ScuDo
Scuola di Dottorato – Doctoral School
WHAT YOU ARE, TAKES YOU FAR

XXXV Cycle

Self-assembled hyperbolic metamaterial-based photonic devices for enhanced single-photon sources

Marwan Channab

Supervisors: Prof. C. F. Pirri/ Dr. A. Angelini

Research context and motivation

- **Hyperbolic metamaterials** (HMMs) show exotic optical properties that are unattainable in natural materials. HMMs are composed of a metal and a dielectric, indeed they show very appealing characteristics for what concerns their photonic properties due to their strong electrical permittivity anisotropy, in particular for applications related to **Quantum Computing**, **Quantum Communication** (i.e. Quantum Key Distribution) and also Bio-sensing. Because of the anisotropy in the optical behavior a hyperbolic isofrequency surface is generated and it theoretically leads to two interesting features: a directional emission and an infinity number of optical states (LDOS). This directly leads to an **enhancement of the spontaneous emission** for a photon source coupled with the metamaterial. Since most room-temperature single photon sources (SPS) are limited by their low emission rate and broadened emission spectrum, e.g. NV centers, the enhancement of spontaneous emission opens up different opportunities to overcome photon source limitations. In this work we present a fabrication method to obtain HMMs with an in-plane optical axis, desirable for different applications related to nanophotonics.

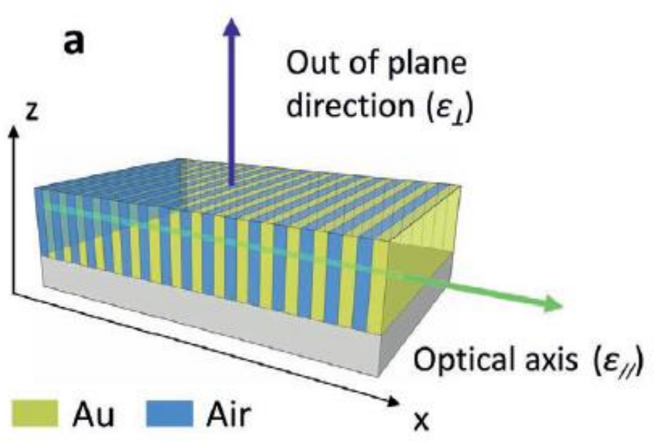

Fig. 1 Proposed HMM

Addressed research questions/problems

- The nowadays solid-state SPSs are characterized by the following issues:

1. Low temperatures functioning (2D materials and Quantum Dots)
2. Strong phononic coupling that leads to a broadband emission spectrum (NV centers)
3. Large lifetime values of the excited electronic states, therefore low emission rate (NV centers)

Increasing the intensity of the emitter without losing the single-photon source behavior to obtain an enhanced bit rate for the computation exploiting the HMM two main features: emission enhancement and emission directivity.

Adopted methodologies

- We have performed simulations with the software **Comsol Multiphysics 5.3** when coupled to a photon source (an electric dipole in the model). In particular, we have computed a frequency sweep to estimate the electric field distribution in the near field and the Purcell factor (see Fig 2.a), where the Purcell factor is estimated as the ratio between the total emitted power by the dipole when is placed 5 nm above the HMM and in an air domain. After the simulations and the **fabrication** of the proposed hyperbolic metasurface, see Fig 3.a-c, we have performed **optical characterizations**. In particular, we have measured the lifetime behavior of a single photon source (NV centers in diamond).

