Quantum Dirac Phase Interferometer in a Plasmonic Waveguide

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We introduce a new quantum interference effect that can be observed in a plasmonic interferometer and is controlled by an applied magnetic field. We show that the introduced phenomenon will result in nonlinear magnetically-tuneable transmission of the interferometer even at low light intensity (few μW) and low applied magnetic field (tens of mT).

The new interference effect stems from the Dirac phase gained by the propagating surface plasmon polaritons. The Dirac phase describes the additional phase gained by charged quantum mechanical particles due to propagation in the electromagnetic field. In particular, Dirac's prescription states that the wavefunction of a particle with charge q in the presence of magnetic vector potential ($\boldsymbol{A}$) can be constructed from the solution in the field-free region by adding an additional phase shift expressed as an integral along particle's path $\Delta\phi = \frac{q}{\hbar}\int d\boldsymbol{r}.\boldsymbol{A}$.

The famous Aharonov-Bohm effect, a quantum mechanical topological phenomenon in which the phase of an electrically charged particle is affected by the presence of a magnetic field, despite being confined to a region in which the field is zero, can be seen as a direct consequence of the Dirac phase. Furthermore, the same phenomenon leads to electromagnetic-field-induced phase gain even for electrically neutral particles, as long as they possess permanent electric or magnetic dipole moments. In particular, in the He-McKellar-Wilkens (HMW) effect (see Fig. 1a), particles with an electric dipole gain extra phase as a result of propagation in the static magnetic field [1]. First predicted in the beginning of 1990s, this effect remained untested until few years ago [2], mainly due to the difficulty of preparing a train of quantum mechanical particles with nonzero electric dipole.

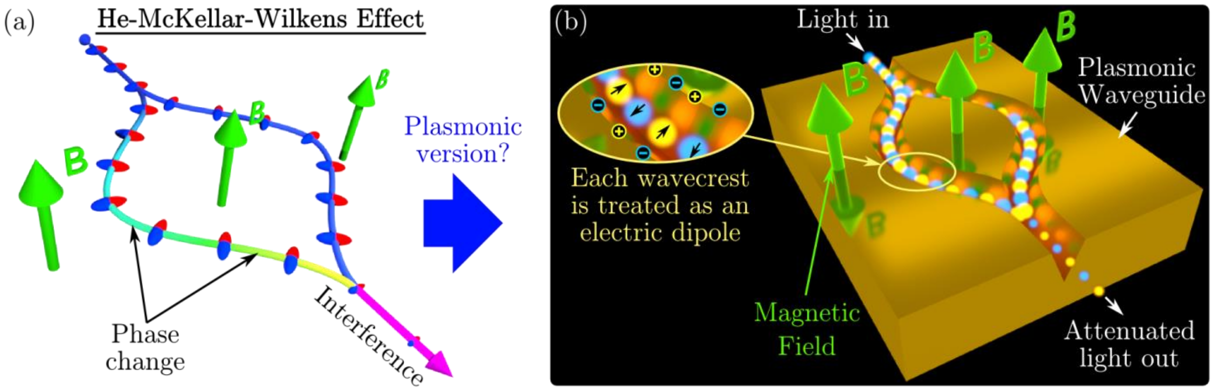

Fig. 1 Adapting the He-McKellar-Wilkens (HMW) effect for plasmonics. (a) The classical HMW effect. A train of quantum mechanical particles with electric dipole is split in two, recombined and then detected. A magnetic field (**B**) is applied along the direction perpendicular to both the dipole orientation and the particle velocity. As a result of applied magnetic field the propagating particles gain additional phase, which leads to quantum mechanical interference. (b) The proposed plasmonic version of the HMW effect. Light is launched into the V-groove plasmonic interferometer. The propagating plasmons induce co-propagating charge density waves that can be viewed as a train of anti-aligned electric dipoles. Applying magnetic field perpendicular to the waveguide plane should lead to the HMW effect affecting the phase of the plasmons, leading to the suppression/enhancement of the mode guided by the waveguide.

We theoretically demonstrate that the HWM effect may be observed using surface plasmon polaritons travelling along a V-groove plasmonic waveguide. We provide numerical analysis to show that the effect should be observable under routinely accessible measurement conditions: with near-infrared light (λ=1.31μm) in the power range 1-100μW and with magnetic field strengths in the range 0.1-100mT. Finally, we discuss the implementation of an experiment to confirm the effect.

The main idea of our proposal, illustrated in Fig. 1b, hinges on the fact that surface plasmon polaritons inside the V-groove waveguide can be viewed as a row of propagating electric dipoles with alternating orientation. Assuming this viewpoint is correct, application of a magnetic field perpendicular to the direction of propagation should cause the wavefunctions of all electric dipoles to shift. Such a shift can be detected in an interferometric setup, wherein a train of plasmon polaritons is first separated and then recombined. The phase difference will lead to the attenuation of the recombined plasmon wave, which will be detected as a reduction of the optical transmission of the interferometer.

References

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[2] S. Lepoutre et al. "He-McKellar-Wilkens topological phase in atom interferometry", Phys. Rev. Lett. **109**, 1204405 (2012)