Fiber Optics for Quantum

How to get light into quantum computers

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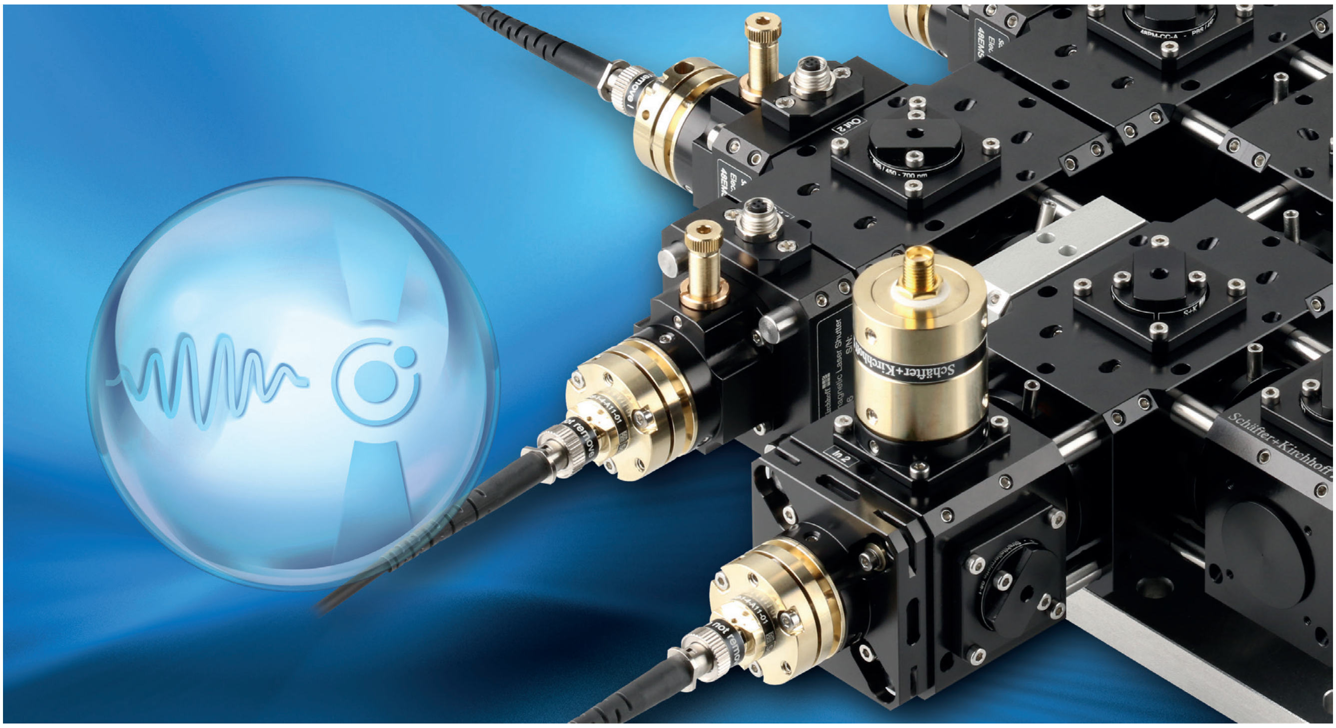


Fig. 1:

Fiber optics has been proven to be a powerful tool for quantum optics experiments for decades. These profit from the increased stability and convenience, as will future quantum computers. The specific needs regarding precision, stability and ruggedness call for high quality components and tailored fiber optic solution.

Technical progress in both industry and science has enabled preparation, manipulation and probing of quantum systems with unprecedented level of control. This provides the basis for a multitude of so-called quantum technologies like quantum cryptography, quantum sensors and quantum computers, which are currently developing from laboratory experiments to commercial applications.

Quantum computers are expected to efficiently solve optimization problems occurring in logistics or urban development and to enable computation-intensive simulations required for biotechnologies and drug design. Billions of dollars are currently being invested in the research of quantum computers in search of the optimal physical platform for its realization.