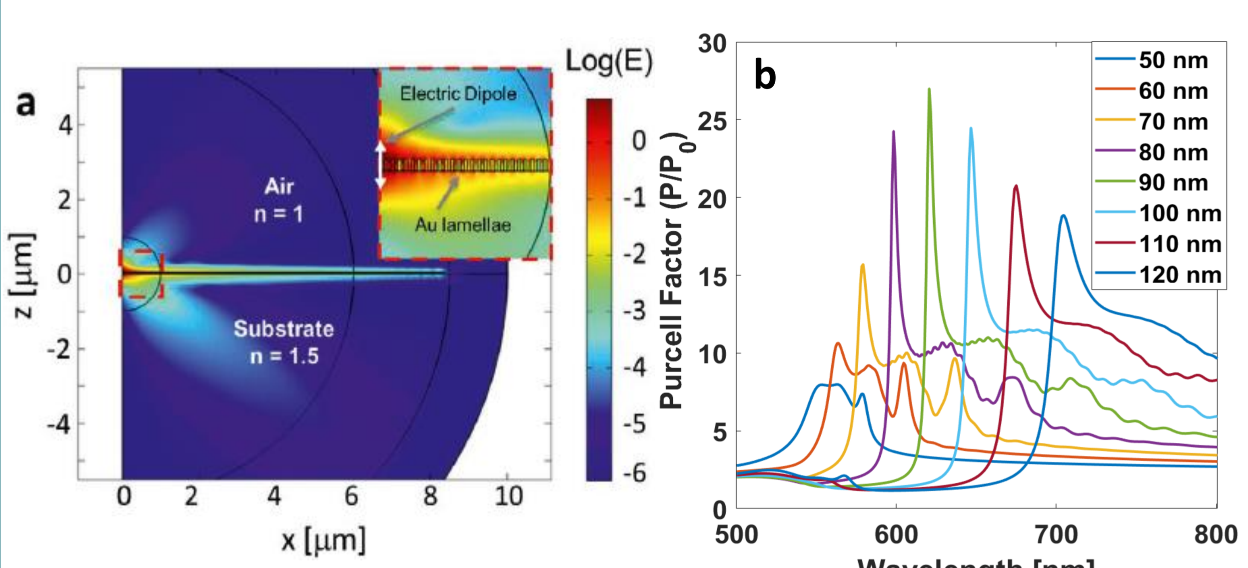

*Fig. 2 (**a**)Magnitude of the electric field in the near field for λ = 594 nm with the metamaterial. The inset shows a zoom of the region marked by the dashed red line. The white arrow in the inset represents the orientation of the dipole. (**b**)Simulated Purcell factor for different HMM heights.*

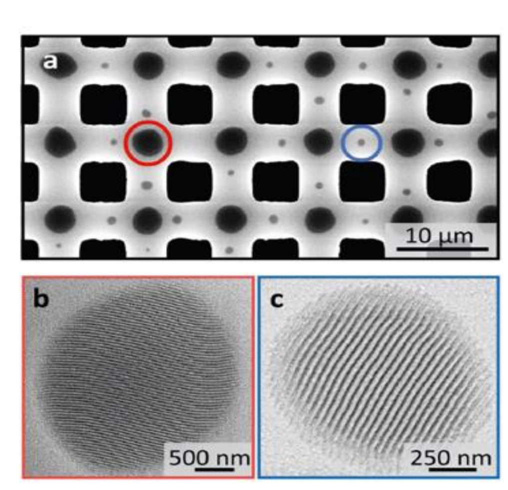

*Fig. 3 (**a**) SEM image of BCP blend dewetting over a large-area substrate. (**b,c**) SEM images of lamellar nanostructured droplets in a single grain configuration related to highlighted areas in figure 3.a*

