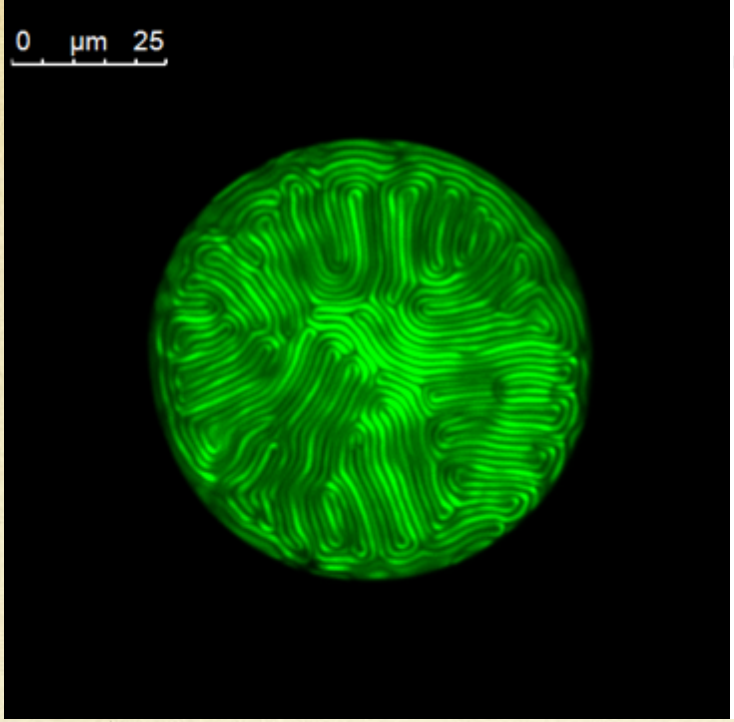

Smart unclonable tags for cyber physical security

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Cyber Physical Security

- The cost of fraud and related corruption at the expense of the European Union economy is estimated to **€120 billion per year**, slightly lower than the annual budget of the EU itself

- According to the Italian Ministry for Economic Development and the Italian Patent and Trademark Office, in Italy between 2008 and 2013 about 100 thousand fraudulent counterfeits have been discovered, for an amount of about 335 million pieces seized and a total economic value of 3.8 billion euros.

- Advanced countries need simple, effective and affordable novel technical solutions for anti-counterfeiting, authentication, identification and traceability of goods for security, health, justice, logistics, and industry

- **Cyber Physical Security** is a new paradigm that extend the ICT approach of **Cyber Security** to the **material science and technology**

- **Novel unclonable tags define a practical method for cyber physical security**

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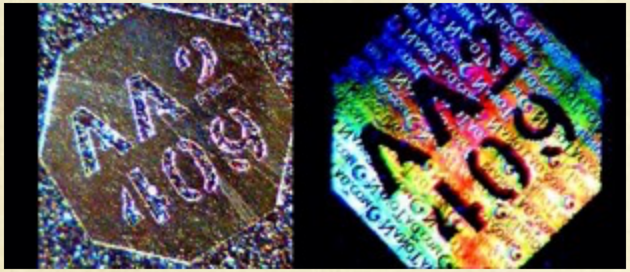
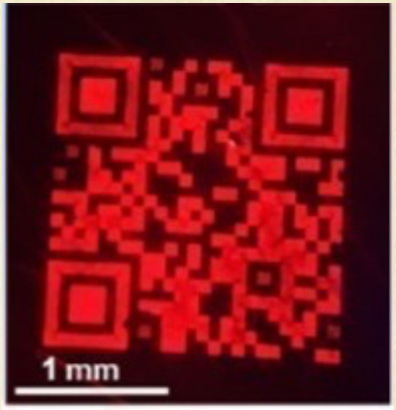
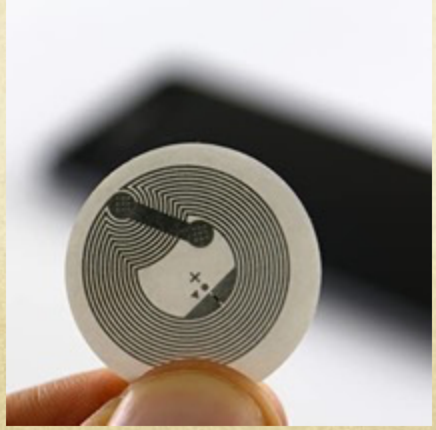
Anti-counterfeiting TAGs

Anti-counterfeiting TAGs are distinctive signs of variable dimensions and materials, which are used for traceability, authenticity and anti-tampering purposes, the substantial difference for all these TAGs is in the material and technology used.







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Physical Unclonable Functions (PUFs)

- **Physical Unclonable Function (PUF)** is a new paradigm for authentication, identification and traceability.

- A **PUF** is a mathematical function that is derived from the behaviour of a **complex physical object or device**. It could be a physical object that, because of an **intrinsic randomness** present within its manufacturing process, inherently possesses **unique, unpredictable and unclonable** challenge–response combinations. Such a quality can be used to uniquely identify an object, assuming that the response can be extracted from the object with high fidelity and represented digitally.

