

Manipulating optical beam flow fronts in 2D materials

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A giant optical path length is created from a few layers of molybdenum disulfide and is used to fabricate an ultra-thin optical lens.

Two-dimensional materials (e.g., graphene) have emerged as promising candidates for use in miniaturized optoelectronic devices.^{1–4} This is because 2D materials exhibit strong inelastic interactions with light.^{5,6} In addition, miniaturized optical systems also require strong elastic light-matter interactions to control the flow of light.⁷ To achieve strong elastic interactions, there need to be significant changes in the amplitude and phase of the light accumulated over a long optical path. For very thin (i.e., 2D) materials, however, these interactions are generally very small.⁸

Although substantial effort has already been devoted to this issue, there has only been success in the mid- to far-IR region, where the plasmonic resonance of graphene can be used to enhance the elastic optical response.^{9–11} A potential way to manipulate the flow of light in 2D materials at visible and near-IR wavelengths is to use 2D materials with large optical path length (OPL) values for refractive optical components. In such components the OPL is used to modify the phase front of an optical beam. The OPL is directly related to the geometrical length of the light path. It is normally thought, however, that the OPL of an ultra-thin 2D material—because of its ultra-thin nature—is too small to have a significant impact on the phase front.

In our work,¹² we have observed a giant OPL (38nm) from a monolayer of molybdenum disulfide (MoS_2), i.e., a high-index 2D material. We created this OPL from relatively strong multiple reflections at the air- MoS_2 and MoS_2 -silica interfaces. This OPL is substantially larger than that of silica (SiO_2), graphene, gold, or silicon. Indeed (see Figure 1), it is more than 50 times larger than the physical thickness of the monolayer (0.67nm) and about one order of magnitude larger than the measured OPL of a graphene monolayer (4.4nm).

By making use of this giant OPL, we have demonstrated phase-front engineering by fabricating the world's thinnest lens. To create this lens (see Figure 2), which is based on a few atomic

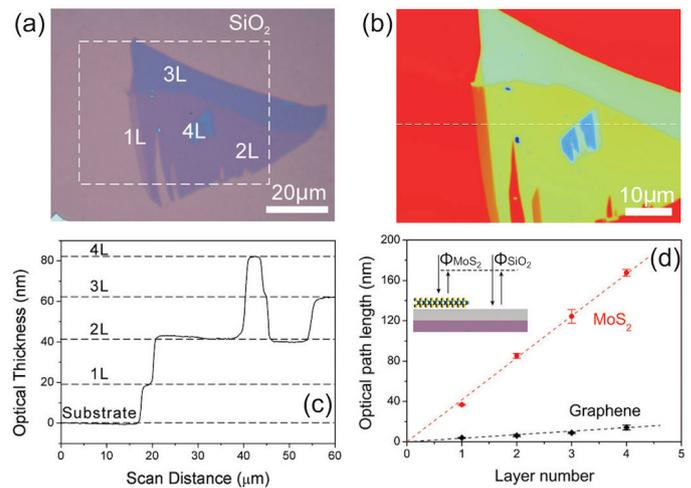


Figure 1. (a) Optical microscope image of a mechanically exfoliated molybdenum disulfide (MoS_2) sample on a silica/silicon (SiO_2/Si) substrate (275nm thermal SiO_2). Different contrasts correspond to MoS_2 flakes of different thicknesses. The areas labeled as 1L, 2L, 3L, and 4L are single, bi-, triple-, and quadruple-layer MoS_2 , respectively. (b) Phase shifting interferometry (PSI) image of the region inside the dashed box in (a). (c) PSI-measured optical path length (OPL) as a function of scan position along the dashed line in (b) for the 1L, 2L, 3L, and 4L MoS_2 . (d) Statistical data for the OPL values from the PSI of the 1L, 2L, 3L, and 4L MoS_2 samples and of a graphene sample. At least five different samples were characterized for each layer of MoS_2 and graphene. The inset shows a schematic diagram of the PSI-measured phase shifts of the reflected light from the MoS_2 flake (ϕ_{MoS_2}) and the SiO_2 substrate (ϕ_{SiO_2}).

layers of MoS_2 , we started with a flake of uniform nine-layer MoS_2 . We then used a focused ion beam process to mill a pre-designed bowl-shaped structure (20 μm in diameter) into the flake, as shown in Figure 2(a) and (b). The gradual change in the thickness of the MoS_2 —from the center to the edge—led to a continuous and curved OPL profile for an incident beam. This served as an atomically thin (reflective) concave microlens: see

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Figure 2(c). Based on the measured OPL profile, we calculated the focal length (f) of our MoS₂ microlens as $-248\mu\text{m}$.