Submitted and published works

- Murataj, Irdi, Channab Marwan et al. "Hyperbolic Metamaterials via Hierarchical Block Copolymer Nanostructures“, Advanced Optical Materials 9.7 (2021), **Published paper**
- Channab, M.; Pirri, C.F.; Angelini, A. “Funneling Spontaneous Emission into Waveguides via Epsilon-Near-Zero Metamaterials”, Nanomaterials 2021, 11, 1410, **Published paper**
- Channab, M.; et al. “Hyperbolic metamaterials via Hierarchical block copolymers Nanostructures”, Photonica 2021 **Conference**, Belgrade,
- Channab, M.; et al. “Hyperbolic metamaterials via Hierarchical block copolymers Nanostructures”,Nanoplasm 2022 **Conference**, Cetraro
- Channab, M.; et al. . “Funneling Spontaneous Emission into Waveguides via Epsilon-Near-Zero Metamaterials”, MNE 2021 **Conference**, Turin
- Channab, M.; et al. “Funneling Spontaneous Emission into Waveguides via Epsilon-Near-Zero Metamaterials”, OSA Congress 2021, Montreal, **Conference**
- Channab, M.; et al. “Hyperbolic metamaterials via Hierarchical block copolymers Nanostructures”, Metamaterials 2022, Siena, **Conference**

Novel contributions

- We propose the use of the **dewetting of block copolymer (BCP)**/homopolymer blend thin film to efficiently fabricate hyperbolic metamaterials (HMM). We exploit this process to obtain an Au/air lamellar structure that shows an in-plane optical axis. The complete fabrication process is described in Fig.4.d. The pattern transfer process onto a flexible substrate creates an Au/air HMM with hyperbolic dispersion in a broad wavelength range in the visible spectrum.

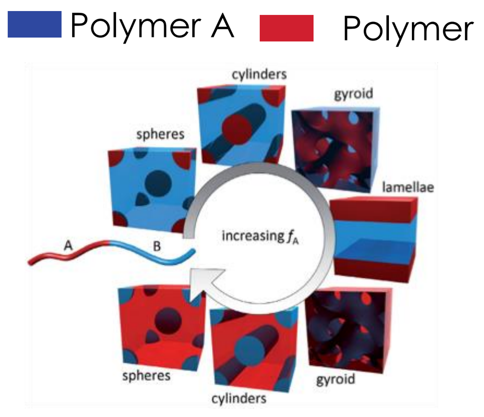

Fig. 4 Possible morphologies that can be achieved through BCP self-assembly

Yu-Chih Tseng et al., Polymers 2010

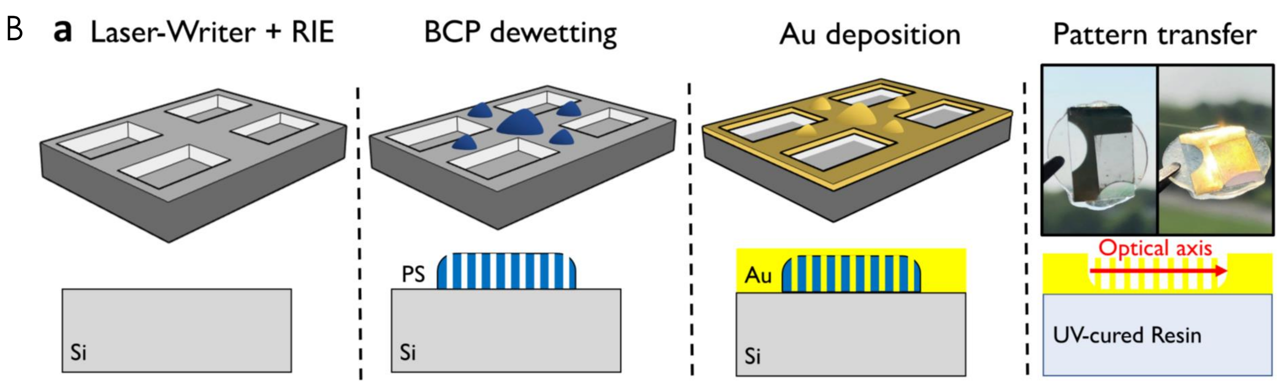

Fig. 5 Schematic fabrication process of the HMM based on hierarchical BCP blend film dewetting over topographical templates.