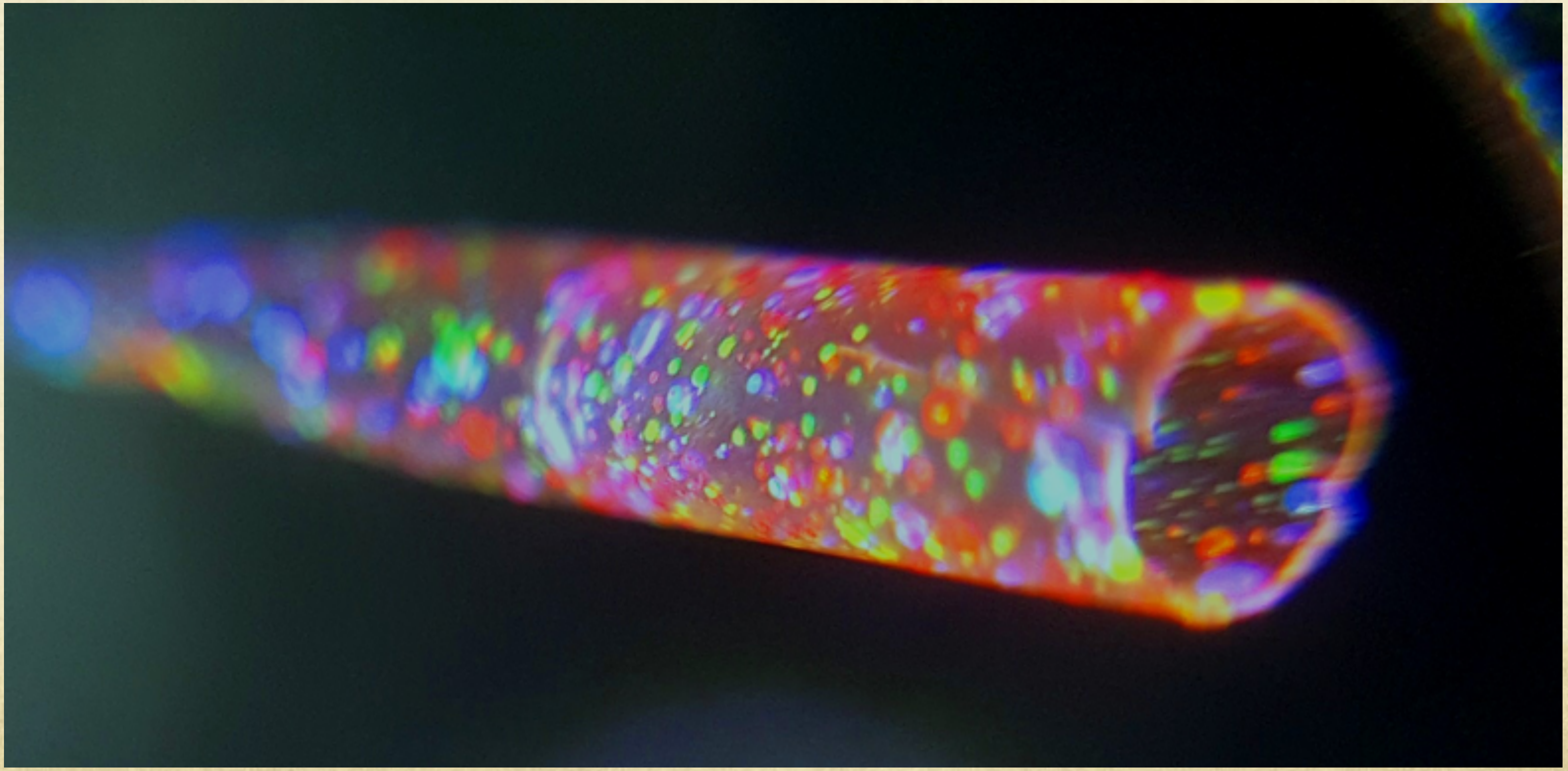
- **PUFs** can be modelled as a black-box challenge– response system

[1] R. Pappu, B. Recht, J. Taylor, N. Gershenfeld, *Physical One-Way Functions*, Science 297, 2026 (2002)
[2] R. Arppe and T.J. Sørensen, *Physical unclonable functions generated through chemical methods for anti-counterfeiting*, Nature Reviews Chemistry 1, 0031, 1 (2017)
[3] R. De Rose, F. Crupi, M. Lanuzza, D. Albano, *A physical unclonable function based on a 2-transistor subthreshold voltage divider*, to be published in International Journal of Circuit, Theory and Applications

Complexity of a physical system can determine its uniqueness

Example:

a photonic thin film can be identified at increasing complexity scale by its image, micro-image, polarization schemes, general spectral response, local spectral response, luminescence, super-luminescence, lasing, ...



(*sample by ITM-CNR and Molecular Physics Group at University of Calabria*)

Application scenario

A combination of hardware and software is required to enhance system security. Matter physics and photonics can provide suitable hardware solutions to achieve

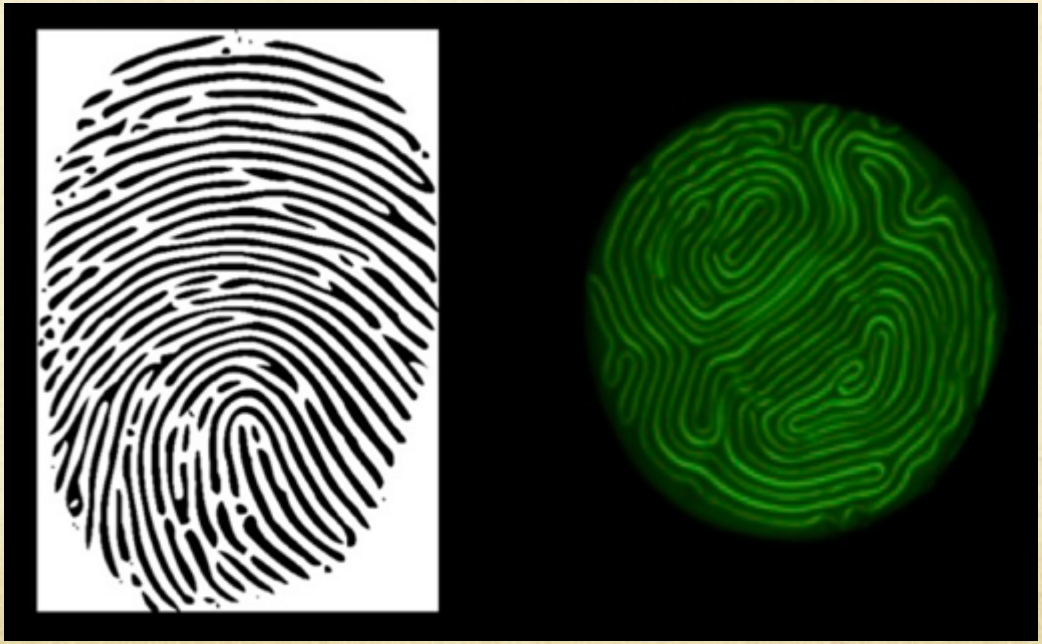
LOW COST SOLUTIONS FOR HIGH VALUE PROTECTION

PUF-based authentication system

PUFs based on Soft Matter

If we would like to use standard software for recognition, as, for instance, in the case of human fingerprints, can we obtain **artificial fingerprints,** which can be compatible with the existing informatics solutions?

YES, by using, for instance, <u>liquid crystals</u> !!!



Photonic micro-fingerprints as anti-counterfeiting device

Examples of PUFs using Soft Matter

In 2015 Bae et al. obtained artificial micro-fingerprints following the random drying procedure of a silicon film deposed on discotic polymeric particles few hundreds of microns in size [1].

