Shifting beams at normal incidence via controlling momentum-space geometric phases

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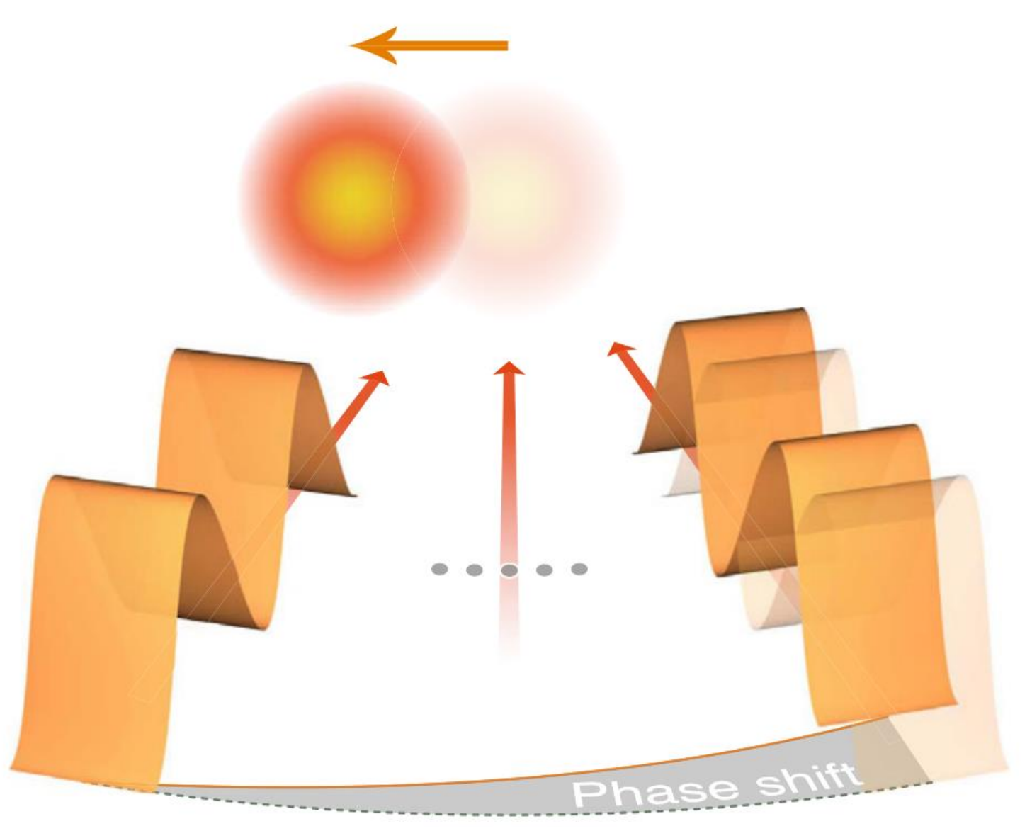
Abstract When hitting interfaces between two different media, light beams may undergo small shifts. Such beam shifts cannot be described by the geometrical optics based on Snell' s law and their underlying physics has attracted much attention. Conventional beam shifts like Goos-Hänchen shifts and Imbert Fedorov shifts not only require obliquely incident beams but also are mostly very small compared to the wavelength and waist size of the beams. Here we propose a method to realize large and controllable polarization-dependent lateral shifts for normally incident beams with photonic crystal slabs. As a proof of the concept, we engineer the momentum-space geometric phase distribution of a normally incident beam by controlling its interaction with a photonic crystal slab whose momentum-space polarization structure is designed on purpose. The engineered geometric phase distribution is designed to result in a large shift of the beam. We fabricate the designed photonic crystal slab and directly observe the beam shift, which is ~5 times the wavelength and approaches the waist radius. Based on periodic structures and only requiring simple manipulation of symmetry, our proposed method is an important step towards practical applications of beam shifting effects.

