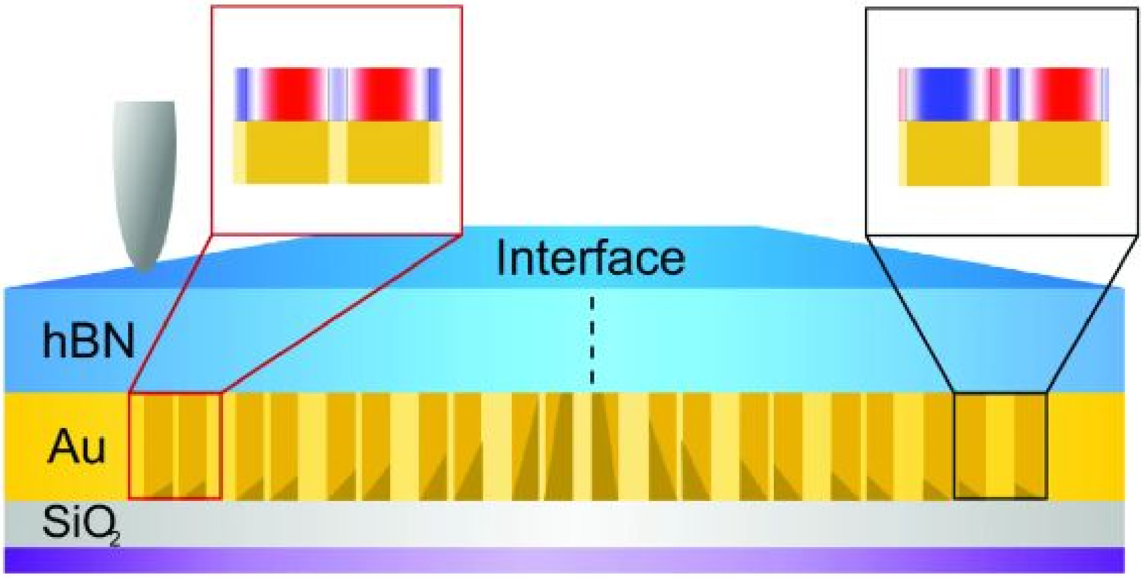

First demonstration of deep subwavelength topological edge states

ICFO leads the first experimental demonstration of a deep subwavelength topological edge state within a nanophotonic system, a turnover in the field of topological Nanophotonics.

September 03, 2024

Topological systems are a foundational and versatile **class of physical systems**, ubiquitous across many fields of physics, with far-reaching implications for both fundamental research and applied technological advancements. These systems are characterized by properties that make them resilient to perturbations. In simpler terms, they possess certain qualities that are not easily affected by external factors, like disorder or changes in other physical conditions. This resilience to perturbations is what makes topological systems so important in physics, as it means their behaviour can be very predictable and reliable under a wide range of conditions. Of particular interest are the topological edge states: states that exist at the boundary of a material and that cannot be suppressed without breaking the material's symmetry.

Topological Nanophotonics: challenges and opportunities

The scientific community, typically attracted by those challenges that are as complex as they are promising, sees the task of bringing topological properties down to the nanoscale as an appealing challenge. Complex because of the ultimate spatial limits of electromagnetic field manipulation that are required; and promising because of the expected consequences, being both fundamental and applied.

To begin with, miniaturizing topological properties to such small physical scales (in the jargon, the **deep subwavelength regime**) would allow the scientific community to explore exotic physical phenomena (nonlinearities, non-locality, multimodal interactions...) that are expected to arise under these circumstances. On a more practical side, topological systems' inherent robustness and protection can be harnessed to develop more resilient deep subwavelength optical components, such as nanocavities or fabrication-disorder tolerant waveguides.

Despite the experimental progress towards achieving topological edge states in the deep subwavelength regime, each proposed platform exhibits some benefits but also some major drawbacks, maintaining the 'hot-topic' status in the search for the ultimate solution.

An international team with ICFO researchers **Lorenzo Orsini**, **Dr. Hanan Herzig Sheinfux**, **Matteo Ceccanti**, **Karuppasamy Soundarapandian**, led by **ICREA Prof. at ICFO Dr. Frank H. L. Koppens**, and in collaboration with Cornell University, CNRS, University of Cambridge and Kansas State University, has now reported in a Nature Nanotechnology article a substantial advancement in this regard. **For the first time, they have demonstrated a deep subwavelength topological edge state within a nanophotonic system**, where the chosen platform -typically not considered by the topological Nanophotonics community- was based on the so-called hyperbolic phonon-polaritons (in short, HPhPs). Not only did they confine light into such small size scales, but **they also maintained high quality factors** through the whole process.

Why hyperbolic phonon-polaritons?

Hyperbolic phonon-polaritons are a type of collective electromagnetic excitation that occurs in hyperbolic materials, where electromagnetic waves (photons) couple with the quanta of vibrations within the atomic lattice of a material (optical phonons). These HPhPs allow light to be confined and guided in very small volumes or along surfaces. ?

Thanks to their special features, HPhPs overcome the challenges faced by previous method for studying topological properties at the nanoscale. These limitations include, for instance high optical absorption -which is detrimental to reaching the deep subwavelength regime i the case of plasmon polaritons-, fabrication difficulties and the need for cryogeni temperatures -which hinder the realization of topological states in the case ofgraphene.

