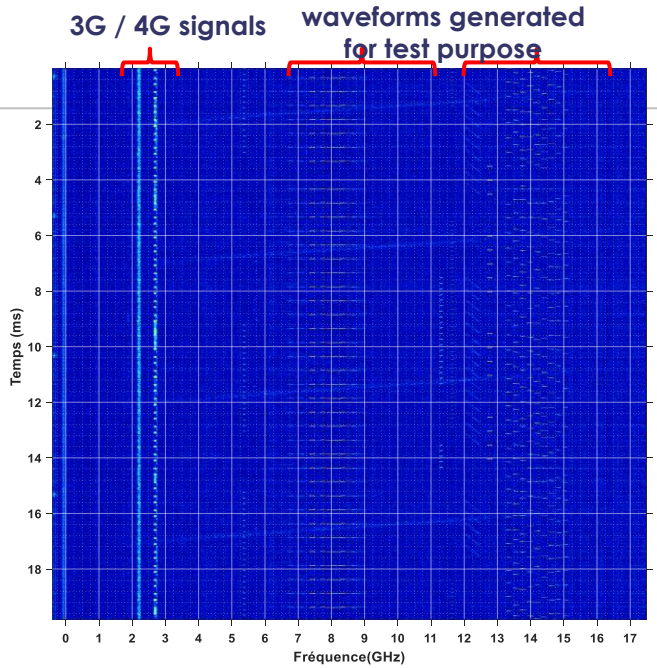
SHB spectrum analyser

SHB : Spectral Hole Burning





Applications

- Electronic warfare
- ELINT
- COMINT
- **EM spectral dominance**

Differentiators

- Instantaneous bandwidth > 40 GHz
- 100% probability of intercept
- 50 dB dynamic range :

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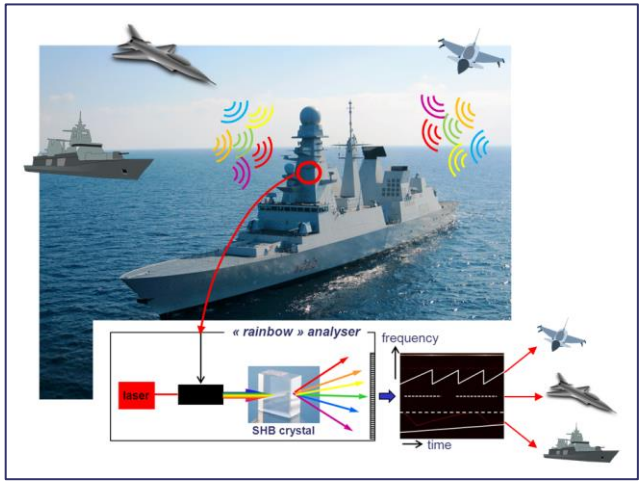
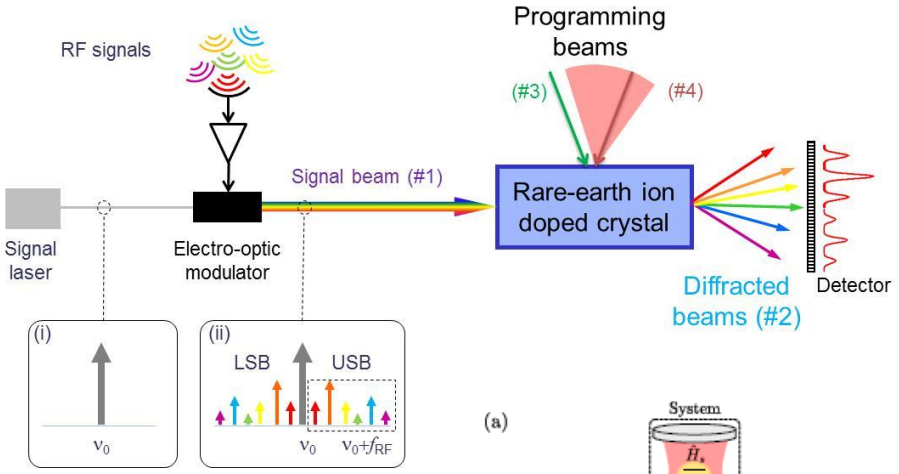
Rare Earth Ion based Quantum Processors