Momentum-space phase gradient → real-space position change

$$\langle \mathbf{P} \rangle = \left\langle \frac{\partial \varphi(\boldsymbol{r}_{\parallel})}{\partial \boldsymbol{r}_{\parallel}} \right\rangle,$$

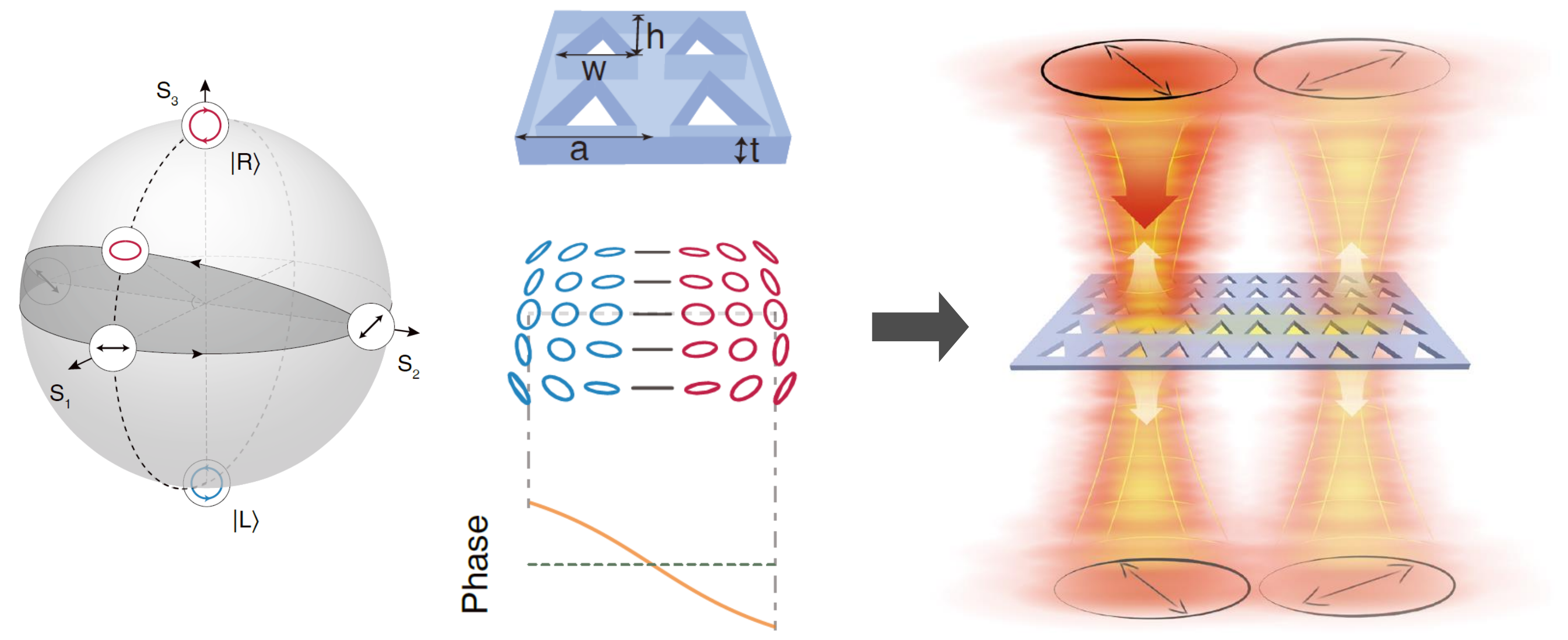
$$\langle \mathbf{R} \rangle = -\left\langle \frac{\partial(\phi(\boldsymbol{k}_{\parallel}) + k_z(\boldsymbol{k}_{\parallel})z)}{\partial \boldsymbol{k}_{\parallel}} \right\rangle$$

$$= \mathbf{R}_{\mathrm{c}} - \left\langle \frac{\partial \phi(\boldsymbol{k}_{\parallel})}{\partial \boldsymbol{k}_{\parallel}} \right\rangle,$$



The momentum space and real space are a pair of reciprocal spaces. $\langle \mathbf{R} \rangle$ and $\langle \mathbf{P} \rangle$ can be modulated by the phase distributions in their corresponding reciprocal space.