Murataj, Irdi, et al. "Hyperbolic metamaterials via hierarchical block copolymer nanostructures." *Advanced Optical Materials* 9.7 (2021)

Results

- We have obtained a strong reduction in the measured fluorescence lifetime of NV centers in nanodiamonds placed on top of the fabricated HMM. This measurement is compatible with the computed Purcell factor estimated for structures with 70 nm height that is equal to 32 at λ = 580 nm, see figures 2.a and 2.b.

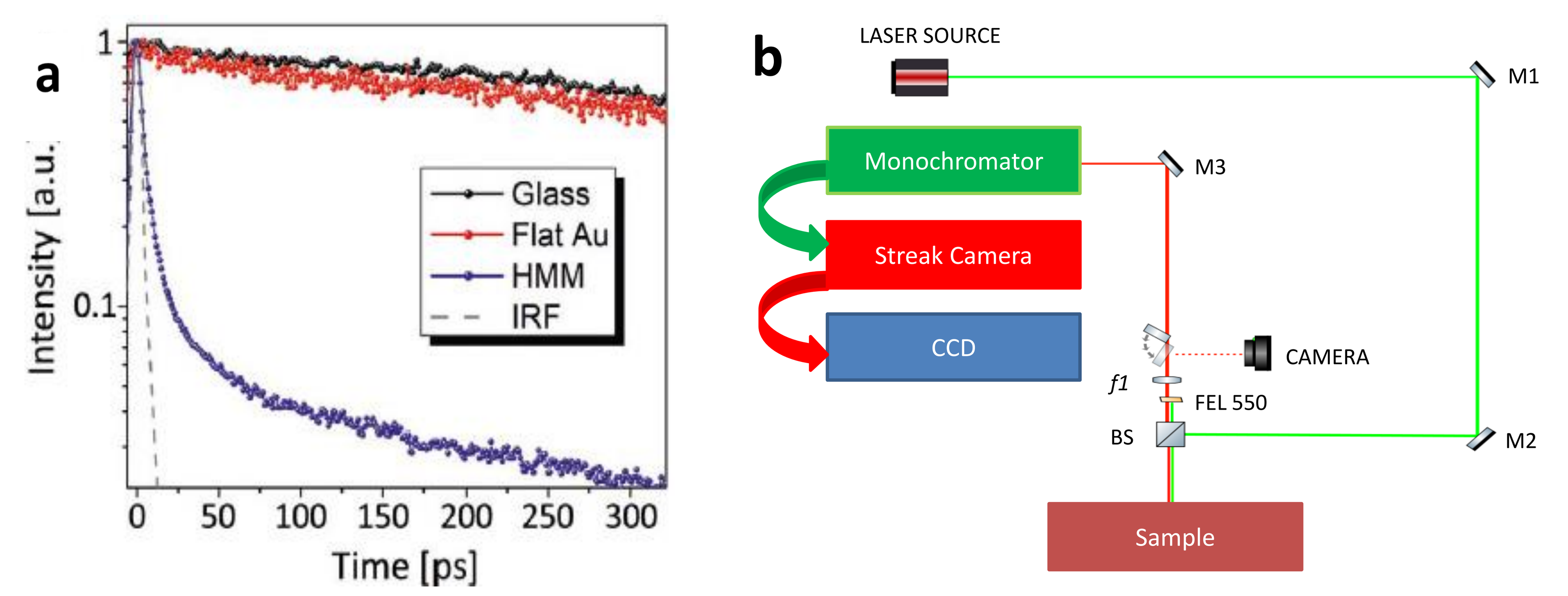

*Fig. 4 (**a**) Lifetime fluorescence measurements for NV centers in nanodiamonds in different conditions: above glass (black), flat Au (red), and HMM (blue). (**b**) Schematic of the setup used for the lifetime measurements*

Future work

- We propose a **diamond-based nano-probe** to measure the PL spectrum modification due to the coupling of an emitting source with the hyperbolic metasurface. The nano-probe is composed of an AFM tip with a nanodiamond with NV centers on top of its tip. Exploiting this technique it should be possible to scan the sample LDOS.