I. Lorgeré, *et al.*, J. of Modern Optics, 49, 2459, 2002

Spectrum analysis and identification of RF signals over 20 GHz bandwidth

- Optically carried RF signals processed with spectral holography in rare earth ion doped crystals



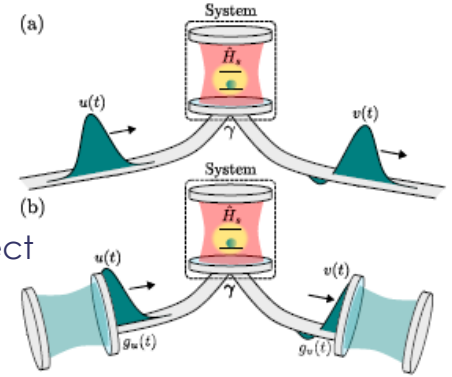


Slow light or time reversal based processing of RF signals

Quantum memories, networks & communication

Processors for quantum computation

SQUARE project



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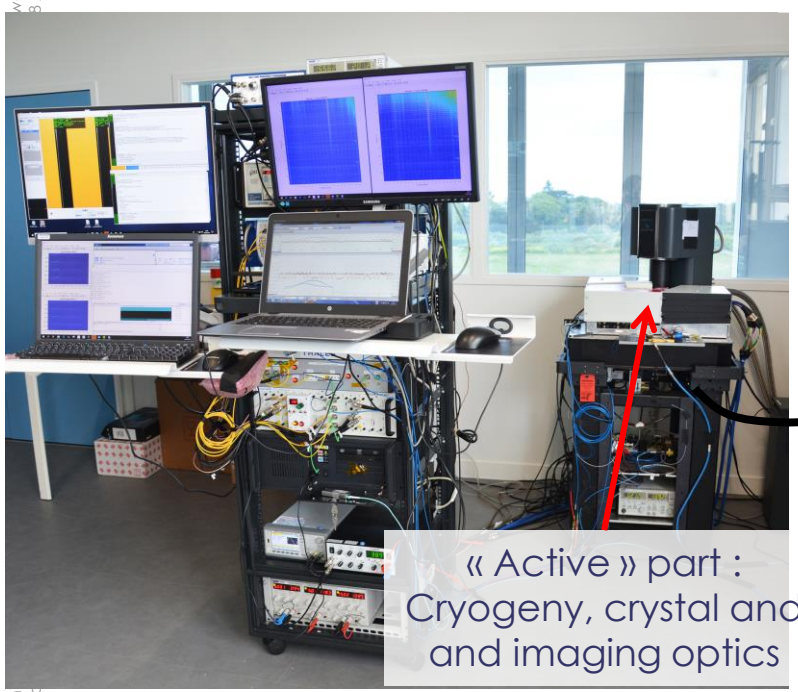
Demonstration in Brest, France

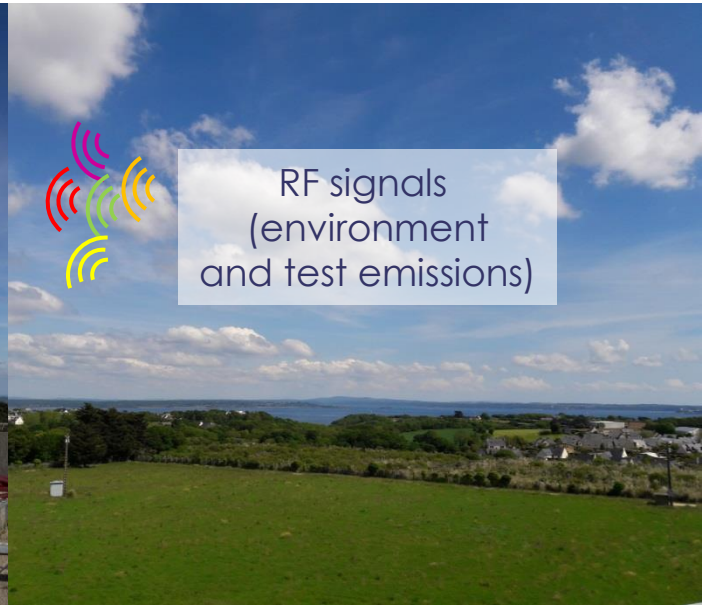
« Rainbow » demonstrator



« Active » part :
Cryogeny, crystal and
and imaging optics

RF antenna and
transposition onto
the optical carrier

40 m
optical fiber
RF-analog link



RF signals
(environment
and test emissions)