One of the most promising platforms is given by ultracold atom or ion systems, where the logical units, the “qubits”, are encoded within the internal states of the single atoms or ions. The preparation, programming and read-out of these systems is based on the reliable use of laser light with highest requirements on control over intensity, frequency as well as the state of polarization.

Fiber optics has been proven to be a powerful tool for these experiments for decades that profit from the increased stability and convenience, as will the final quantum computers. The specific needs regarding precision, stability and ruggedness call for high quality components and tailored fiber optic solutions.

How do Qubits profit from Fiber Optics?

The basis for most quantum optics experiments is a laser system that provides coherent laser light with a specific intensity, frequency, and state of polarization. In order to use this light for cooling, manipulation, and detection of atoms and ions, it has to be transported, distributed, and analyzed. Polarization-maintaining fiber cables, fiber couplers and collimators, fiber port clusters, and polarization analyzers can be used for this task.

Traditional setups often require large breadboard configurations that require frequent adjustment of opto-mechanical devices because of their instability. Compact, robust and modular fiber optic solutions as building blocks for laser systems add both stability and convenience. They are the perfect basis for developing laboratory setups into turnkey, low-maintenance end products. In addition, these self-contained setups increase laser safety and reduce laser safety classification.

In addition, fiber-based light transport provides a defined interface between the laser sources and the more sensitive environment of the quantum gas experiment or quantum information platform. It thus provides a physical separation that allows mechanical and thermal decoupling, which helps to suppress mutually adverse effects. The assurance of stability in the opto-mechanics means that the full focus can be on the experiment (and not on the equipment).

A large and complex quantum setup can be built by using fiber optics to connect each individual module, as well as using fiber optics in different parts of the modules needed for a quantum computer.

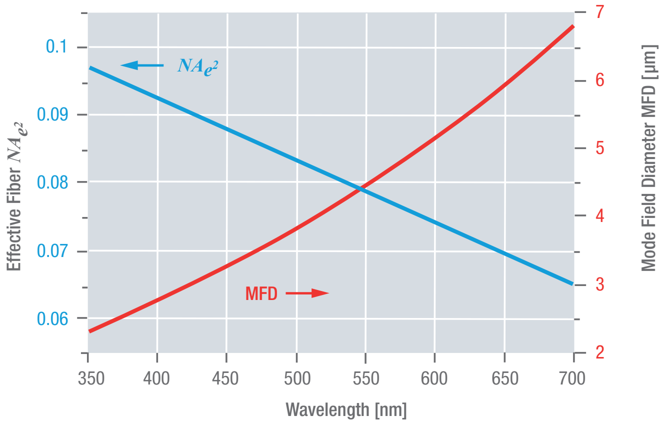
Single-mode and PM fiber cables

Single-mode fibers are specialized fibers that transmit light in the LP_{01} transverse fundamental mode. The field distribution (mode field) of the light exiting the fiber is nearly Gaussian. In standard single-mode fibers, light is guided in two principal polarization states. However, imperfections in the fiber cause random power transfer between the two principal polarization states, so that the polarization is not maintained.

Polarization-maintaining single-mode fibers (PM fibers) are rotationally asymmetric, e.g., due to integrated strain elements that break the degeneracy of the two principle states of polarization (SOP). Light is guided in either the "fast" or "slow" axis. Linearly polarized light coupled into one of these axes is preserved. The polarization extinction ratio (PER) – the ratio of the power carried in the two polarization axes – is a critical measure of fiber alignment. Since polarization is essential for many stages of a quantum experiment, PM fibers are often preferred over standard single-mode fibers for light transport.

Standard single-mode and PM fibers are characterized by their numerical aperture NA, mode field diameter (MFD), and cut-off wavelength λ_0. Only at wavelengths above this cut-off, the coupled light is guided in a single-mode and not in multiple modes, where the beam and intensity profiles are no longer stable and Gaussian. The MFD is wavelength dependent and inversely proportional to the fiber NA. While fibers used for telecommunications in the infrared, around wavelengths of 1550 nm, are characterized by relatively large mode field diameters of about 10 µm, the MFD in the UV is small for a typical single-mode or polarization-maintaining fiber, e.g. 3 µm for 405 nm and a fiber with nominal NA = 0.12.

