# Bound in the continuum modes and multimodal physics in indirectly-patterned hyperbolic media


**Hanan Herzig Sheinfux[1]**

Lorenzo Orsini[1], Minwoo Jung[2], Iacopo Torre[1], Matteo Ceccanti[1], Rinu Maniyara[1], David Barcons Ruiz[1], Sebastian Castilla[1], Niels C.H. Hesp[1], Eli Janzen[3], Valerio Pruneri[1], James H.

*1 ICFO-Institut de Ciencies Fotoniques, 08860 Castelldefels (Barcelona), Spain*

*2 Department of Physics, Cornell University, Ithaca, New York, 14853, USA*

*3 Department of Chemical Engineering, Kansas State Uni., Durland Hall, Manhattan, KS 66506-5102, USA*

*4 School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA*

lightmatterinteractions@gmail.com


The general premise of nanophotonics involves shrinking light to the subwavelength nanometric scale, thereby compressing and enhancing light-matter interactions. Innovations in nanocavity design approach new regimes of light-matter-interactions[1]. However, shrinking light typically comes at a cost – absorption losses, which plague all existing nanocavity designs. Fig. 1a visually summarizes the state of the art in nanocavity research, showing that cavity performance progressively worsens beneath the 100 nm scale (i.e. for $V < 10^{-4}\,\lambda_0^3$, with $\lambda_0$ the vacuum wavelength). A possible route to strong nanoscale confinement lies with hyperbolic Phonon polaritons (PhPs), which can exhibit very high momenta modes. Indeed cavities with $Q > 200$ and of sizes of $\sim 300$ nm have been demonstrated in hexagonal Boron Nitride (hBN) [2]. However, further size reduction is inhibited by nanoscale damage intrinsic to the conventional cavity design.

Here, we use ideas from bound in continuum (BIC) physics [3] to make nanocavities that combine high-quality factors with ultra-small modal volumes, reaching the previously unattainable $Q > 100$ in a cavity size <100nm and with mode volume confinement above $10^9$. Unlike conventional cavities our nanocavities are indirectly patterned and consequently, the cavity modes have a plethora of modes the cavity can couple to. Accordingly, cavity is performance is limited by leakage to impedance mismatched modes outside of the cavity. But to our surprise, we find the cavities perform significantly better then expected from impedance mismatch considerations. We attribute this quality factor enhancement to a novel model of multimodal reflection. We investigate this multimodal reflection mechanism in both theory and experiment (using scattering-type near-field microscopy) and show it's conceptual relation to a new (hyperbolic) type of BICs.

## REFERENCES


[1] Baumberg, J. J., Aizpurua, J., Mikkelsen, M. H. & Smith, D. R., *Nature Materials,* 18 (2019).

[2] Tamagnone, M. *et al. Arxiv, 1905.02177,* (2019).

[3] Hsu, C. W., Zhen, B., Stone, A.D., Joannopoulos, J.D., Soljačić, Marin, *Nat. Rev. Mater.* **1**, 16048 (2016).


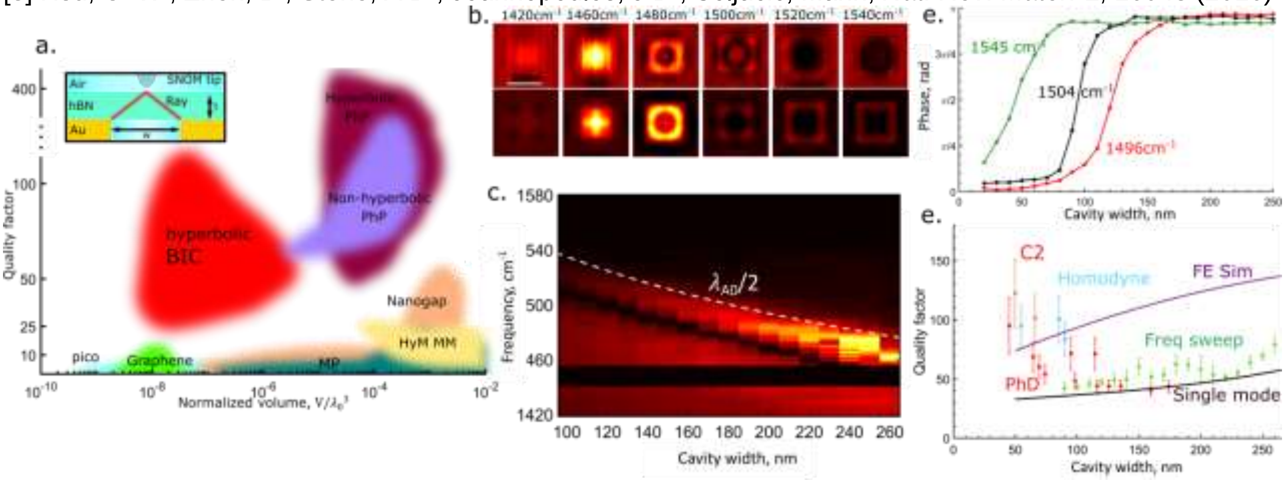


**Figure 1: a.** Survey of nanocavity quality factors and volumes. Different colors correspond to reported values of different cavity types (HyM MM stands for hyperbolic metamaterial, MP stands for metallic particle) and the red blob represents the values in this work. Inset shows system schematics **b.** Measured nearfield signal at different excitation wavelengths, showing the passage through a resonance in a 200nm wide cavity **c.** Spectrum of cavity response as a function of the cavity width. The narrowness of the spectral response is indicative of high quality factors. The weakening of the signal below 100nm size is due to sample drift and detailed measurements show that the quality of the cavity does not diminish. The white line represents the half wavelength of the zero order PhP mode, where the cavity mode is expected. **d.** Measured SNOM phase as a function of cavity showing a π phase-jump across the resonance. **e.** Quality factor vs. cavity. Solid black line shows the theoretical upper-bound limit that can be attained by neglecting higher order modes and the purple line is a finite element simulation that includes the ray-like propagation and reflection. The measured values have been extracted by three different type of measurements (see SI): frequency sweeps (green), pseudoheterodyne scans (red for cavity set C1 and orange for cavity set C2) and homodyne amplitude scans (light blue). Different extraction methods are in general agreement and in all cases exceed the single mode theory. Theory and simulations are for a 25nm h11BN flake, similar to cavity set C1.