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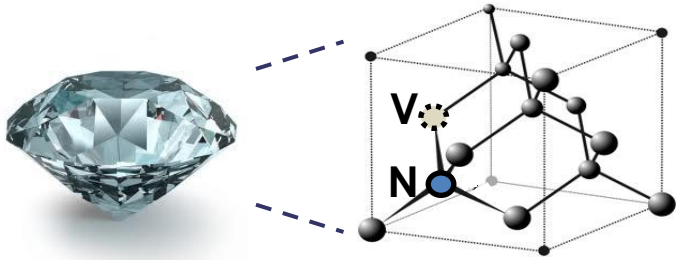
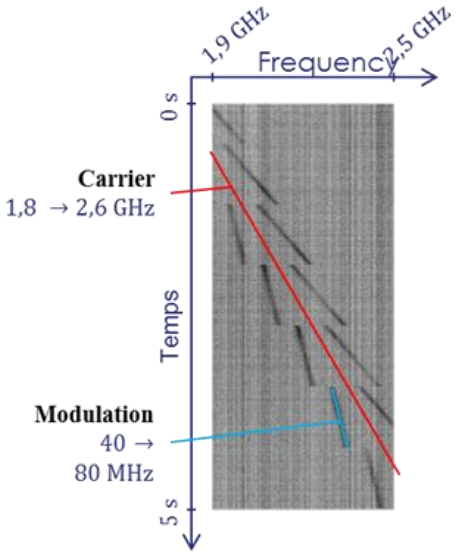
NV centers for magnetometry and spectrum analysis

NV center as an artificial atom hosted in the diamond matrix





Applications

- Magnetic Anomaly Detection (MAD)
- Electronic warfare

Differentiators

- **Small size (Solid-state device)**
- **Room temperature operation**
- Present status : Bandwidth 25 GHz, linewidth : 1 MHz

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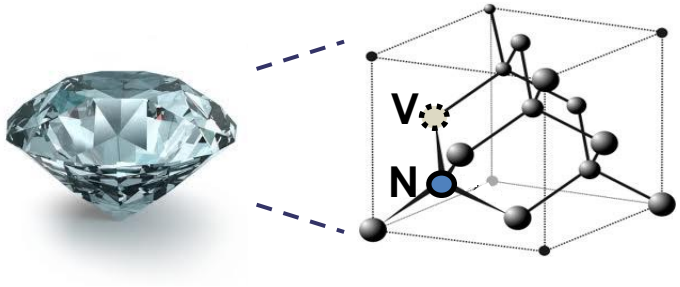
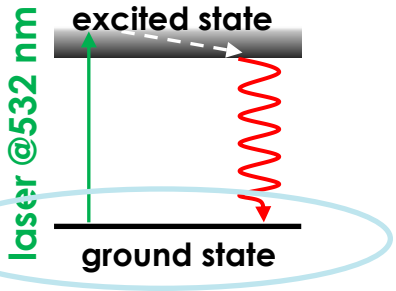
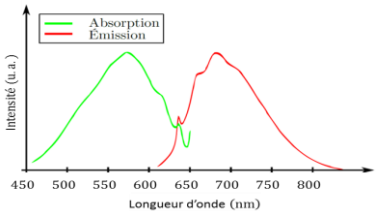
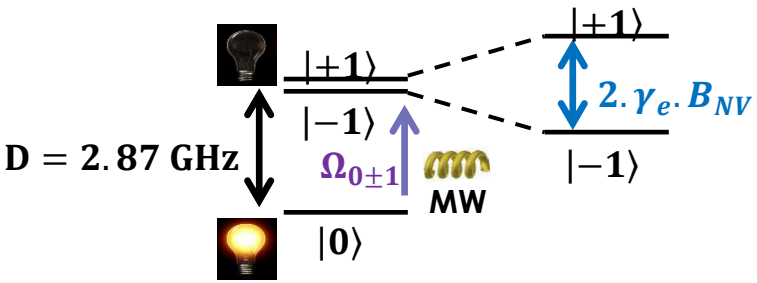
Nitrogen-vacancy center in diamond