In 2014, J. Kim et al. obtained nanoscopic fingerprints using randomly distributed silver nanowires coated with fluorescent dyes embedded in a PET film [2]. From an encoding point of view, the fingerprint approach has a huge coding capacity that can be further increased if the pattern is enriched with other unique features.

As an example, in the work of Tian et al., in 2016, [3] a random folded ultrathin gelatinous polymer was doped with plasmonic nanostructures in the form of silver coated gold nanorods. Then, in addition to the random pattern, the structure exhibited a unique Surface Enhanced Raman Spectroscopy signal.

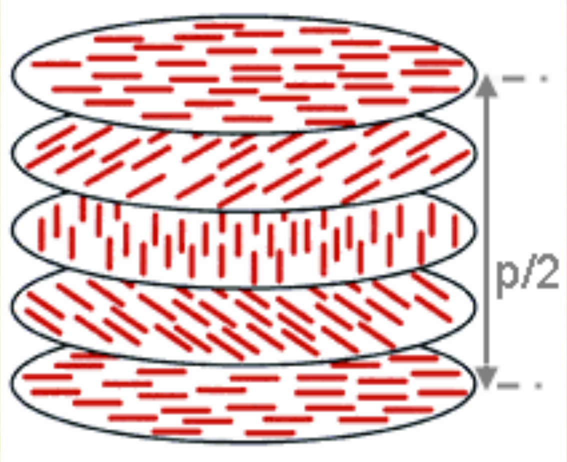
[1] H.J. Bae, S. Bae, C. Park , S. Han, J. Kim, L.N. Kim, K. Kim, S.-H. Song, W. Park and S. Kwon, Adv. Mater., 27, 2083 (2015).
[2] J. Kim, J.M. Yun, J. Jung, H. Song, J.-B. Kim and H. Ihee, Nanotechnology, 25, 155303 (2014).
[3] L. Tian, K.-K. Liu, M. Fei, S. Tadepalli, S. Cao, J.A. Geldmeier, V.V. Tsukruk and S. Singamaneni, ACS Appl. Mater. Interfaces, 8, 4031 (2016).

Cholesteric liquid Crystals (CLCs)

A **cholesteric liquid crystal** is a nematic material with an inherent helical structure, which can behave as a **unidimensional photonic crystal**.

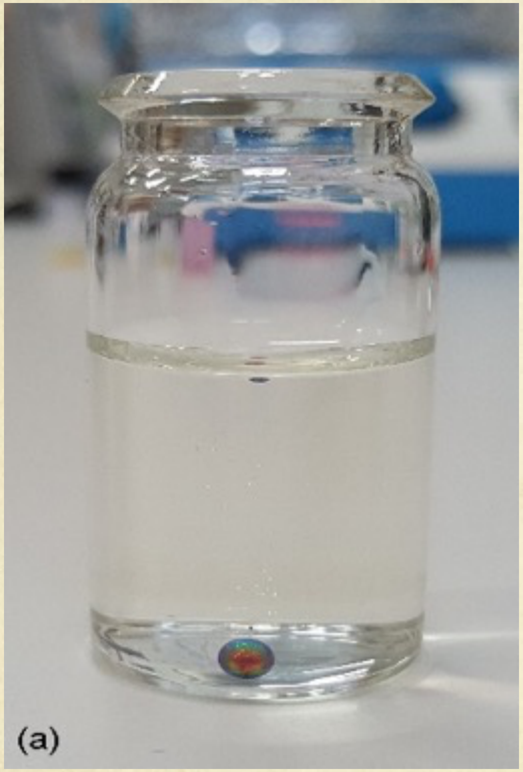
CLCs organize in layers without positional order, but the director rotates passing from a layer to another one, defining an helix.

The distance to have a full rotation is called *pitch* and this periodical structure determines Bragg reflection, so **CLCs are unidimensional photonic materials.**

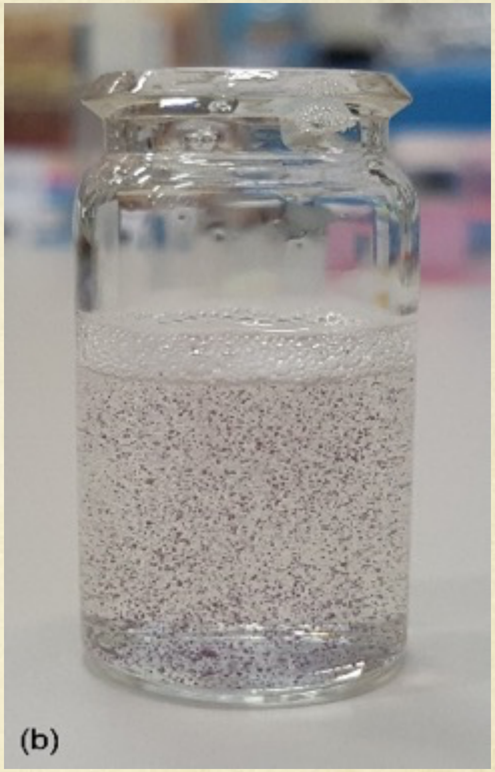


Materials:
- Nematic BL036 ($\Delta n = 0.25$, $\Delta\varepsilon > 0$) and chiral dopant R-2011 (Merck);
- Fluorescent dye Pyrromethene 650 from Exciton;
- Monomer RM-257 from Merck and photoiniziator Darocur 1173 from Ciba.