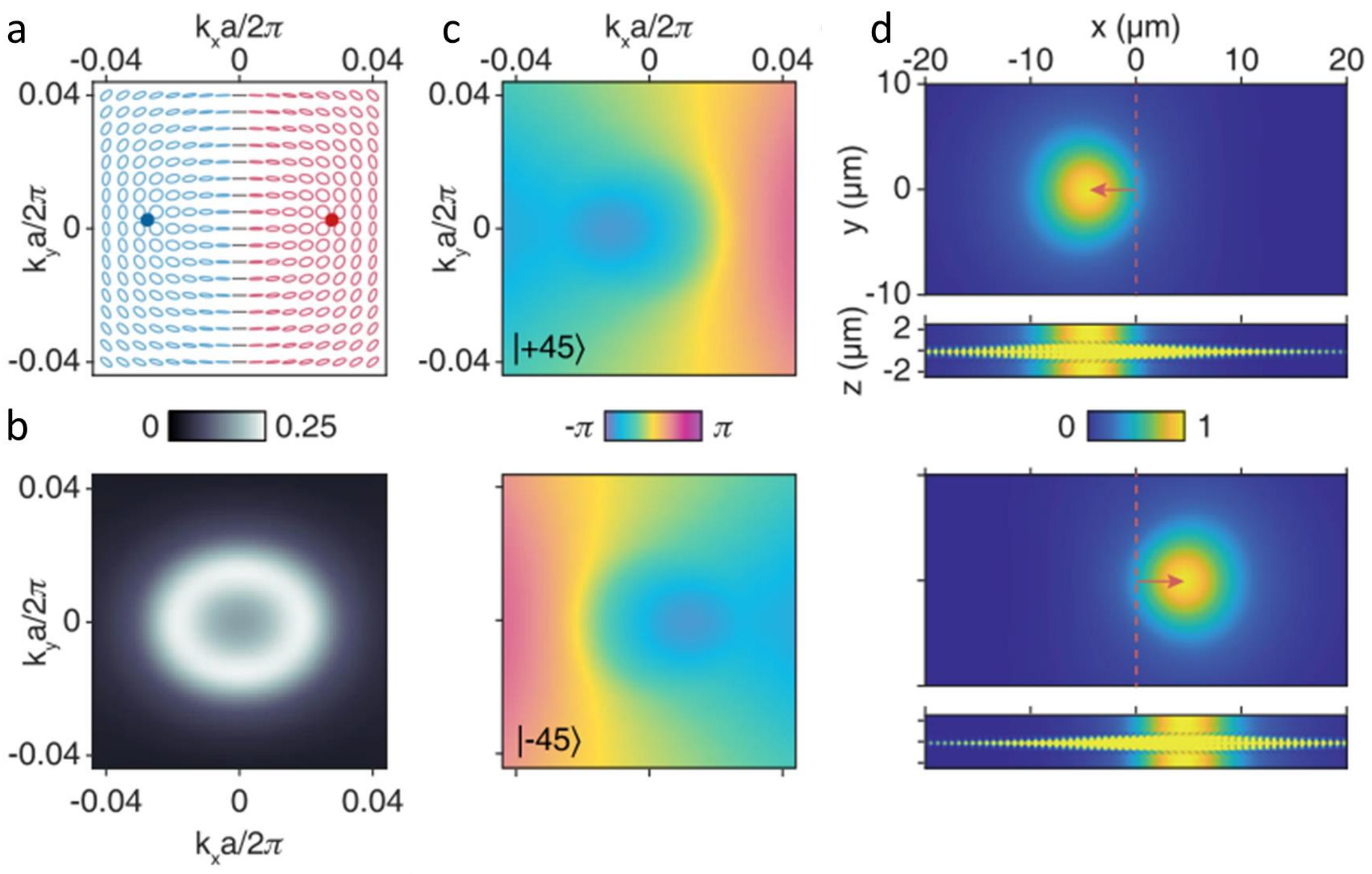
Engineering momentum-space phase to shifting the light beams at normal incidence



Left, The Poincaré sphere. The shadowed area correspond to two times the difference in the geometric phases induced by two trajectories through two different states of polarization. **Middle**, The schematic of the applied PhC slab, the corresponding momentum-space polarization distribution and the induced geometric phase along the k_x direction. **Right**, Schematic view of the lateral shifts.

With the wave-vector-variant states of polarization, geometric phases can be introduced in the resonant process between the light in free space and the optical modes. Then with the induced polarization-dependent in-plane momentum-space geometric phase gradients, the light beam would undergo a lateral shift in real space.

