"Meta-Optics" for Matter Waves

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With the fast development of matter-wave optics, many of the functions previously operated in light optics have been realised: atom diffraction, mirrors, beam splitters, atom holography, quantum reflection, etc. Similarities and differences originate in the properties of the associated particle: non-zero atom mass, vacuum dispersion for the "*de Broglie*" waves, influence of the internal atomic degrees of freedom… Along this viewpoint, novel areas in the field of atom optics are presently explored. For instance, it includes the devising of non-diffracting atom nano-beams thanks to a specially designed transverse Stern-Gerlach interferometer [1]. The non-diffracting character is linked to the special shape of the resulting transverse profile which is of the Lorentz type, recalling Bessel beams in light optics [2].

The extension of so-called "left-handed" optical meta-materials to negative-index media (NIM) for matter waves is a topic of particular importance [3]. Since the seminal paper of V.G. Veselago [4], many works have been devoted to optical NIM's and their properties (negative refraction, perfect focussing, reversed Doppler Effect, cloaking, etc.). Such artificial media are essentially characterised by a negative value of the optical index, which results into the reversal of the wave vector **k** with respect to the Poynting vector **R**. What should be the "*de-Broglie* optics" equivalent of those meta-materials [3]? To the energy flux in electromagnetism (**R** vector) corresponds the atomic probability flux, namely the current density of probability **J**, or equivalently the group velocity $\mathbf{v}_g = |\psi|^{-2}\mathbf{J}$, where ψ is the wave-function. Therefore, one has to reverse $\mathbf{v}_g$ with respect to the wave vector **k** or the phase velocity. However, contrarily to light optics where **R** remains directed outwards whereas **k** is directed towards the light source [5], for matter waves the direction of the phase velocity (**k**) remains unchanged, whereas $\mathbf{v}_g$ is now directed towards the source [3]. Obviously, because of the conservation of probability, such an effect is necessarily a *transient* effect. Indeed, when one uses an external time-independent potential to act on the matter wave, in a semi-classical description, this is equivalent to a "refraction index" which will be either positive or purely imaginary, depending whether the space region is classically allowed or forbidden to the atom. Our approach relies on both position- and time-dependent magnetic potentials to devise an atomic "meta-lens" [3]. We have shown that a novel class of recently introduced potentials - "*comoving" potentials* [6] - provides us with a remarkably simple solution to devise negative-index media for matter waves [3]. These co-moving potentials are oscillating magnetic potentials which, by an adequate choice of the spatial period and oscillation frequency, can be made co-propagating with the atom wave [6]. The calculation of the matter-wave phase-shift for a Zeeman-degenerate atomic system demonstrates the possibility of producing, for an appropriate choice of pulsed magnetic fields, transient *negative group velocities* for the atomic wave packet. With an adequate time-dependence of the co-moving field, it allows us to devise cylindrical or spherical "meta-lenses" able to re-focus the atom wave. This represents an extension of "meta-optics" down to the nanometre wavelength range. Among the predictable amazing properties of such materials, one could be the possibility of sub "*de-Broglie-wavelength*" focussing, below the diffraction limit. The latter characteristics should appear provided that evanescent matter waves can be properly reconstructed inside the atomic meta-medium [7]. This would open novel applications in atom nano-lithography and interferometry. This and other properties of negative-index media for atom optics will be discussed.

References

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