NV center as an artificial atom hosted in the diamond matrix









A. Gruber *et al.*, *Science*, 276, 2012, 1997
J. Achard *et al.*, Journal of Crystal Growth 284, 396, 2005

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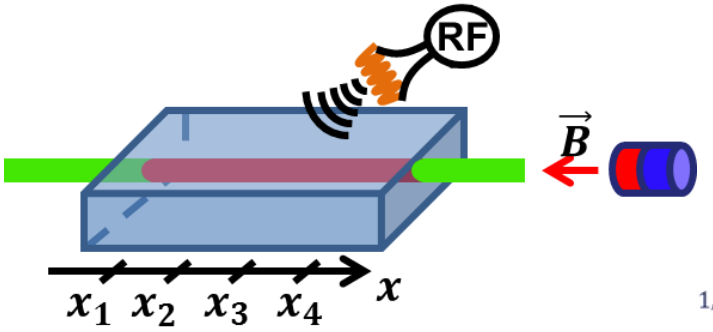
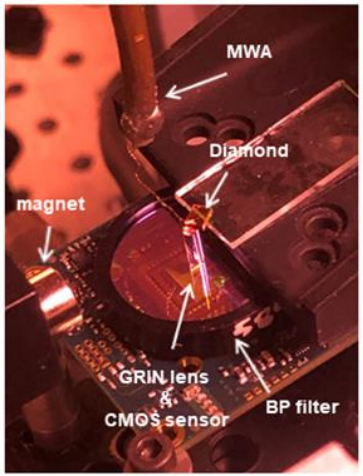
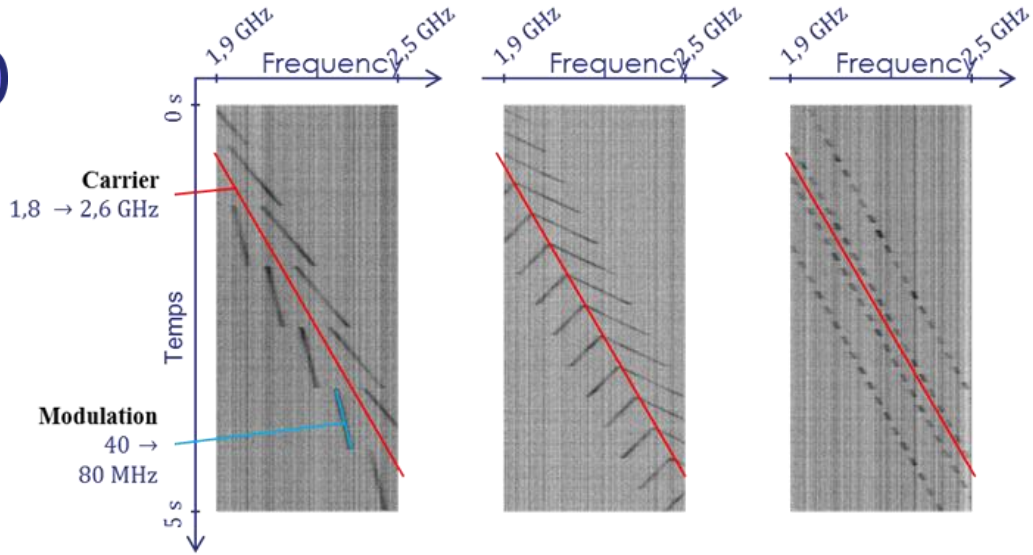
Spectrum analysis with NV centers in diamond







Preliminary results

- up to 25 GHz BW
- > 25 dB dynamic range

Coll. Thales R&T, Thales DMS, Thales SIX, Paris XIII

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RF signal detection using Rydberg atoms