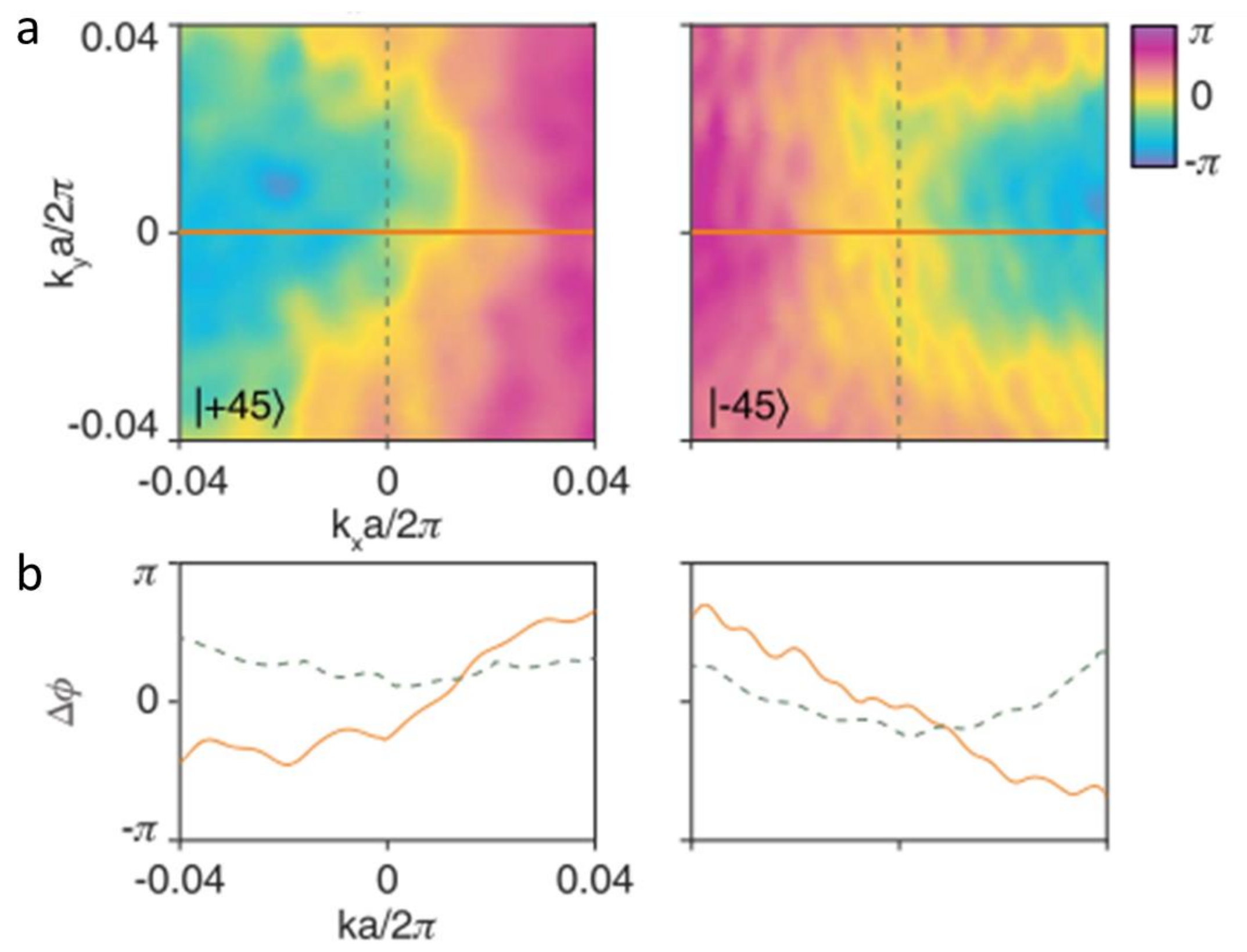
Simulated results of the linear-polarization-dependent lateral shifts