The nominal NA does not reflect exactly the divergence properties of the emitted radiation. However, for coupling a beam into a fiber the



Values:
NA_{e^2} (405nm) = 0.092 ± 0.005
NA_{e^2} (450nm) = 0.088 ± 0.005
NA_{e^2} (514nm) = 0.082 ± 0.005
NA_{e^2} (635nm) = 0.071 ± 0.005

Figure 2.

Effective numerical aperture NAe^2 and the corresponding MFD for an RGB fiber that can be used between 400 nm and 640 nm. The NAe^2 decreases significantly with increasing wavelength.

divergence properties define (among the collimated beam diameter) the best coupling focal length, see below. Therefore, it is important to measure an effective NAe^2 for each fiber, for different wavelengths, and for each fiber reel. These detailed measurements, as shown in Figure 2, show that for short wavelength fibers, the effective numerical aperture varies with wavelength and is not constant as assumed in the standard model and for telecom fibers.

Typically, the effective NAe^2 for standard single-mode fibers and PM fibers decreases with increasing wavelength [1].

Long-term stable coupling into PM fibers

Long-term stable, rugged and highly efficient fiber coupling is the foundation of all fiber-based setups. This is even more important when the goal is to build low-maintenance turnkey products. A fiber coupler or laser beam coupler is often used for coupling into the (PM) fiber cable.

When coupling into single-mode fibers, laser beam couplers should produce a diffraction-limited spot that matches the mode field diameter and effective numerical aperture of the fiber to achieve maximum coupling efficiency. Fiber coupling with high coupling efficiencies of up to 85% can only be achieved if this condition is met.

Accurate information about the effective NAe^2 is essential to determine the correct coupling focal length, which is calculated from both the laser beam diameter and the effective fiber NAe^2. A focal length that is too large is inefficient because the focused laser spot is larger than the mode field diameter. If the focal length is too small, the convergence angle of the focused laser spot is larger than the maximum acceptable divergence angle of the fiber – the coupling efficiency is reduced. For an optimally chosen focal length, an ideal Gaussian beam is almost completely coupled, except for losses due to Fresnel reflection at both uncoated fiber ends of about 4% each.

The required pointing stability of the laser beam coupler when coupling a free beam into a polarization-maintaining fiber can be illustrated by an example: At a focal length of 5 mm, an angular misalignment of the coupler of only 0.2 mrad (0.01°) would result in a lateral displacement between the laser spot and the mode field of the fiber of 1 µm. At $\lambda = 400$ nm and a nominal NA of 0.12, a displacement of just 0.4 µm is sufficient to reduce the coupling efficiency by as much as 10%. Therefore, for high coupling efficiency and long-term stability, sub-micron precision and pointing stability of the coupling optics is required, especially in the blue region.

The high stability of fiber coupling using a fiber coupler is demonstrated in temperature stability tests using different focal lengths and wavelengths. The test setup is shown in Figure 3. The setup is described in detail in [1].

Figure 4 shows typical results of the relative transmitted power over 5 measurement cycles using a focal length of 4.5 mm and a wavelength of 405 nm. The power is normalized with respect to the mean power obtained over all measurement cycles. The power deviation from the mean power is ±1.5%.

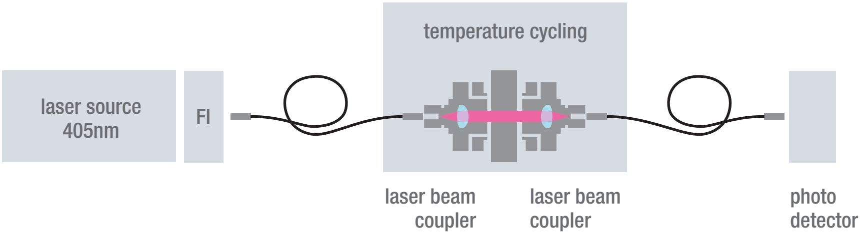


Fig. 3:

Test setup for measuring the stability of two laser beam couplers (f = 4.5 mm, $\lambda = 405$ nm) during successive temperature cycling between 15 °C and 35 °C.

