

Visible-frequency long-distance subwavelength focusing via surface plasmon hyperbolic polaritons (SPHPs)

Zhengjun Zhang

z.jzhang@tsinghua.edu.cn

Tsinghua University <https://orcid.org/0000-0001-8727-6373>

Jianqiao Zhao

Tsinghua university, School of Materials Science and Engineering

Yuxin Zhang

Peking University

Xiaotian Xue

Tsinghua University

Haodong Zhong

Tsinghua University

Tongzhou Xu

Tsinghua University <https://orcid.org/0009-0006-8210-7486>

Yaolong Li

Peking University <https://orcid.org/0000-0002-1457-190X>

Jingbo Sun

Tsinghua University <https://orcid.org/0000-0002-6947-2984>

Weipeng Wang

Tsinghua University <https://orcid.org/0000-0002-1576-3700>

Ji Zhou

Tsinghua University <https://orcid.org/0009-0006-4523-2421>

Shufeng Wang

Peking University <https://orcid.org/0000-0003-3536-8000>

Article

Keywords:

Posted Date: March 13th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9015011/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Visible-frequency long-distance subwavelength focusing via surface plasmon hyperbolic polaritons (SPHPs)

Jianqiao Zhao^{1,‡}, Yuxin Zhang^{2,‡}, Xiaotian Xue^{1,‡}, Haodong Zhong¹, Tongzhou Xu¹, Yaolong Li²,
Jingbo Sun³, Weipeng Wang^{1*}, Ji Zhou³, Shufeng Wang^{2,4,5*}, and Zhengjun Zhang^{1*}

¹ Key Laboratory of Advanced Materials (MOE), School of Materials Science and Engineering,
Tsinghua University, Beijing 100084, China.

² State Key Laboratory for Mesoscopic Physics & Department of Physics, Collaborative
Innovation Center of Quantum Matter & Frontiers Science Center for Nano-optoelectronics,
Peking University, Beijing 100871, China.

³ Key Laboratory of New Ceramics and Fine Processing, School of Materials Science and
Engineering, Tsinghua University, Beijing 100084, China

⁴ Peking University Yangtze Delta Institute of Optoelectronics, Nantong, Jiangsu 226010, China.

⁵ Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006,
China.

[‡] Authors contribute equally.

* Corresponding Authors: zjzhang@tsinghua.edu.cn; wangsf@pku.edu.cn;
wpwang@tsinghua.edu.cn

18 **Abstract**

19 Hyperbolic polaritons offer a promising approach for subwavelength light confinement and
20 manipulation. While extensively explored across mid-infrared to terahertz bands, achieving long
21 distance focusing at visible frequency remains challenging due to the trade-off between long
22 propagation and strong compression. In this work, we demonstrate a mode-selection strategy and
23 experimental approach to achieve long-distance subwavelength in-plane focusing at visible
24 frequency. By integrating an Au metastructure with the natural hyperbolic material MoOCl_2 , we
25 convert surface plasmon polaritons (SPPs) into surface plasmon hyperbolic polaritons (SPHPs),
26 enabling selective excitation and focusing of the low-momentum (low- k) mode in the hyperbolic
27 material. Furthermore, by modulating the thickness of the MoOCl_2 layer, we leverage the intrinsic
28 high- k component to synergistically enhance both long propagation distance and strong field
29 compression. Using transmission-mode scanning near-field optical microscopy (SNOM) and
30 quantitative methods, we demonstrate a focal length of 2.5λ and a focal spot with a full width at
31 half maximum (FWHM) of $\lambda/5$ under 633 nm excitation, accompanied by a three-fold energy
32 enhancement. This visible-band long-focus system offers significant potential for non-contact
33 nanoscale probing, integrated photonics, and optical interconnects. The proposed mode-selection
34 methodology provides a versatile design paradigm for coupling hyperbolic polaritons with
35 multiple plasmonic excitations, paving the way for advanced applications in photonic information
36 processing.

Introduction

Achieving deep subwavelength control of light is a crucial challenge in nanophotonics¹⁻³. Hyperbolic polaritons (HPs) in anisotropic van der Waals materials^{4,5} and metamaterials^{6,7} have emerged as a promising solution beyond traditional resonant cavities and nanoantennas, which enables diffraction-unlimited light confinement and manipulation^{8,9}, facilitating applications including super-resolution imaging^{10,11}, thermal management^{12,13}, and integrated nanophotonic circuits¹⁴, etc.

The potential of hyperbolic polaritons has been extensively demonstrated from mid-infrared^{15,16} to terahertz^{17,18} frequencies, achieving remarkable deep subwavelength manipulation. Specifically, the dispersion and propagation of these polaritons can be precisely engineered through multilayer stacking^{19,20}, structural geometry design^{21,22}, and changes in the dielectric environment²³⁻²⁵, enabling applications such as directional wavefront steering²⁶⁻²⁹, negative refraction³⁰⁻³⁴ and hyperlensing³⁵⁻³⁹.