Cholesteric micro-droplets



Shaking procedure at 20 Hz for 40s, at a temperature of 40° C in a laboratory vortex mixer

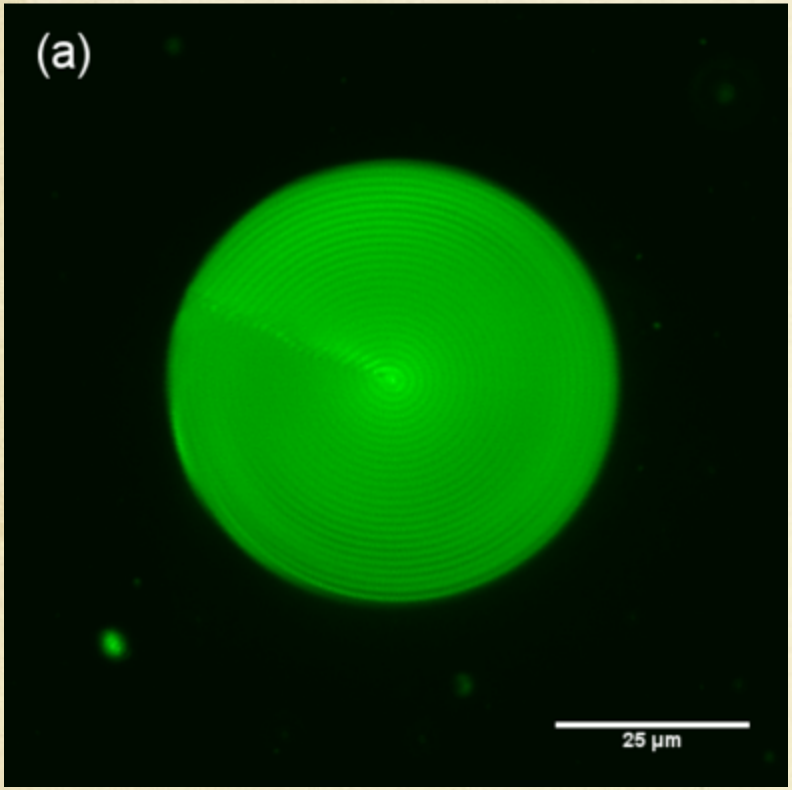


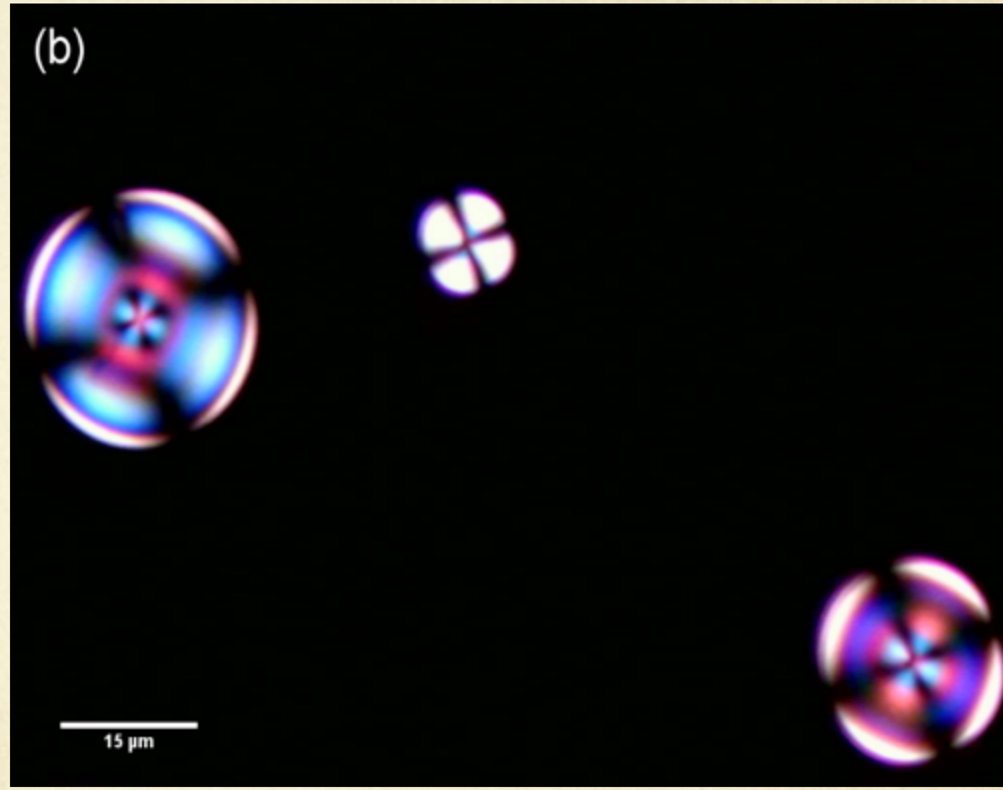
A millimetric drop of cholesteric liquid crystal in a glicerol matrix

Emulsion of micrometric cholesteric micro-droplets

Cholesteric micro-droplets

The emulsion is filled by capillarity inside an optical planar cell with conductive plates (ITO).
The thickness cell is about 200 μm.

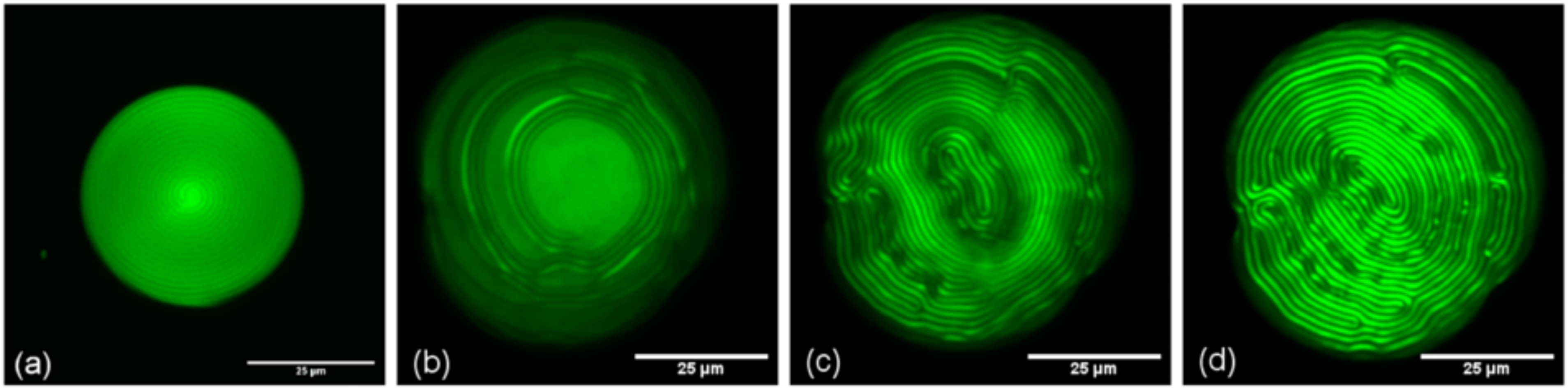




Cholesteric microsphere (d≈50 μm) observed through a Confocal Laser Scanning Microscope

Cholesteric microspheres observed through a standard polarizing optical microscope between crossed polarizers, with a well defined Maltese cross