In addition, we have used far-field scanning optical microscopy to characterize our fabricated MoS₂ microlens. In this procedure, we moved—using a piezoelectrically driven stage—the microlens along the z -axis in steps of $10\mu\text{m}$. We used the camera to record a series of light intensity distributions, with the MoS₂ microlens at the different z -axis positions. After some data processing, we thus generated a 3D data set, and we obtained—see Figure 2(d)—a cross-sectional profile along the x - and z -axes to illustrate the average distribution of light intensity in these directions. Our results indicate that when the MoS₂ microlens was placed at a distance of $2|f|$ above the focal plane, the focused incident light was exactly re-imaged (i.e., equivalent to the light coming from a point source). The camera had therefore recorded a well-focused light spot. We also measured the f of the microlens as $-240\mu\text{m}$ ($2f=-480\mu\text{m}$), which was in good agreement with the value obtained from the simulation of the microlens OPL profile value ($-248\mu\text{m}$).

The extraordinary elastic interactions of high-index 2D materials with light that we have demonstrated are uniquely enabled by the ultra-thin nature of the 2D materials. As a result, wavefront shaping^{13,14} can be accomplished with atomically

thin 2D materials and may give rise to a new class of optical components that are based entirely on high-index 2D materials. Moreover, compared with conventional diffractive optical components, the spatial resolution of phase-front shaping is much smaller than the wavelength (only limited by the nanofabrication resolution). This makes it possible to eliminate undesired diffractive orders.¹⁴

Two-dimensional materials also offer many other unique advantages. First, the extremely uniform thickness, and the perfect surfaces with atomic roughness, in layered high-index 2D materials provide good ways to precisely control the phase front of a wave. Second, the unique and large tunability of the refractive index by an electric field¹⁵ in layered MoS₂ may enable various applications in electrically tunable, atomically thin optical components (e.g. microlenses with electrically tunable focal lengths and electrically tunable phase shifters with ultra-high accuracy), which cannot be realized with conventional bulk solids. We have also observed similar giant OPLs in other transition-metal dichalcogenide-family YX₂ semiconductors (where Y is molybdenum or tungsten and X is sulfur, selenium, or tellurium). The availability of different functional materials such as these offers rich opportunities for the combination of optical and electronic properties (e.g., stacked, atomically thin heterostructures for 2D optoelectronics). Lastly, 2D optical components present a significant advantage in manufacturing compared with conventional 3D optical components. This is because the different functionalities can all be achieved in a 2D platform from a shared fabrication process. This should facilitate simple large-scale manufacturing and integration.

In summary, we have used a giant optical path length to engineer the phase front of optical beams and have demonstrated, to the best of our knowledge, the world's thinnest optical lens. This lens consists of a few layers of MoS₂ and is less than 6.3nm thick. This capability of manipulating the flow of light in 2D materials opens up an exciting avenue toward unprecedented miniaturization of optical components and the integration of advanced optical functionalities. In the next stage of our work we will use an electric field to tune the OPL of the MoS₂ layer. We will also fabricate an optical lens with tunable focal length, as well as other tunable optical components.

We acknowledge support from the Australian Capital Territory node of the Australian National Fabrication Facility and, particularly, the technical support on the focused ion beam provided by Lily Li. We also acknowledge financial support from an Australian National University (ANU) PhD scholarship, the US Office of Naval Research

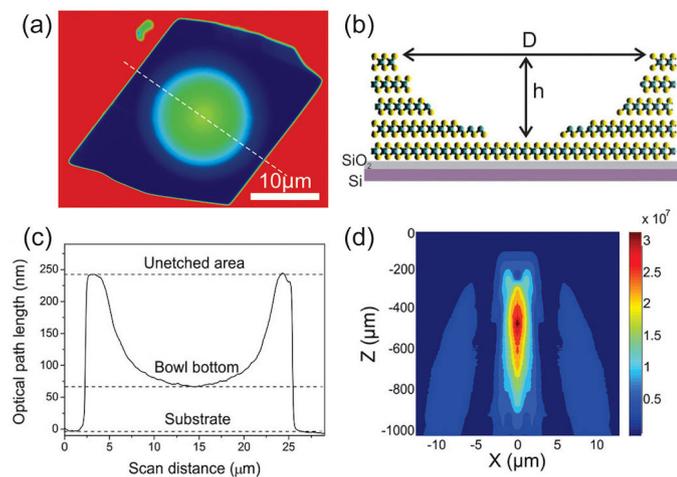


Figure 2. (a) PSI image of an atomically thin microlens fabricated on a nine-layer MoS₂ flake. (b) Schematic diagram of the microlens bowl-shaped structure (with diameter, D , and height, h). This structure was fabricated through focused ion beam milling, with atomic resolution in the vertical direction and sub-20nm resolution in the lateral direction. (c) Measured OPL values as a function of position along the dashed line shown in (a). (d) Intensity distribution pattern (across the X and Z directions) of the MoS₂ microlens, as measured with scanning optical microscopy.

(under grant N00014-14-1-0300), the Australian Research Council (grant DE140100805), and the ANU Major Equipment Committee.

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