While these capabilities are well-established at lower frequencies, extending hyperbolic polariton operations to the visible spectrum remains highly desirable, as it would provide access to standard optical communication bands and enable advancements in quantum devices^{40,41}. Recent studies have shown that MoOCl_2 exhibits hyperbolic properties in the visible frequency with significant tunability⁴²⁻⁴⁶, making it feasible to achieve strong light compression and unlocking applications such as hyperlensing in this range.

However, achieving long-focal-length subwavelength focusing in the visible frequency remains challenging due to the trade-off between long propagation distances and strong compression. Conventional designs rely on localized surface plasmon resonances (LSPR) to excite intrinsic high-momentum (high- k) hyperbolic modes. This approach locks the excitation to the fixed hyperbolic angle of the material, offering strong confinement but resulting in excessively short focal lengths in the visible band. Conversely, low-momentum (low- k) excitation modes with longer propagating distance suffer from momentum mismatch with the high- k hyperbolic states, restricting the selective excitation and the practical application of hyperbolic materials at visible frequency.

In this work, we demonstrate a mode-selection strategy and experimental approach to achieve long-focal-length subwavelength in-plane focusing at visible frequency. By integrating an Au metastructure with the hyperbolic material MoOCl_2 , we convert surface plasmon polaritons (SPPs) into a new electromagnetic mode, namely surface plasmon hyperbolic polaritons (SPHPs), enabling selective excitation and focusing of the low- k mode in the hyperbolic material. Furthermore, by modulating the thickness of the MoOCl_2 layer, we exploit the intrinsic high- k component to synergistically enhance both long propagation distance and strong field compression. Using transmission-mode scanning near-field optical microscopy (SNOM) and quantitative analysis, we verify a focal length of 2.5λ and a focal spot with a full width at half maximum (FWHM) of $\lambda/5$ under 633 nm excitation, accompanied by a three-fold energy enhancement. This visible-frequency long-focal-length system offers potential for non-contact nanoscale probing, integrated photonics, and optical interconnects. The proposed mode-selection methodology provides a versatile design paradigm for coupling hyperbolic polaritons with multiple plasmonic excitations, paving the way for advanced photonic applications.

Results

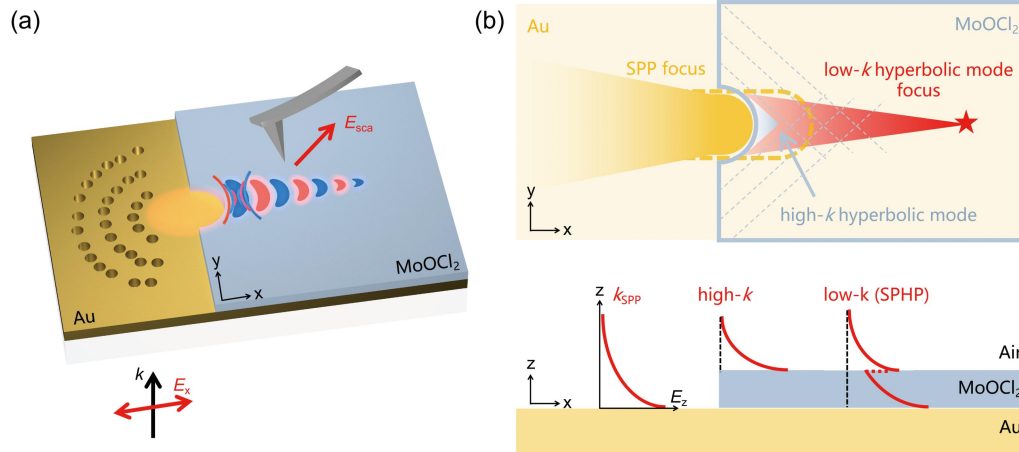


Figure 1. Core setup and mechanisms of the two-step focusing. (a) Structure and measurement apparatus. (b) Mechanisms of the two-step focusing process through mode-selection design, featuring the conversion of SPPs into SPHPs and the synergy between low- k and high- k components. The cross-sectional profile of the electric field intensity along the z -direction reveals the propagation of different momentum components.

Figure 1(a) depicts the core setup of our experiment, where a thin MoOCl_2 layer (Mo-O chain along the x-axis with $\varepsilon_x < 0$, $\varepsilon_y, \varepsilon_z > 0$) is transferred onto an Au film with a 2 nm Al_2O_3 spacer, followed by focused ion beam (FIB) milling of through holes on the Au film and the edge profile of MoOCl_2 . Fabrication details and sample images are shown in Figure S1 and S2. Near-field measurements are performed using a transmission-mode SNOM configuration that selectively excites propagating SPPs while eliminating direct laser excitation and tip-induced field changes (full optical path shown in Figure S3). More importantly, our previously established quantitative method allows for direct measurement of the near-field electric field strength, providing a reliable approach to analyze absolute field intensities across different material regions and evaluate focusing performance (for details on the effective charge sphere quantitative method, see Ref. [47]).

Based on the structure and measurement apparatus, Figure 1(b) illustrates our two-step focusing mechanism through mode-selection strategy. In the region of interest, SPPs on the Au film are excited and undergo initial interference focusing via the designed metastructure of holes⁴⁸. Upon reaching the semicircular edge of MoOCl_2 (400 nm in diameter, optimized to assist focusing), the SPPs are converted into SPHPs, where the in-plane hyperbolicity of MoOCl_2 reshapes the wavefront, enabling subsequent focusing.