Cholesteric micro-fingerprints

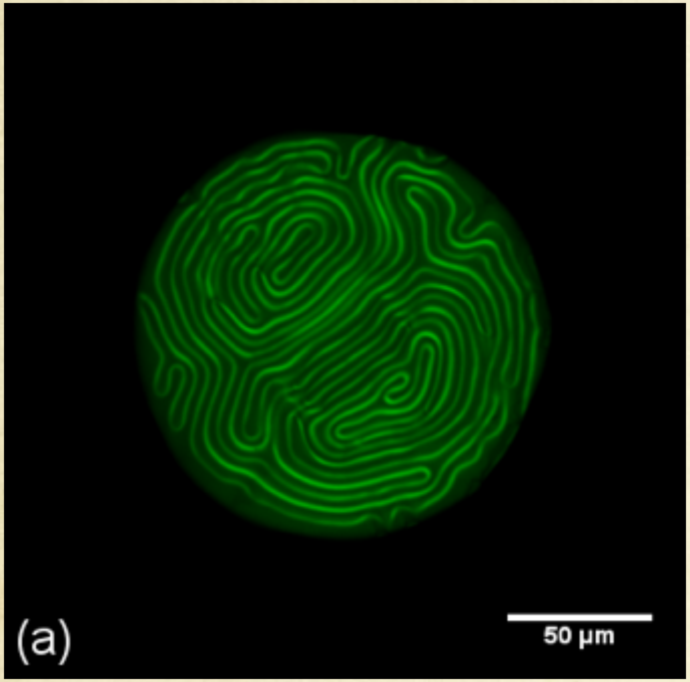


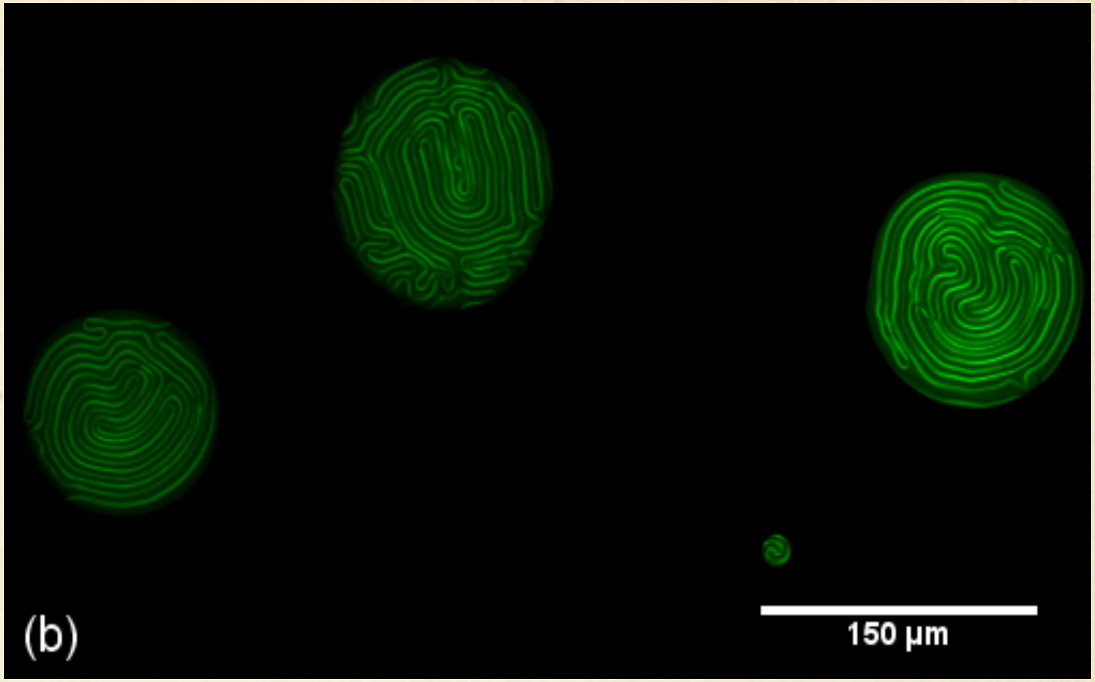
Confocal Laser Scanning Microscope images of the same droplet (d≈50 μm) with increasing external voltage passing from (a) to (d)

At about a V/μm and *f*≈1 Mhz, one observes fingerprint-like structures!!!

One also observes that the micro-droplet area increases about twice its original dimension. Since the droplet volume is fixed, such an increase in the planar direction leads to a shrinkage in the perpendicular direction, simplifying the observation of the fingerprint-like structures.

Cholesteric fingerprints examples





For practical applications, this texture has to be fixed and it can be obtained doping the CLC mixture with a monomer and a photoinitiator and inducing **photo-polymerization**. Irradiating the emulsion with a 100 W Mercury lamp, with the electric field on, fixed the fingerprint texture. After 2 minutes the UV lamp and the electric field were switched off and the fingerprint remained stable. The presence of monomer, RM-257, and photoinitiatior, Darocur 1173, (<4% in wt in total) did not affect the electric field parameters necessary to obtain the fingerprint structure. The fixed micro-fingerprints are stable for months.

Can we use cholesteric fingerprints with standard recognition software tools?