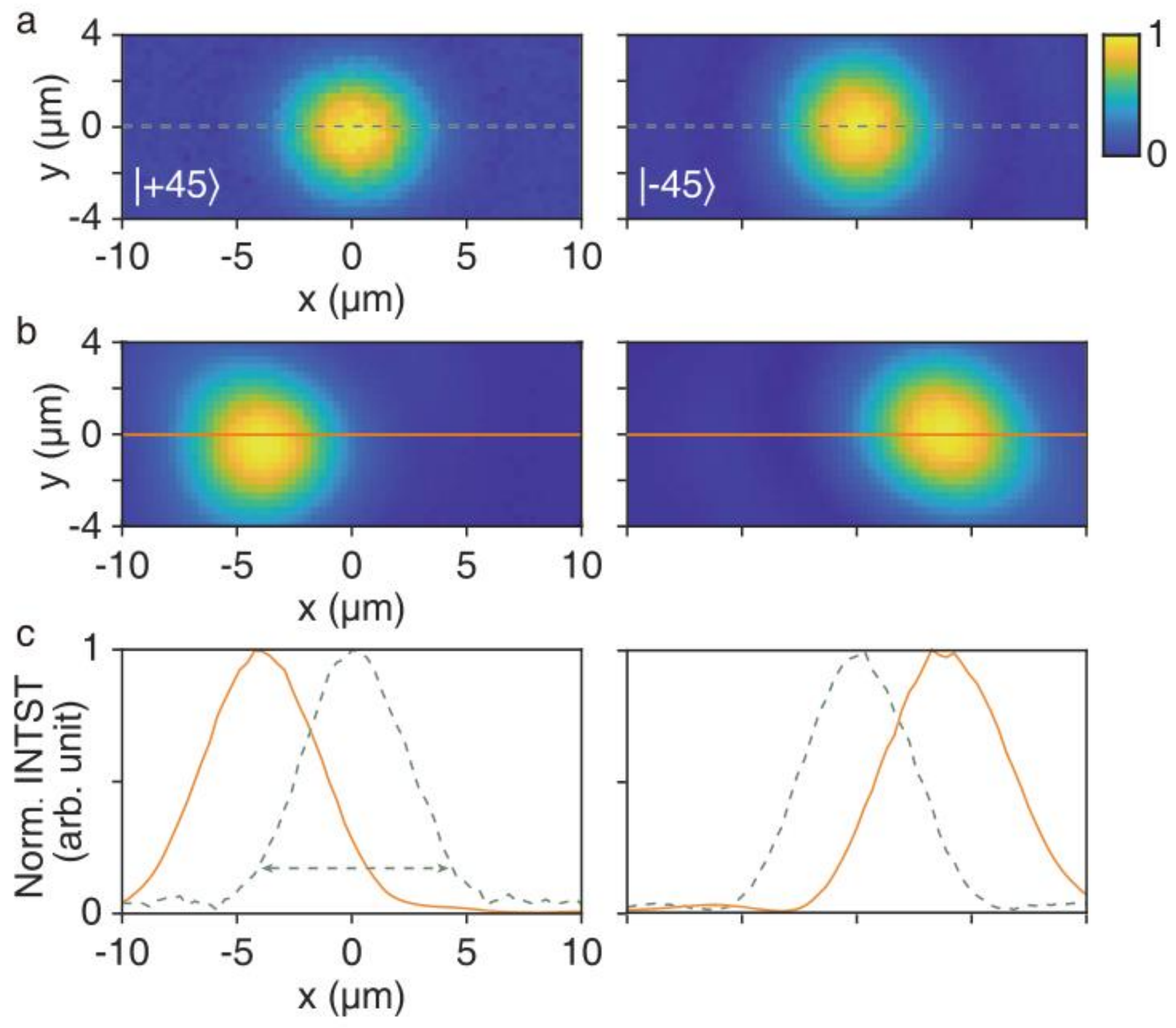
a, Simulated structure of polarization eigenstates. The red (blue) color corresponds to right-handed (left-handed) polarization eigenstates. **b**, Simulated wave-vector-dependent cross-polarized conversion efficiency. **c**, Simulated wave-vector-dependent phase distribution induced by the $|\pm45\rangle$ to $|\mp45\rangle$ conversion. **d**, Top and cross-section view of the realized lateral shifts.

To shift light beams at normal incidence, the PhC slab with two C points is designed and the polarizations of the incident light beams are chosen as $|\pm45\rangle$ (whose normalized second Stokes parameters are ±1).

Experimental results of the linear-polarization-dependent lateral shifts



Measured momentum-space phase distribution. **a**, The incident and the analyzed polarizations in the left (right) panel are $|+45\rangle$ ($|-45\rangle$) and $\langle -45|$ ($\langle +45|$) respectively. **b**, The phase distributions along the lines marked in **a**.



Experimentally observed polarization-dependent lateral shifts. **a**, The normalized intensity distributions of the original beam passing through an unstructured Si_3N_4 film after the two setups of cross-polarized analyzing. **b**, The normalized intensity distributions of the beam passing through the fabricated PhC slab after the two setups of cross-polarized analyzing. **c**, The normalized intensity distributions of the observed beams along the x axis, sliced from **a** and **b**.

The PhC slab is fabricated based on a 100-nm-thick free-standing Si_3N_4 film. The beam shifts of transmitted light beams were directly observed.

Summary

we presented a method to realize lateral shifts at normal incidence by utilizing the momentum-space polarization structure of PhC slabs. Momentum-space geometric phase gradients are introduced to light beams via cross-polarized conversion. A large linear-polarization-dependent lateral shift up to 4.2 microns was realized by a 100-nm-thick PhC slab.

References

[1] Physical Review Letters, 123(11), 116104. (2019)
[2] Nature Photonics, 14(10), 623-628. (2020)
[3] **Nature Communications, 12(1), 1-7. (2021)**