The SPHP introduced here is a hybrid interfacial mode that combines the characteristics of both SPPs and hyperbolic polaritons (HPs), representing a distinct electromagnetic mode in the visible frequency. It originates from the selective excitation of low- k modes, without requiring dedicated nanostructures to generate specific high- k states. The SPHP effectively modulates the wavefront, converting a diverging SPP wave into a convergent, long-focal-length beam. Meanwhile, the high- k modes excited at the MoOCl_2 edge further compress the propagating field. The momentum synergy between high- k and low- k modes ultimately achieves subwavelength focusing with an extended focal length, which relies on precise structural design to ensure momentum matching between the SPPs on the Au substrate and the HPs in the MoOCl_2 layer, and to balance the contributions of both high- k and low- k modes for coordinated performance.

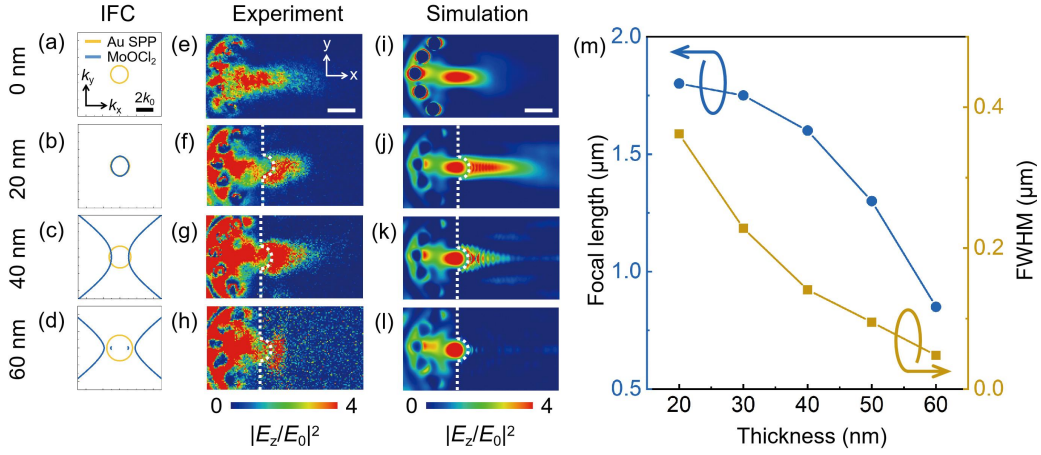


Figure 2. Controlling the momentum matching and synergy by varying the MoOCl₂ thickness. (a)-(d) Momentum matching through thickness-dependent IFCs. (e)-(h) Experimentally measured z-component of the surface electric field distribution $|E_z/E_0|^2$ for 0 nm (bare Au), 20 nm, 40 nm, and 60 nm MoOCl₂ layers, respectively. (i)-(l) FEM simulation results corresponding to the experimental measurement in (e)-(h). (m) Focal length and FWHM for different MoOCl₂ thicknesses. Scale bar, 500 nm.

Following the mode-selection theory, isofrequency contour (IFC) analysis⁴⁹ was performed to verify the low- k matching condition for efficient wavefront shaping. Figure 2(a)-(d) shows the IFC of Au SPP and MoOCl₂ layers with MoOCl₂ thicknesses ranging from 0 to 60 nm under 633 nm excitation, respectively. It is seen that as thickness increases, the MoOCl₂ dispersion transitions from elliptical to hyperbolic, with an increasing hyperbola vertex. Specifically, near 40 nm thickness, the dispersion of Au SPP intersects that of hyperbolic MoOCl₂, satisfying momentum matching and enabling efficient wavefront modulation. For comparison, Figure S4 shows IFCs of MoOCl₂ on a quartz substrate and in freestanding form, where the hyperbola vertex remains beyond k_{SPP} for all thicknesses. This confirms the role of the Au substrate in facilitating momentum matching and selective excitation.

Based on the models and methods, transmission-mode SNOM measurements and finite element method (FEM) simulations were performed on samples with 0 nm (bare Au substrate) and 20, 40, and 60 nm thick MoOCl₂ layers. The resulting squared ratio of the z-component of the surface electric field $|E_z/E_0|^2$ are shown in Figure 2(e)-(h) and (i)-(l), respectively, with the edge profile of

the MoOCl₂ layer indicated by the white dashed line. Notably, the experimentally measured field strength was processed using our established quantitative method to remove dielectric-induced signal variations, revealing the intrinsic field distribution, as discussed in Figure S5. One can see that the experimental field strength and distribution show excellent agreement with that of the FEM simulations.

Across the four thicknesses, the hotspot patterns consistently exhibit SPP propagation on the Au film, along with thickness-dependent wavefront modulation by MoOCl₂ (except for the bare Au case). For the 20 nm sample, the MoOCl₂ layer is too thin to significantly alter the wavefront, and the behavior remains similar to that observed on bare Au. The 40 nm sample shows clear wavefront shaping, resulting in an extended focal length and a smaller focal spot. In the 60 nm case, higher propagation loss restricts the effect primarily to the edge hotspot.

