The general interest in the investigation of ultra-cold atoms and their distinct features has been constantly growing over the last few decades [1]. Whereas in the beginning, the process of cooling down presented the major challenge, now the extraordinary features of these ultra-cold systems – for example Bose-Einstein-Condensates – motivate researchers worldwide to look closer than ever.

Using fiber-optic equipment has proven to be a powerful tool for these experiments as they profit from the increased stability and convenience. The large variety of requirements e.g. on the collimation for the different experiments in quantum optics, is reflected in the number of specially designed fiber collimators (Fig. 1). These include fiber collimators with integrated quarter-wave plate for the direct generation of circularly polarized light or anamorphic optics to produce elliptical beams.

Both the cooling processes and the experimental investigations themselves highly rely on the successful manipulation and observation of atoms by light. This imposes strict requirements on the quality and stability of the equipment used. A widely used effective cooling and trapping method is the magneto-optical trap (MOT). A MOT requires highly frequency-stabilized, narrow width laser radiation to be launched into a vacuum chamber from up to six different directions. There are different type of MOTs, e.g. rubidium MOTs (working wavelength 780 nm), potassium (767 nm) or strontium – only to name but a few.

The beam delivery and distribution can be achieved by using a fiber port cluster [2, 3], a compact opto-mechanical unit that splits the radiation from one or more polarization-maintaining (PM) fibers (Polarization Extinction Ratio, PER >26 dB at 780 nm) into multiple output polarization-maintaining fiber cables with high efficiency and variable splitting ratio [4]. Fiber port clusters often utilize a cascade of rotary half-wave plates in combination with polarization beam splitters as a radiation-splitting mechanism.

The polarization-maintaining fiber optics serves as a defined interface between the laser and the very sensitive environment of the experiment. The physical separation enables a mechanical and thermal decoupling, avoiding any negative mutual impacts – both on the laser source and the experiment.

Upon exiting the polarization-maintaining singlemode fiber, the diverging Gaussian beam is collimated and launched into the vacuum chamber. The optimum collimation focal length is determined by the beam diameters required by the experiment and can be calculated from the NA (commonly defined at the 5 %-level of the Gaussian beam) of the fiber and the target beam diameter (defined on the 13.5 % or 1/e²-level). Focal lengths from 2.7 mm up to 200 mm for example when using a fiber with NA 0.11 can produce beam diameters ranging from 0.5 mm to 36 mm. The collimators are focussable and posses an integrated tilt mechanism, which allows...
the alignment of the beam axis with the optical axis, avoiding diffraction arising from a clipped beam and vignetting of the collimated beam. If desired, the collimators can be made from amagnetic titanium.

**Fiber collimators with integrated quarter-wave plate**

The circularly polarized radiation required for the cooling and trapping mechanism in a MOT can be provided by using fiber collimators with directly integrated quarter-wave-plates (Fig. 2).

The retardation plate is integrated into the divergent beam and can be rotated with respect to the linear input polarization to produce right-handed as well as left-handed circular polarization.

Analysis of the polarization states that are produced during the rotation can be made using a Polarization Analyzer [3] that continuously maps the current state of polarization on a Poincaré sphere. In this representation, linear states of polarization are located on the equator whereas circularly polarized light is located at the poles.

As can be seen in Fig. 2, a full rotation of the quarter-wave plate corresponds to a figure-of-eight on the Poincaré sphere [4]. At the poles, circularly polarized light is produced with right-handed circular polarization located at the north pole, and left-handed polarization located at the south pole. If the actual retardation of the optics deviates from the desired value then the extreme values do not reach the poles.

Depending on the application, zero-order, low order, multiple order or compound zero-order wave plates are used. Since they are placed into the divergent beam, the wave plates can be chosen to be small and rather thin.

The different kind of wave plates all exhibit a different susceptibility to possible error sources which include temperature variations, angle of incidence, as well as wavelength variations.

The change in retardance as a function of wavelength, as well as the change in retardance as a function of temperature, are both directly proportional to the total retardance of the wave plate itself. Thus, true zero-order, compound zero order or low order wave plates are typically less sensitive to temperature or wavelength variations compared to multiple order wave plates (retardance > 1).

Additionally, true zero order wave plates are often hardly sensitive to variations in incidence angle.

For a quarter-wave plate placed into a diverging beam that exits a fiber with NA 0.11, the incidence angle (5 % level) ranges from ± 6.2°. For such small angles the change in retardance as a function of incidence angle, is minimal and can often be neglected.

**Dichroic fiber collimators**

Some traps – e. g. strontium traps – are operated with multiple input wavelengths. If the wavelength difference needed is so large that the radiation cannot be transmitted by...
one single PM fiber, dichroic fiber collimators are used for collimation.

The optical scheme shows the two input laser beam couplers that collimate the input beams, the dichroic beam combination and the expansion of the single collimated beam (Fig.3). Even for these collimators, it is possible to generate circularly polarized beams by using appropriate dichroic quarter-wave plates that generate circularly polarized beams at both wavelengths simultaneously.

Elliptical fiber collimators

In the special case of a dipole trap, laser beams with an elliptical cross-section are required. This is achieved by using fiber collimators with integrated anamorphic beam expanders, producing beams with an elliptical aspect ratio of up to 3:1 (Fig.4).

Here the beam is collimated and then one beam axis is expanded and recollimated using both a positive and negative cylinder lens. Finally, the beam is expanded to the desired value using a telescope. If needed, a quarter-wave plate can be integrated into these fiber collimators as well.

Conclusion

Fiber optics can significantly enhance stability and convenience of measurement setups. For MOTs, the different beams needed can be delivered using a fiber port cluster - a compact and stable modular unit that splits the radiation into multiple polarization-maintaining fibers.

In order to meet the varying requirements and high demands of these experiments a large variety of fiber collimators was specially designed which include collimators with integrated quarter-wave plate, dichroic collimators or collimators that produce an elliptical beam profile.

References

Fig.4 Fiber collimators with integrated anamorphic beam shaping optics to produce a collimated Gaussian beam with elliptical cross-section. These fiber collimators are used in dipole traps.