Motivation

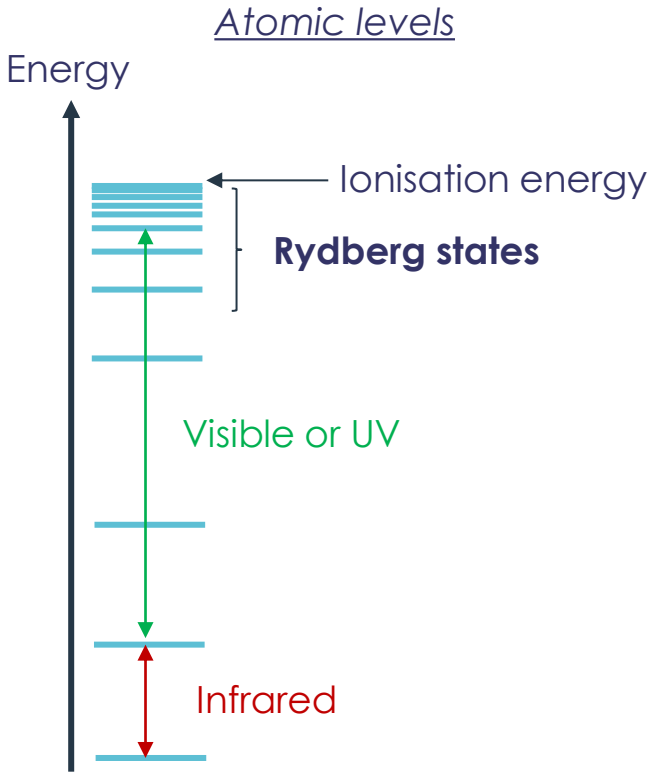
Elect. field probe for antenna and field measurement

- High sensitivity
- Self calibration
- Vector measurement
- Small size (spatial resolution)
- Dielectric sensor (weak field disturbance)

RF detection (for radar, communications or antenna calibration)

- High sensitivity
- [0 - 300] GHz range with the same hardware

Rydberg Technologies LLC



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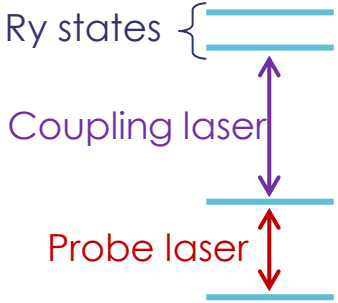
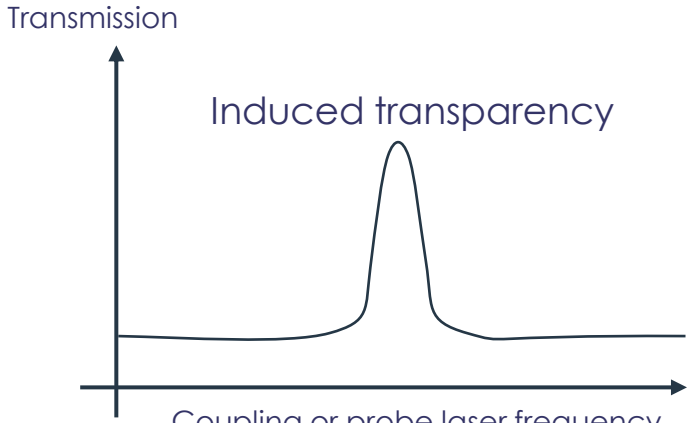
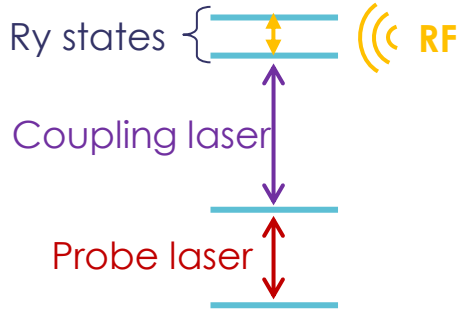
AC electric field measurements (typ > GHz)