Furthermore, the focal length and FWHM extracted from simulations as functions of the MoOCl₂ thickness are shown in Figure 2(m) (left and right axes, respectively). The focal length is defined as the distance from the right edge of the middle hole in Figure 2(i) to the focal point. It is observed that as the MoOCl₂ thickness increases, both the focal length and the FWHM decrease, indicating a shift of the focusing behavior toward stronger spatial confinement but reduced propagation distance. This thickness dependence reveals that thicker MoOCl₂ layers enhance the contribution of high-*k* components, leading to tighter confinement, while thinner layers preserve low-*k* components, favoring long-distance propagation. Consequently, a moderate thickness of 40 nm represents an optimal compromise that simultaneously enables an extended focal length and a narrowed focal spot size, and is therefore selected for subsequent quantitative analysis.

In addition, the proposed momentum synergy is further validated through two-dimensional fast Fourier transform (FFT) filtering (Figure S6) and rotation of the MoOCl₂ crystal axis (Figure S7). Both approaches clearly separate the low-*k* and high-*k* contributions and consistently demonstrate that the low-*k* component is responsible for extending the propagation distance, while the high-*k* component enhances the spatial confinement. Their effective synergy enables long-distance subwavelength focusing in the visible-frequency hyperbolic system.

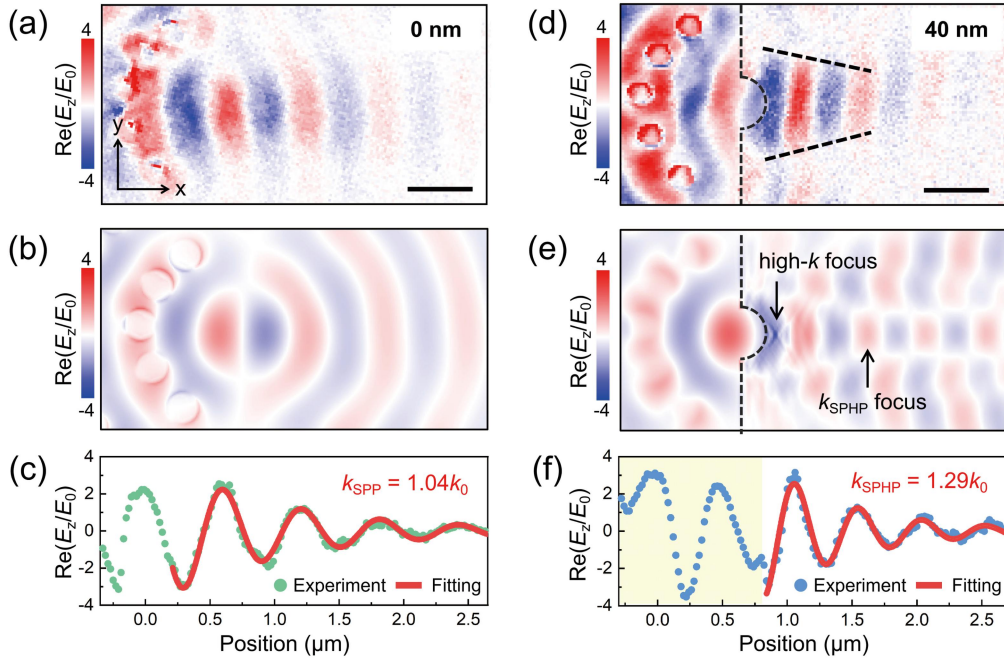


Figure 3. Verification of SPHP mode focusing. (a) and (d) Experimentally measured real part of the electric field distribution $\text{Re}(E_z/E_0)$ for the 0 nm MoOCl_2 (bare Au) and 40 nm MoOCl_2 sample, respectively. (b) and (e) Corresponding FEM simulation results for the 0 nm and 40 nm sample, respectively. (c) and (f) $\text{Re}(E_z/E_0)$ profile along the x-axis for the 0 nm and 40 nm sample, with wavevectors fitted as $k_{\text{SPP}} = 1.04k_0$ and $k_{\text{SPHP}} = 1.29k_0$, respectively (fitting of the 40 nm sample performed only on the MoOCl_2 -covered area, with the uncovered Au area indicated by the yellow region). Scale bar, 500 nm.

To further validate the SPHP wavefront shaping mechanism, Figure 3(a) and 3(d) display the real part of the electric field distributions for the 0 nm (bare Au) and 40 nm MoOCl_2 samples, respectively. In contrast to the circular wavefront on the bare Au substrate, SPHP in the 40 nm MoOCl_2 sample exhibits an inversely curved wavefront with a characteristic focused profile (indicated by the black dashed line), confirming effective hyperbolic wavefront shaping. Minor wavefront deformation results from a slight misalignment between the SPP propagation direction and the MoOCl_2 crystal axis. The corresponding simulation results shown in Figure 3(b) and 3(e) demonstrate well agreement between experiment and simulation. Notably, the simulation for the 40 nm sample also includes the high- k focal point, which is of a small size and positioned close to the MoOCl_2 edge as expected. However, due to resolution and attenuation limitations, these high- k

signals cannot be distinguished in the experiment, highlighting the importance of extending the focal length.