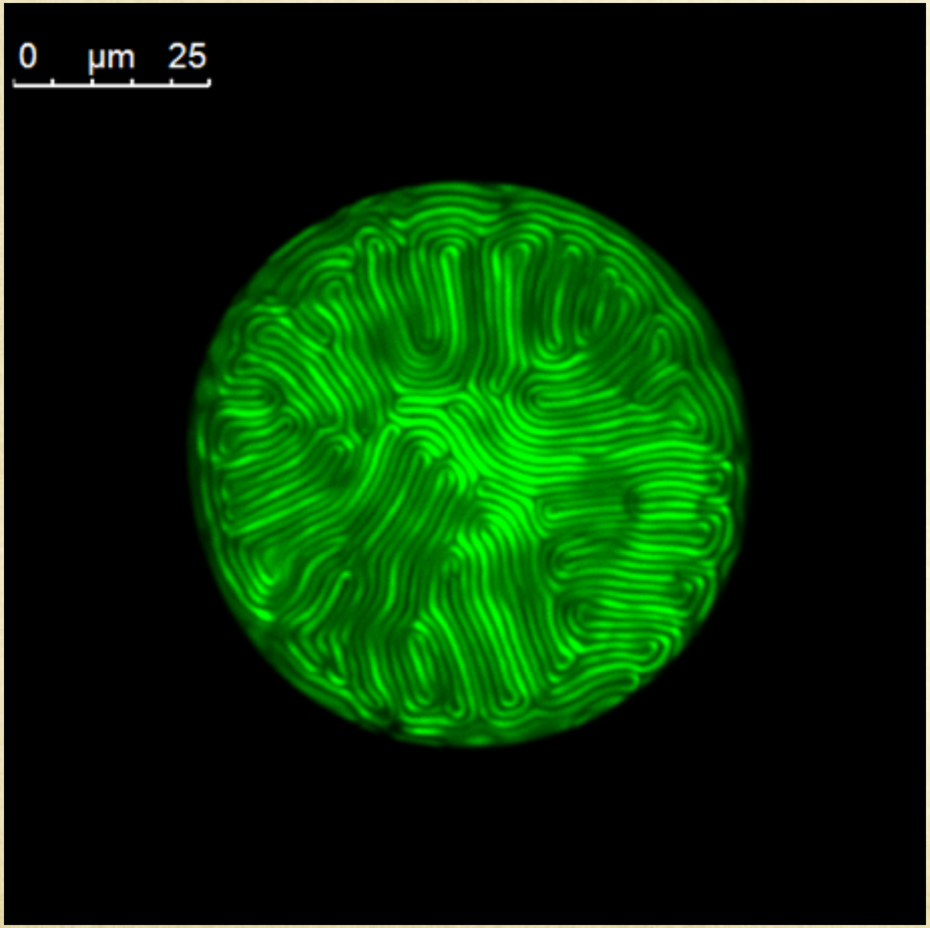
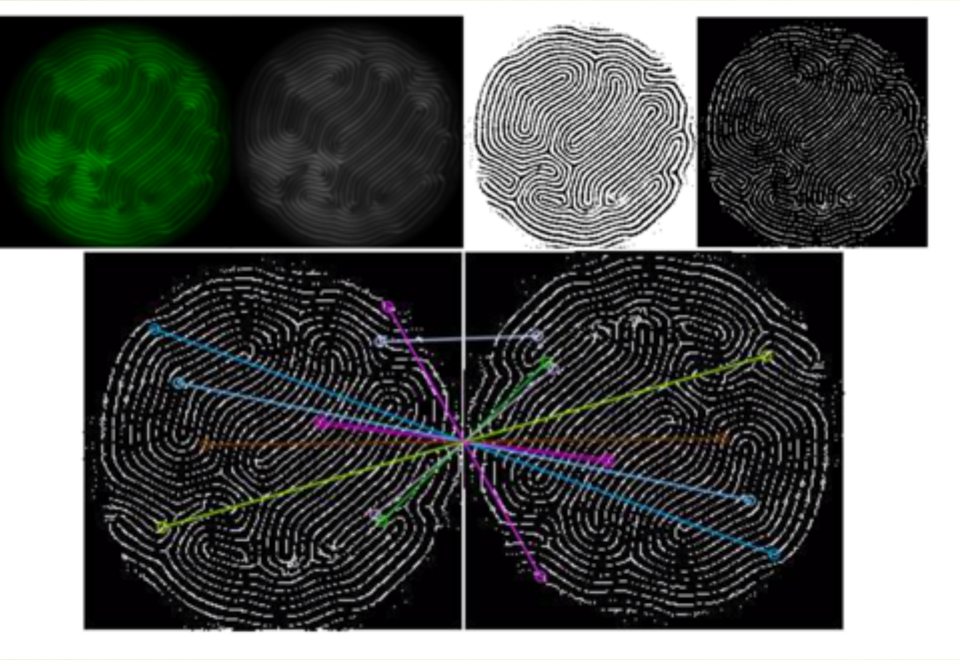


Image treatments:

- Grey scale
- Binarization/thresholding
- Skeletonization/thinning
- Minutiae recognition



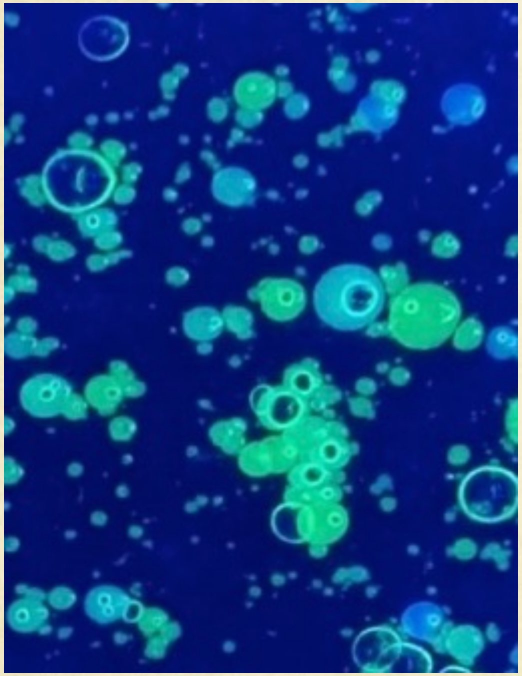
The software development has been carried out using the **Python** language and, as an external tool, the **OpenCV** library (Open source Computer Vision library).

Keypoints (minutiae) are recognized by means of the **ORB** technique [1]. ORB = oriented FAST (Features from Accelerated Segment Test) and rotated BRIEF (Binary Robust Independent Element Features).

Other extraction methods could be used: DoG, SIFT, SUSAN, Harris corner, ...).