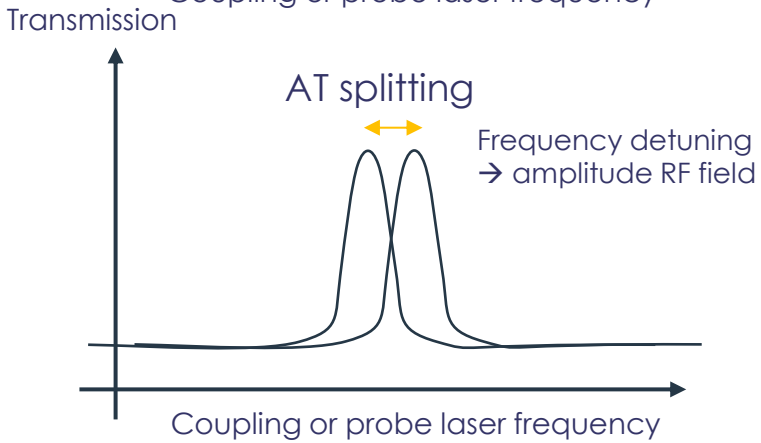
EIT signal

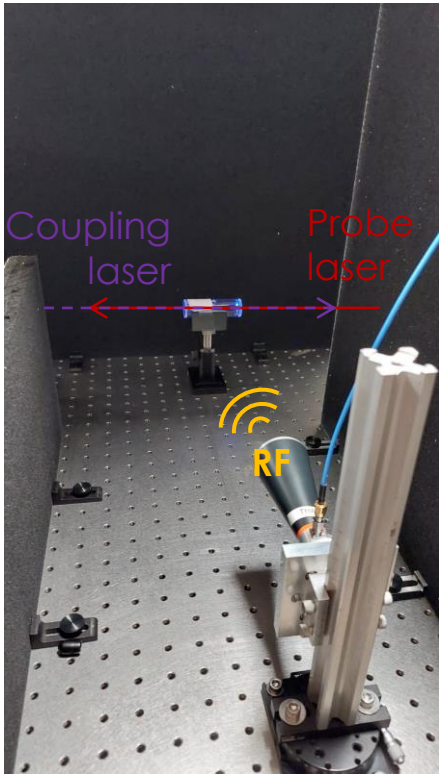




AT splitting







EIT: electromagnetically induced transparency
AT: Autler-Townes

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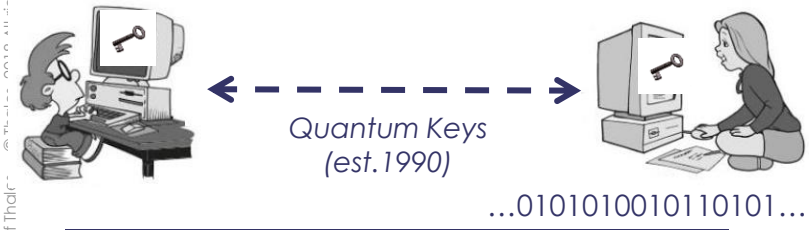
Two services of quantum communications

ThalesAlenia Space
a Thales / Leonardo company

To share confidential random…

…0101010010110101…



… or better, to share states

$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$

Quantum-Secured Networks

- Unconditional security
- \+
- Perfect forward secrecy
- \+
- Defence in depth

Quantum-Information Network

Networks of

- Q-computers to increase exponentially the processing power
- Q-sensors to allow more accurate quantum sensors