With **hyperbolic phonon-polaritons** these problems are minimized, since they **exhibit low absorption even at room temperature and can be relatively easy to fabricate**. These features, together with the fact that they allow for **high volume confinement**, give HPhPs excellent performance characteristics. As attractive as they may seem, HPhPs have been largely unexplored for topological applications due to their deeply complex nature, which has hindered theoretical development in this area.

Nevertheless, the team saw in the hyperbolic phonon polaritons great promise, and their ambitious goal stir them into action. ï¿½At the beginning of the project, it was uncertain h w these edge states would manifest and what specific properties they would exhibitï¿½, sh res Lorenzo Orsini, first author of the article. ï¿½While we anticipated their formation, f nally observing them in our experiments was a fascinating confirmation of our expectations nd an exciting development in the fie

The experimental setup that led to success

To enable the emergence of topological edge states, the team constructed a one-dimensional polaritonic lattice platform.

First, they sharply defined rectangular holes periodically milled through a 10-nanometer gold film. On top of that, they placed a tens of nanometers thick hexagonal Boron Nitride (hBN) flake. In there, hyperbolic phonon-polaritons would be hosted. The gold layer structure was engineered such that there were two different distributions of the rectangular holes, defining two distinct regions, one next to the other. The researchers expected that, due to the presence of two different arrangements, topological edge states would form right at the boundary where both meet.

After the fabrication process, the characterization and analysis of the system took place. They used the s-SNOM (Scattering-type Scanning Near-field Optical Microscopy) spectroscopy technique to confirm the existence of a localized edge state and that it was indeed in the deep subwavelength regime.

Because of the scarcity of theoretical models, they had to rely heavily on their own experimental results, which made the need to meticulously prove and double-check each step even more crucial than usual. This rigorous, step-by-step approach allowed them to refine the experimental design and achieve clear, reliable results, **finally demonstrating deep subwavelength topological edge states within an HPhPs platform**.

The powerful potential of HPhPs platforms

In addition to the relevance inherently present in this milestone by itself, the present study also constitutes a big step forward toward the precise control of light at the nanoscale, offering an alternative platform for the realization and investigation of topological physics in nanophotonic systems. Moreover, the authors claim that their results can be extrapolated to other hyperbolic materials, something that would facilitate a broader coverage of the

electromagnetic spectrum.
As Orsini concludes: ï¿½In the end, taking a chance on hyperbolic phonon polaritons paid of
, and now we have opened new possibilities for robust and precise control of light at t
e nanoscale. A continued exploration and development in this direction could, in turn, lead
o breakthroughs in areas as diverse as telecommunications, sensing technologies or quant
m information processingï?

Reference:
Orsini, L., Herzig Sheinfux, H., Li, Y. et al. Deep subwavelength topological edge state in a hyperbolic medium. Nat. Nanotechnol. (2024). https://doi.org/10.1038/s41565-024-01737-8

Acknowledgements

We thank D. B. Ruiz, S. Castilla, D. De Fazio, M. Amir Ali, G. Li, A. Berdyugin, M. Polini, V. Mkhitaryan, G. Kumar, and I. Torre for technical discussions. We further thank M. Ceccanti for making the illustration presented in Fig. 1a. H.A., K.N. and R.B. acknowledge funding from the European Union's Horizon 2020 research and innovation programme under Marie Sk?odowska-Curie grant agreement no. 665884, 713729 and 847517, respectively. S.B.-P. acknowledges funding from the Presidencia de la Agencia Estatal de Investigacion within the PRE2020-094404 predoctoral fellowship. G.S. and A.F. gratefully acknowledge funding from the ERC grant CHIC (no. 724344), and J. Faist for discussions. A.P. acknowledges support from the European Union's Horizon 2020 research and innovation programme under Marie Sklodowska-Curie grant agreement no. 873028 and from the Leverhulme Trust under grant agreement RPG-2019-363. K.W. and T.T. acknowledge support from the Elemental Strategy Initiative conducted by MEXT Japan with grant no. JPMXP0112101001, JSPS KAKENHI (JP19H05790, JP20H00354 and JP21H05233) and CREST (JPMJCR15F3), JST. R.K.K. acknowledges the EU Horizon 2020 programme under MarieSk?odowska-Curie grants 754510 and 893030 and the FLAG-ERA grant (PhotoTBG, PCI2021-122020-2A), by ICFO, RWTH Aachen and ETHZ/Department of Physics. A.B. acknowledges support from ERC advanced grant no. 692876, MICINN grant no. RTI2018-097953-B-I00 and PID2021-122813OB-I00, AGAUR (grant no. 2017SGR1664), the Fondo Europeo de Desarrollo, the Spanish Ministry of Economy and Competitiveness through Quantum CCAA, EUR2022-134050, and CEX2019-000910-S [MCIN/AEI/10.13039/501100011033], MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1), Fundacio Cellex, Fundacio Mir-Puig, Generalitat de Catalunya through CERCA. F.H.L.K. acknowledges support from the ERC TOPONANOP (726001), Fundacio Cellex, Fundacio Mir-Puig, Generalitat de Catalunya (CERCA, AGAUR, SGR 1656, program TWIST), the Government of Spain [PID2019-106875GB-I00; PCI2021-122020-2A; PDC2022-133844-I00 (Teracomm); Severo

Ochoa CEX2019-000910-S] funded by MCIN/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR. Furthermore, the research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 881603 (Graphene flagship Core3), 820378 (Quantum flagship) and 101034929 (Fastera). This material is based upon work supported by the Air Force Office of Scientific Research under award number FA8655-23-1-7047. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Air Force.