Crucially, the distributions of the electric field's real part along the x-axis, along with their corresponding damped plane waves fitting curves, are shown in Figure 3(c) and 3(f), respectively. It is seen that the wavevectors align with those expected for the SPP at the Au-air interface ($k_{\text{SPP}} = 1.04k_0$), and with the slight increase in the SPHP wavevector ($k_{\text{SPHP}} = 1.29k_0$) due to the dielectric change after covering the MoOCl_2 layer. This confirms that the long-range propagating and finally focused wavefront results from the low- k SPHP mode, rather than the intrinsic high- k modes.

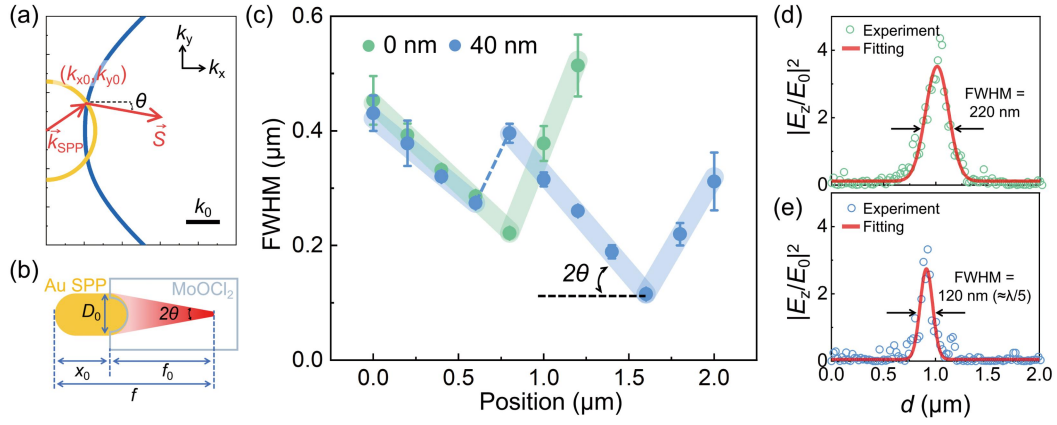


Figure 4. Quantitative analysis of the focal performance. (a) k -space wavefront direction under momentum engineering theory. (b) Schematic illustration of real-space propagation and focal length. (c) FWHM as a function of position for the 0 nm and 40 nm samples. (d) and (e) $|E_z/E_0|^2$ profile at the focus for the 0 nm and 40 nm samples, with FWHM fitted as 220 nm and 120 nm, respectively.

Following the momentum modulation theory and approach, we quantitatively analyzed the relationship between the k -space propagation direction and the real-space focal performance. As shown in Figure 4(a), the k -space intersection points of the SPP wavevector and the hyperbolic curve are determined at (k_{x0}, k_{y0}) , where a normal (at an angle θ with the x-axis) is drawn to define the SPHP propagation direction. The focal length can be determined by the following equation,

198

$$f_0 = \frac{D_0}{2 \tan \theta} = \frac{D_0}{2 \tan(\frac{\pi}{2} - \arctan(\frac{dk_{y_0}}{dk_{x_0}}))} \quad (1),$$

199

200

201

202

where f_0 represents the distance from the focal point to the edge of the MoOCl₂ layer, and D_0 is the spot size of the SPP when it reaches the MoOCl₂ edge. Based on the two-step focusing process, the SPHP focusing combined with the SPP focusing yields a total focal length of $f = x_0 + f_0$, where x_0 is the distance from the start point of SPP to the MoOCl₂ boundary, as shown in Figure 4(b).

203

204

205

206

207

208

209

For quantitative evaluation of the focal performance, Gaussian peak fitting was applied on the y-direction profiles of the field intensity $|E_z/E_0|^2$ along the SPP and SPHP propagation path. The extracted FWHM as a function of position is shown in Figure 4(c), where the data points represent the experimental results and the solid lines indicate piecewise linear fits. A clear discontinuity is observed for the 40 nm sample, which originates from scattering at the semicircular MoOCl₂ edge. This scattering induces an abrupt change in the field profile at the edge where SPPs are converted into SPHPs, as indicated by the blue dashed line in the figure.

210

211

212

213

214

215

As shown in Figure 4(c), the SPHP focusing in the 40 nm sample exhibits a longer focal length and a smaller final spot size than the bare Au case, demonstrating that the two-step focusing via SPHP achieves better performance than direct SPP focusing. Based on geometric considerations and the small-angle approximation, the slope of the FWHM evolution with propagation distance is expected to be $\tan(2\theta)$. The experimentally extracted slope agrees well with this theoretical prediction, confirming the long-focal-length characteristic of the SPHP mode.