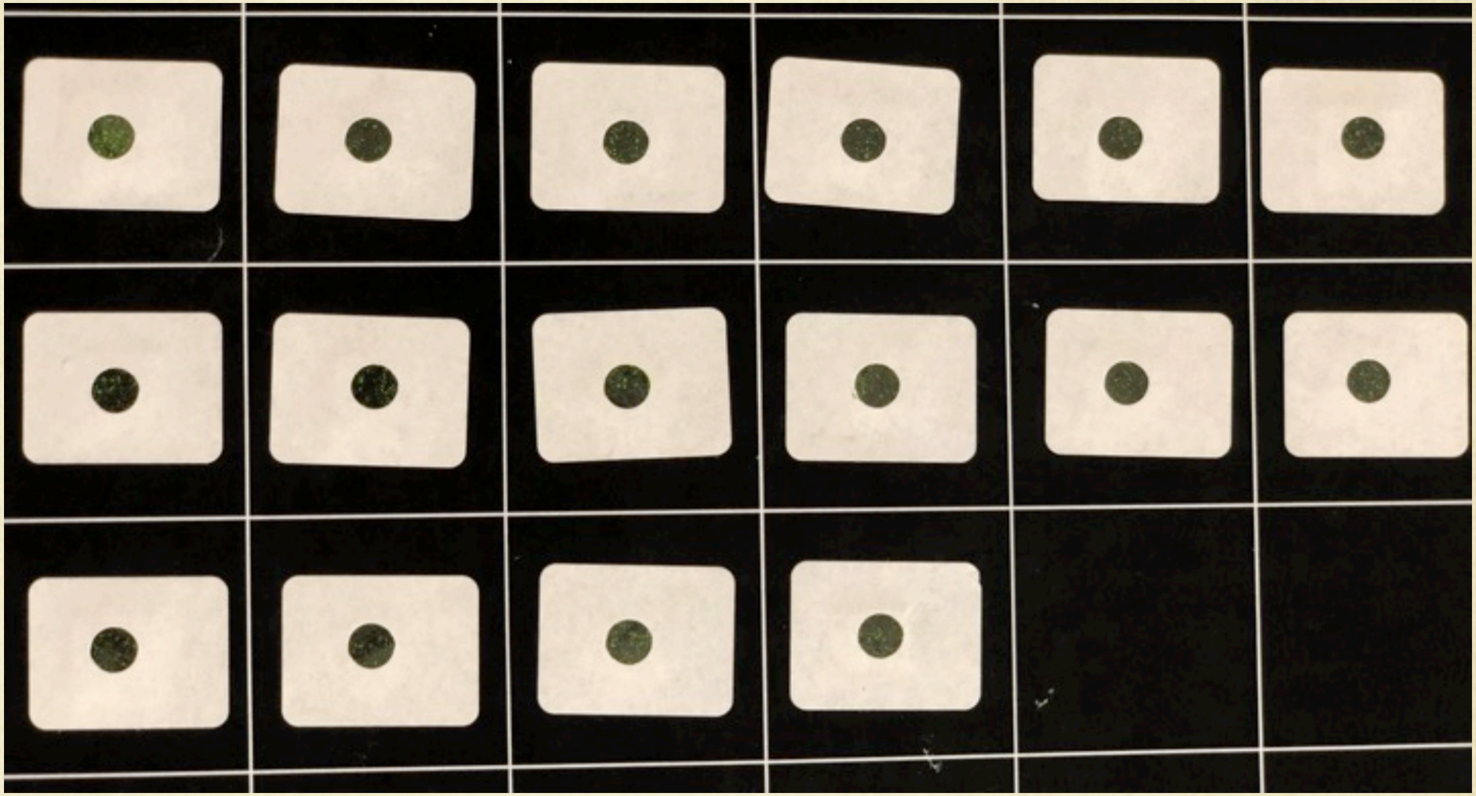
[1] E. Rublee, V. Rabaud, K. Konolige, and G. Bradski, *ORB: An efficient alternative to SIFT or SURF*, Proceedings / IEEE International Conference on Computer Vision, November 2011

Another (simpler) solution



Thin, flat, flexible plastic films
made by mixtures of polymers,
liquid crystals, dyes.
They present very complex,
unique, image details, with
also photonic properties.
They can be cut in any shape

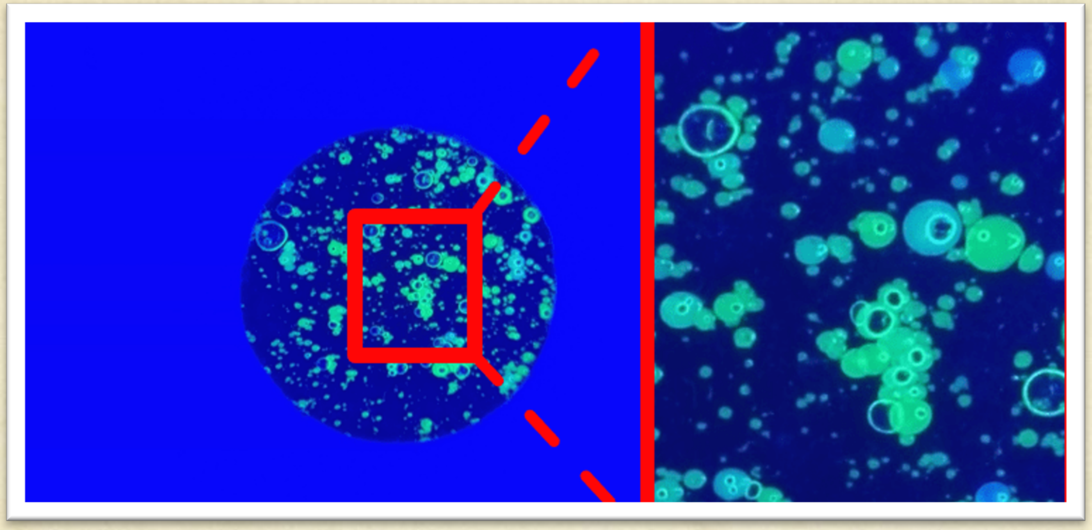
Circular tags of 6 mm in diameter on paper