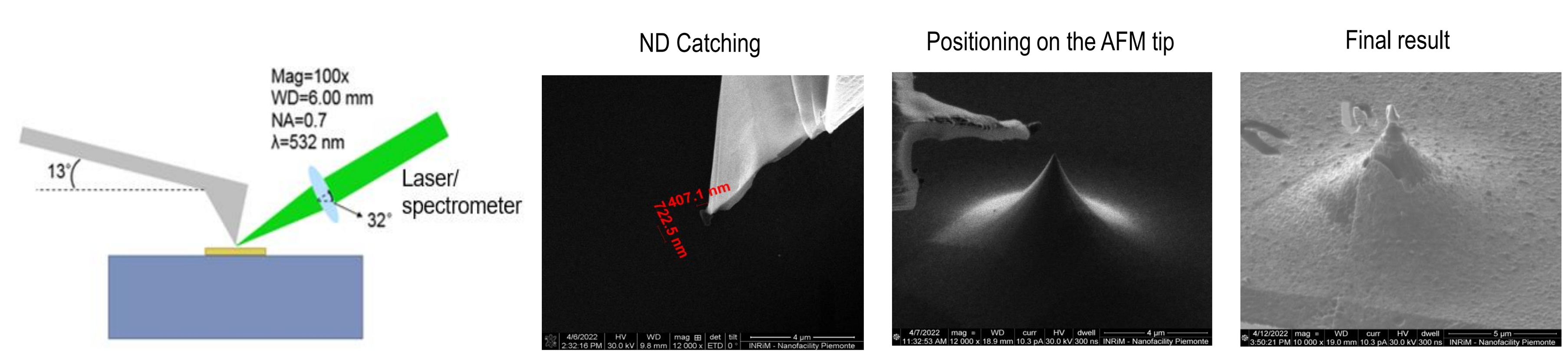

*Fig. 4 (**a**) It is also schematically reported the functioning of the photoluminescence measurement by means of the proposed modified AFM tip (**b**) Schematic of the steps necessary for the fabrication of the modified AFM tip.*

List of attended classes

- 01SINPG Antropologia dei contesti scolastici ed educativi (16/6/2021, 6 CFU)
- 02LWHRV Communication (05/02/2020, 1 CFU)
- 01SIOPG Didattica, tecnologie e ricerca educativa (23/07/2021, 6 CFU)
- 01SHMRV Entrepreneurial Finance (14/02/2020, 1 CFU)
- 01DMLKG Introduzione alla microscopia ottica - Scienza e Tecnologia (didattica di eccellenza vp) (24/03/2022, 4 CFU)
- 01QCOKG Introduzione all'ottica e all'informazione quantistiche (20/02/2020, 4 CFU)
- 01QUWRV Mathematical-physical aspects of electromagnetism(23/09/2020, 3 CFU)
- 01SFVRV Metamaterials: Theory and multiphysics applications (17/04/2020, 4 CFU)
- 01MLHKG Microscopia a scansione di sonda per la fisica e l'ingegneria (01/06/2021, 6 CFU)
- 01SILPG Pedagogia della scuola e dell'inclusione (19/07/2021, 6 CFU)
- 02SFURV Programmazione scientifica avanzata in matlab (27/04/2021, 6 CFU)
- 01RISRV Public speaking (15/01/2020, 1 CFU)
- 02RHORV The new Internet Society: entering the black-box of digital innovations (19/02/2020, 1 CFU)
- 01SYBRV Research integrity (14/02/2020, 1 CFU)
- 01SWPRV Time management (28/01/2020,1 CFU)
- 01QORRV Writing Scientific Papers in English (20/02/2020, 3 CFU)

External courses:

- Quantum communication (5/06/2020, 3 CFU)
- Introduction to Quantum Technologies (25/06/2021, 4 CFU)
- COMSOL Multiphysics® Intensive Course