216

217

218

219

220

221

222

223

Specifically, the $|E_z/E_0|^2$ profiles and their Gaussian fits at the focus are shown in Figure 4(d) and 4(e) for the 0 nm and 40 nm cases, respectively. It is seen that the bare Au SPP yields a focal length of 800 nm and a FWHM of 220 nm. In contrast, SPHP in the 40 nm MoOCl₂ sample achieves a focused spot with a focal length of 1600 nm (approximate 2.5λ under 633 nm excitation) and a FWHM of 120 nm (about $\lambda/5$), below the diffraction limit. Moreover, using our established quantitative method, the field intensity at the focus shows a 3-fold enhancement over the incident illumination and a 4-fold enhancement relative to the SPP intensity at the same position on bare Au. These performances collectively demonstrate the capability of our approach

to realize subwavelength focusing with an extended focal length in the visible frequency.

These results not only validate our theoretical model but also establish practical design principles for coupling and modulating hyperbolic polaritons with other plasmonic modes through dispersion engineering in momentum space. The demonstrated two-step focusing approach through our proposed SPHP mode differs from traditional combination between localized plasmon resonances and high- k hyperbolic polaritons, providing stronger field enhancement, customizable wavevectors, and extended focal lengths. Future work could comprehensively leverage multiple hyperbolic modes through methods such as structural geometry design, boundary modification, and changes in the dielectric environment, unlocking the potential of mode-selection approach to achieve greater design freedom in advanced nanophotonic devices.

Conclusions

In conclusion, we have established a mode-selection strategy and experimental approach for achieving long-distance subwavelength in-plane focusing at visible frequency. By selectively exciting and matching low- k modes in the Au metastructure and MoOCl₂ layer, we have converted SPPs into a new electromagnetic mode, SPHPs, achieving two-step focusing. Transmission-mode SNOM measurements and quantitative analysis confirm a focal length of 2.5λ and a focal spot with a FWHM of $\lambda/5$ at 633 nm, along with a three-fold energy enhancement, validating the effectiveness of our mode-selection strategy for long-distance subwavelength confinement and manipulation.

Furthermore, the mode-selection approach introduced here significantly expands the design freedom of visible-frequency hyperbolic systems. By tailoring the accessible dispersion of the hyperbolic material, multiple excitation channels can be efficiently matched and coupled, without relying on dedicated nanostructures to generate specific high- k states. This compatibility with diverse incident wavevectors enables selective mode excitation, flexible wavefront shaping, and advanced polariton engineering, offering a versatile platform for multifunctional nanophotonic operations. Overall, this mode-selection paradigm opens promising opportunities for non-contact nanoscale probing, photonic circuitry, and integrated polaritonic devices.

Methods

Samples fabrication

A 4 nm Ti layer followed by a 110 nm-thick Au layer was deposited on a quartz substrate (sequentially cleaned in acetone, alcohol and deionized water baths ultrasonically) by an e-beam evaporation system with a background vacuum level of 9×10^{-5} Pa, at a rate of 0.3 Å/s. Subsequently, a 2 nm Al₂O₃ spacer layer was grown at 200°C via atomic layer deposition (Micro & Nano Tech). The MoOCl₂ flakes with designated thickness were mechanically exfoliated on polydimethylsiloxane (PDMS) sheets from bulk crystals (Nanjing MKNANO Tech. Co., Ltd. (www.mukenano.com)), and then transferred onto the substrates. The MoOCl₂ and exposed Au regions were sequentially patterned to form the designed geometry by focused ion beam milling (ZEISS) using gallium ions at a rate of 5 pA. Detailed fabrication steps are provided in Figure S1.

Transmission-mode SNOM measurement

The near-field electric fields were measured using a modified commercial transmission-mode SNOM system (Neaspec GmbH), where samples were illuminated from the substrate side with a vertically incident 633 nm He-Ne laser (Necsel), polarized along the x-axis. A Pt-Ir coated AFM tip (Nanoworld), operating in tapping mode ($f \approx 280$ kHz), served as the near-field scatterer. The scattered signal was collected through a parabolic mirror positioned above the sample and recorded by an MCT detector. The signal was then converted into electrical signals, amplified, and demodulated to obtain both amplitude and phase information, with third-order demodulation applied in this work. The complete experimental setup is illustrated in Figure S3.

FEM simulation

Commercially available COMSOL Multiphysics software was used to simulate the near-field electric fields of the samples upon illumination of a laser linearly polarized along the x axis. The surrounding perfect match layer (PML) and two ports along the light propagation direction were applied in the simulation. The dielectric functions of the Au film and silica substrate were taken from ellipsometric measurements, and that of MoOCl₂ was adopted from Ref. [42]. The

z-component of electric-field at the sample surface was extracted as simulation results.

FFT Processing

The surface electric field distribution (including both real and imaginary components) obtained from simulations was processed using FFT in MATLAB. The original electric field was subjected to FFT, filtered, and then inverse FFT was applied to obtain the electric field distributions for the high- k and low- k components. The filtering cutoff frequency was based on the SPHP wavevector, and a Butterworth smoothing filter was used, ensuring that the SPHP remained in the low- k range.