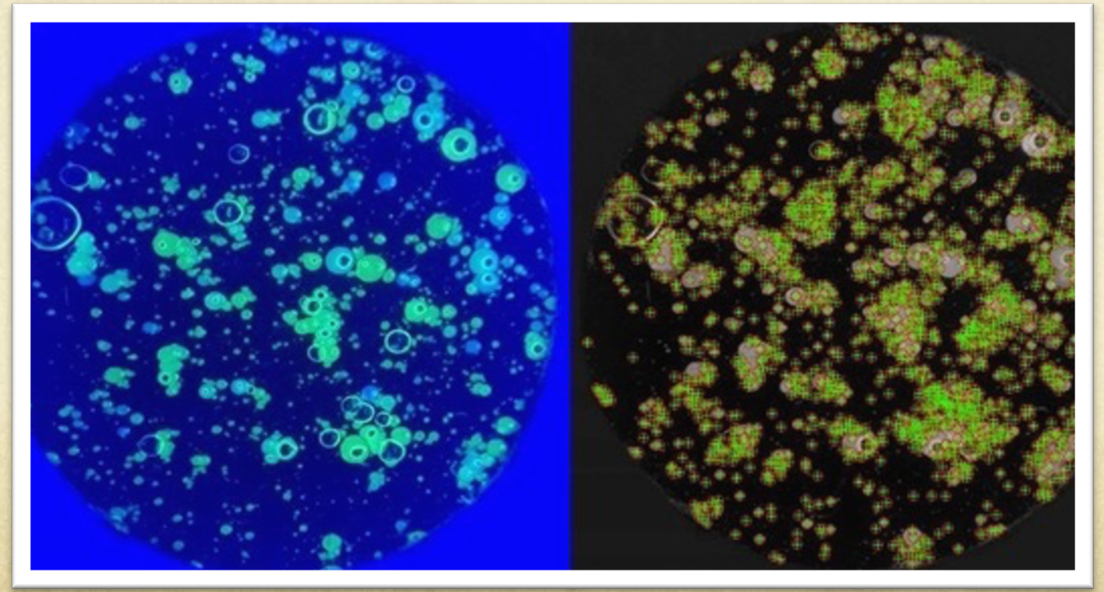


The circular tags can be read by using a cellular phone camera, a lens and UV photodiodes

Example of acquired image

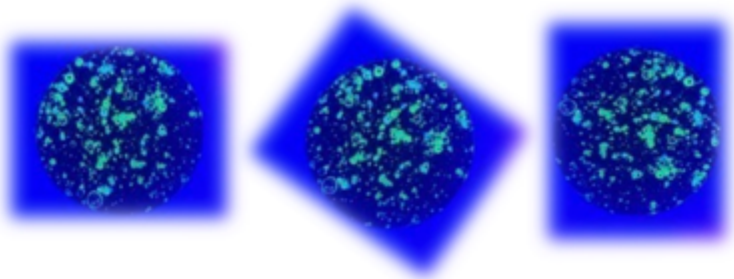
Details level

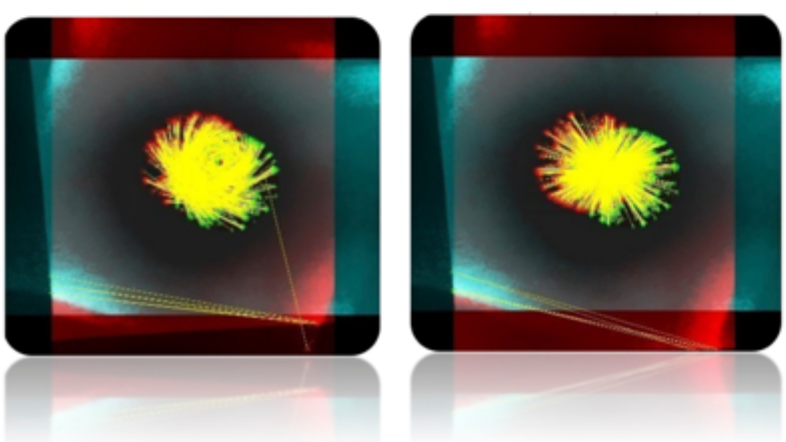




Features matching

The software recognizes the characteristic features regardless of the acquisition angle



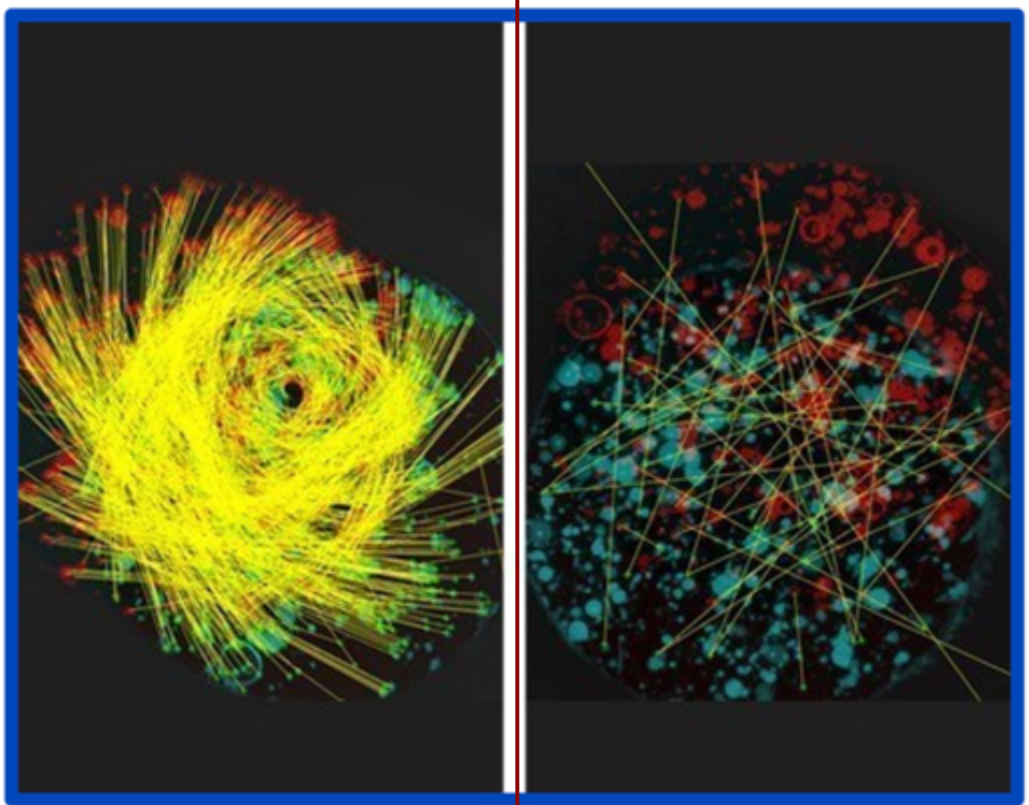


Features recognition

identical tag pictures with different acquisition angles

Features recognition

different tag pictures



Integration of a smart tag with a standard QR code

Conclusions

- Liquid crystals are suitable materials to generate (cheap) unclonable stable textures for advanced smart tags (with photonic properties!!!) satisfying requirements of the PUF paradigm
- Each label is unique and cannot be reproduced even by those who made it
- Standard software tools can be used for the tag recognition
- The picture acquisition procedure and the recognition software can be implemented in a common smartphone
- Overt and Covert protection till Forensic level