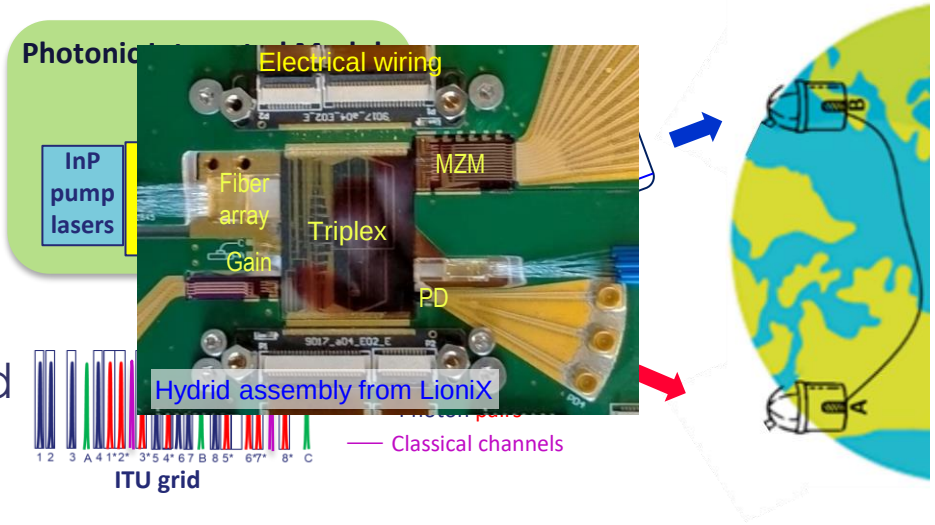
Challenges: from high speed QKD to QIN

- Micius is based on solid-state entangled-photon sources
- Well-established & keeping improving for 20 years
- However : key distribution rate ~0.12Hz

*Micius distributing quantum keys over 1200 km on earth – J. Yin et al, Science **356**, 6343 (2017)

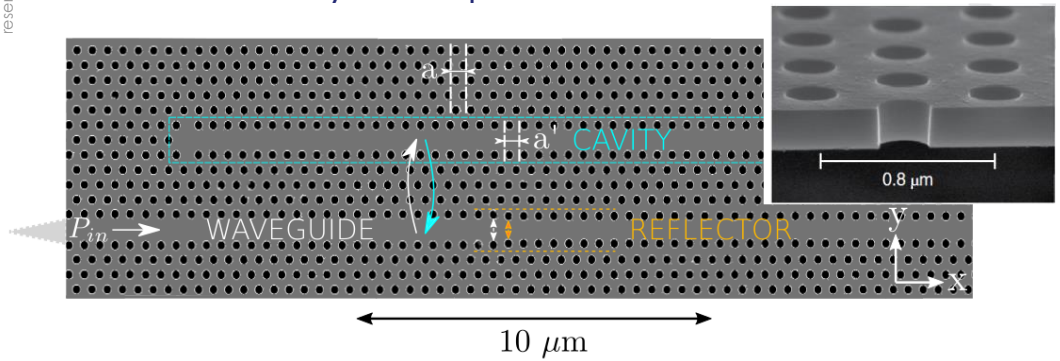
Quantum integrated photonics

- Entangled photon pair generation
- Improved emission efficiency
- Compact and lightweight (SWaP)
- Wavelength multiplexing is enabled



Nanoscale Quantum Source developed by THALES and CNRS

Photonic Crystal Optical Parametric Oscillator



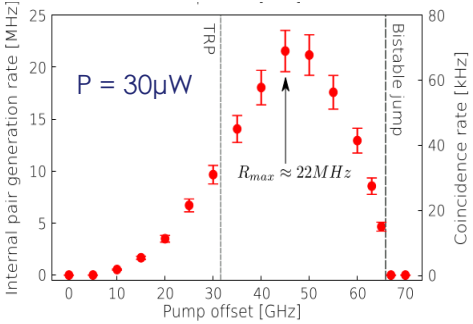
Nanoscale Resonator : V is small
III-V semiconductor : no TPA
microWatt power threshold

Marty, et al., Nat. Photonics (2021)

operation below threshold :
=> spontaneous FWM

Entanglement

Generation Rate



tuning parameter

two-photon (Franson) interference

P_0 [µW]	T_{int} [s]	V_{raw} [%]	V_{net} [%]	$(V_{raw} - V_{bell})/\sigma_V$
15	1	93.88 ± 4.07	96.58 ± 4.19	5.7
23	1	89.22 ± 4.11	91.79 ± 4.23	4.5
36	1	77.13 ± 1.98	79.35 ± 2.04	3.2

A. Chopin *et al.* accepted Nat. Comm. Physics (2023)

Quantum sensing

- Accelerometers, gravimeters (cold atoms)
- Compact CPT clocks
- Spectrum analyser (SHB, NV centers)
- Magnetometers (NV centers)
- RF electromagnetic sensors (SQIFs, Rydberg atoms)
- Fiber based sensors & Lidars

Quantum communications

- Secure communications (QKD), quantum networks (QIN)
- Quantum processors, quantum memories

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