Analytical calculations of the IFC

The IFCs of hyperbolic modes supported by MoOCl₂ thin layers are described using the established theory in Ref. [49]. We consider an MoOCl₂ thin slab with thickness d between two isotropic media with dielectric permittivity ε_1 and ε_3 , respectively. The dispersion relation for electromagnetic modes is given as,

$$\left[\alpha_x q_y^2 + \alpha_y q_x^2 + \frac{q_x^2 + q_y^2}{2} \left(i\sqrt{q_x^2 + q_y^2 - \varepsilon_1} + i\sqrt{q_x^2 + q_y^2 - \varepsilon_3} \right) \right] \left[\alpha_x q_x^2 + \alpha_y q_y^2 + \frac{q_x^2 + q_y^2}{2} \left(\frac{\varepsilon_1}{i\sqrt{q_x^2 + q_y^2 - \varepsilon_1}} + \frac{\varepsilon_3}{i\sqrt{q_x^2 + q_y^2 - \varepsilon_3}} \right) \right] = q_x^2 q_y^2 (\alpha_x - \alpha_y)^2$$

where $\alpha_{x,y} = \frac{k_0 d \varepsilon_{x,y}}{2i}$ are the normalized effective conductivity components and $q_{x,y} = \frac{k_{x,y}}{k_0}$. In

our case, $\varepsilon_1 = 1$ (air) and ε_3 takes values of -11.66 (Au), 2.25 (quartz), or 1 (freestanding), corresponding to the cases shown in Figure 2 and Figure S4.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

- 298 1. Y. Wu et al., Manipulating polaritons at the extreme scale in van der Waals materials. *Nat.*
299 *Rev. Phys.* **4**, 578-594 (2022).
- 300 2. D. Basov et al., Polaritons in van der Waals materials. *Science* **354**, aag1992 (2016).
- 301 3. Q. Zhang et al., Interface nano-optics with van der Waals polaritons. *Nature* **597**, 187-195
302 (2021).
- 303 4. E. Galiffi et al., Extreme light confinement and control in low-symmetry phonon-polaritonic
304 crystals. *Nat. Rev. Mater.* **9**, 9-28 (2024).
- 305 5. H. Wang et al., Planar hyperbolic polaritons in 2D van der Waals materials. *Nat. Commun.* **15**,
306 69 (2024).
- 307 6. P. Huo et al., Hyperbolic Metamaterials and Metasurfaces: Fundamentals and
308 Applications. *Adv. Optical Mater.* **7**, 1801616 (2019).
- 309 7. D. Lee et al., Hyperbolic metamaterials: fusing artificial structures to natural 2D materials.
310 *eLight* **2**, 1 (2022).
- 311 8. Y. Ma et al., In-plane hyperbolic phonon polaritons: materials, properties, and nanophotonic
312 devices. *npj Nanophoton.* **1**, 25 (2024).
- 313 9. G. Hu et al., Phonon Polaritons and Hyperbolic Response in van der Waals Materials. *Adv.*
314 *Optical Mater.* **8**, 1901393 (2020).
- 315 10. P. Li et al., Hyperbolic phonon-polaritons in boron nitride for near-field optical imaging and
316 focusing. *Nat. Commun.* **6**, 7507 (2015).
- 317 11. S. Dai et al., Subdiffractional focusing and guiding of polaritonic rays in a natural hyperbolic
318 material. *Nat Commun.* **6**, 6963 (2015).
- 319 12. K. Tielrooij et al., Out-of-plane heat transfer in van der Waals stacks through
320 electron-hyperbolic phonon coupling. *Nature Nanotech* **13**, 41-46 (2018).
- 321 13. Y. Jin et al., Infrared-Reflective Transparent Hyperbolic Metamaterials for Use in Radiative
322 Cooling Windows. *Adv. Funct. Mater.* **33**, 2207940 (2023).
- 323 14. N. Chen et al., Flatland wakes based on leaky hyperbolic polaritons. *Nat. Mater.* **24**,
324 1569-1575 (2025).
- 325 15. W. Ma et al., In-plane anisotropic and ultra-low-loss polaritons in a natural van der Waals
326 crystal. *Nature* **562**, 557-562 (2018).
- 327 16. H. Sheinfux et al., High-quality nanocavities through multimodal confinement of hyperbolic
328 polaritons in hexagonal boron nitride. *Nat. Mater.* **23**, 499-505 (2024).
- 329 17. R. Kowalski et al., Ultraconfined terahertz phonon polaritons in hafnium dichalcogenides.
330 *Nat. Mater.* **24**, 1735-1741 (2025).
- 331 18. S. Chen et al., Real-space observation of ultraconfined in-plane anisotropic acoustic terahertz
332 plasmon polaritons. *Nat. Mater.* **22**, 860-866 (2023).
- 333 19. G. Hu et al., Topological polaritons and photonic magic angles in twisted
334 α -MoO₃ bilayers. *Nature* **582**, 209-213 (2020).
- 335 20. J. Duan et al., Multiple and spectrally robust photonic magic angles in reconfigurable
336 α -MoO₃ trilayers. *Nat. Mater.* **22**, 867-872 (2023).
- 337 21. M. Suriyage et al., Long-propagating ghost phonon polaritons enabled by selective mode
338 excitation. *Light: Science & Applications* **14**, 254 (2025).
- 339 22. N. Chen et al., Boundary-induced excitation of higher-order hyperbolic phonon polaritons.

Nat. Photon. **19**, 1225-1232 (2025).

23. J. Duan et al., Enabling propagation of anisotropic polaritons along forbidden directions via a topological transition. *Sci. Adv.* **7**, eabf2690 (2021).
24. J. Zhu et al., Multiple Hyperbolic Dispersion Branches and Broadband Canalization in a Phonon-Polaritonic Heterostructure. *Nano Lett.* **25**, 2610-2617 (2025).
25. J. Liang et al., Manipulation of In-Plane Hyperbolic Phonon Polaritons for Configurable Focusing. *ACS Photonics* **11**, 5031-5038 (2024).
26. Q. Zhang et al., Unidirectionally excited phonon polaritons in high-symmetry orthorhombic crystals. *Sci. Adv.* **8**, eabn9774 (2022).
27. F. Tresguerres-Mata et al., Directional strong coupling at the nanoscale between hyperbolic polaritons and organic molecules. *Nat. Photon.* **19**, 1196-1202 (2025).
28. S. Zhang et al., Phonon engineering enables hyperbolic asymptotic line polaritons. *Nat. Nanotechnol.* (2025).
29. L. Liu et al., Long-range hyperbolic polaritons on a non-hyperbolic crystal surface. *Nature* **644**, 76-82 (2025).
30. H. Hu et al., Gate-tunable negative refraction of mid-infrared polaritons. *Science* **379**, 558-561 (2023).
31. G. Álvarez-Pérez et al., Negative reflection of nanoscale-confined polaritons in a low-loss natural medium. *Sci. Adv.* **8**, eabp8486 (2022).
32. A. High, et al., Visible-frequency hyperbolic metasurface. *Nature* **522**, 192-196 (2015).
33. A. Sternbach et al., Negative refraction in hyperbolic hetero-bicrystals. *Science* **379**, 555-557 (2023).
34. K. Cohen et al., Deep-Subwavelength Focusing and Reflectionless Negative Refraction in Visible-Light Hyperbolic Metasurface. *Adv. Optical Mater.* **13**, 2402591 (2025).
35. K. Chaudhary et al., Polariton nanophotonics using phase-change materials. *Nat. Commun.* **10**, 4487 (2019).
36. Z. Zheng et al., Controlling and Focusing In-Plane Hyperbolic Phonon Polaritons in α -MoO₃ with a Curved Plasmonic Antenna. *Adv. Mater.* **34**, 2104164 (2022).
37. J. Martín-Sánchez et al., Focusing of in-plane hyperbolic polaritons in van der Waals crystals with tailored infrared nanoantennas. *Sci. Adv.* **7**, eabj0127 (2021).
38. Y. Qu et al., Tunable Planar Focusing Based on Hyperbolic Phonon Polaritons in α -MoO₃. *Adv. Mater.* **34**, 2105590 (2022).
39. J. Duan et al., Planar refraction and lensing of highly confined polaritons in anisotropic media. *Nat. Commun.* **12**, 4325 (2021).
40. X. Lu et al., Emerging integrated laser technologies in the visible and short near-infrared regimes. *Nat. Photon.* **18**, 1010-1023 (2024).
41. D. Assumpcao et al., A thin film lithium niobate near-infrared platform for multiplexing quantum nodes. *Nat Commun.* **15**, 10459 (2024).
42. G. Venturi et al., Visible-frequency hyperbolic plasmon polaritons in a natural van der Waals crystal. *Nat Commun.* **15**, 9727 (2024).
43. F. Ruta et al., Good plasmons in a bad metal. *Science* **387**, 786-791 (2025).
44. Y. Zhang et al., Manipulating Hyperbolic Plasmon Polaritons at Near-Infrared in an Anisotropic van der Waals Crystal. *Nano Lett.* **25**, 15534-15541 (2025).
45. Y. Li et al., Broadband near-infrared hyperbolic polaritons in MoOCl₂. *Nat. Commun.* **16**,

6172 (2025).

46. N. Melchioni et al., Giant Optical Anisotropy in a Natural van der Waals Hyperbolic Crystal for Visible Light Low-Loss Polarization Control. *ACS Nano* **19**, 25413-25421 (2025).
47. Y. Fan et al., Direct measurement of the real strength of near-field electric field. *Appl. Phys. Lett.* **125**, 211105 (2024).
48. X. Xue et al., High-Throughput On-Demand Design Platform for Plasmonic Nanocavities: A Wavefunction Theory Approach. *Nano Lett.* **24**, 11859-11864 (2024).
49. G. Álvarez-Pérez et al., Analytical approximations for the dispersion of electromagnetic modes in slabs of biaxial crystals. *PHYSICAL REVIEW B* **100**, 235408 (2019).

Acknowledgements

This work was supported by NSFC under grant No. 52427801, 52388201 and 12274008, National Key Research and Development Program No. 2022YFA1604303, Tsinghua-Foshan Innovation Special Fund (Grand No. 2021THFS0103), the Tsinghua University Initiative Scientific Research Program.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialsforVisiblefrequencylongdistancesubwavelengthfocusingviaSPHPs.pdf](#)