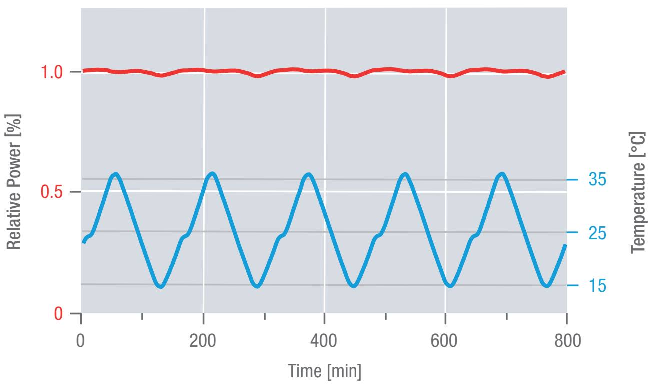


Fig. 4:

The relative power (normalized with respect to the mean power) shows a repetitive pattern following the temperature (below) and has a maximum deviation of ±1.5 %.

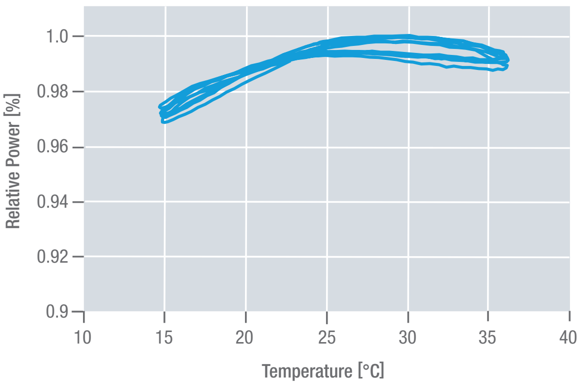


Fig. 5:

The relative power curves (normalized with respect to the maximum power) are almost coincident and confirm the high reproducibility of the pointing stability during temperature cycling. The maximum deviation is only 3 %.

The repetitive pattern in relative power caused by temperature cycling is more clearly shown in Figure 5, where relative power (normalized to the maximum) is plotted against the temperature of the laser beam couplers. The maximum coupling efficiency is reached just above 25 °C and decreases faster at lower temperatures than at higher temperatures, with the smallest slope near the desired operating point (25 °C).

The corresponding power curves for each measurement cycle are nearly coincident, and the power variation at points of equal temperature is <1%. This demonstrates the reproducibility of the pointing stability during temperature cycling and the long-term stability of the fiber coupling. The maximum deviation with respect to the maximum power is only 3%, making it an ideal basis for quantum endeavors.

As an alternative to laser beam couplers, fiber collimators can also be used in reverse for coupling into PM fibers. Fiber couplers and collimators with fine-focusing mechanisms provide easy, highly defined adjustment of the focus without backlash. This ensures high coupling efficiency even when the divergence or wavelength of the laser source used varies frequently.

Beam Distribution - Fiber Port Clusters

The preparation and manipulation of quantum gases requires the illumination of the atomic ensembles with coherent laser light from different spatial directions. Therefore, the laser light must be split into different beam paths while maintaining control over its polarization state.

Fiber port clusters are compact opto-mechanical units that split the radiation from one or more polarization-maintaining (PM) fibers into multiple output polarization-maintaining fiber cables with high efficiency and variable splitting ratio. The beam delivery system consists of compact, modular opto-mechanical units. The modularity ensures that almost any desired system can be assembled in a compact and sealed manner. Due to the polarization sensitive nature of the optical components within the fiber port cluster, PM fibers are used to transport light to the cluster with defined linear polarization. The fibers used have a polarization extinction ratio (PER) greater than 26 dB (measured at 780 nm).

For single input wavelength fiber port clusters, beam splitting is achieved using a cascade of rotating half-wave plates in combination with polarization beam

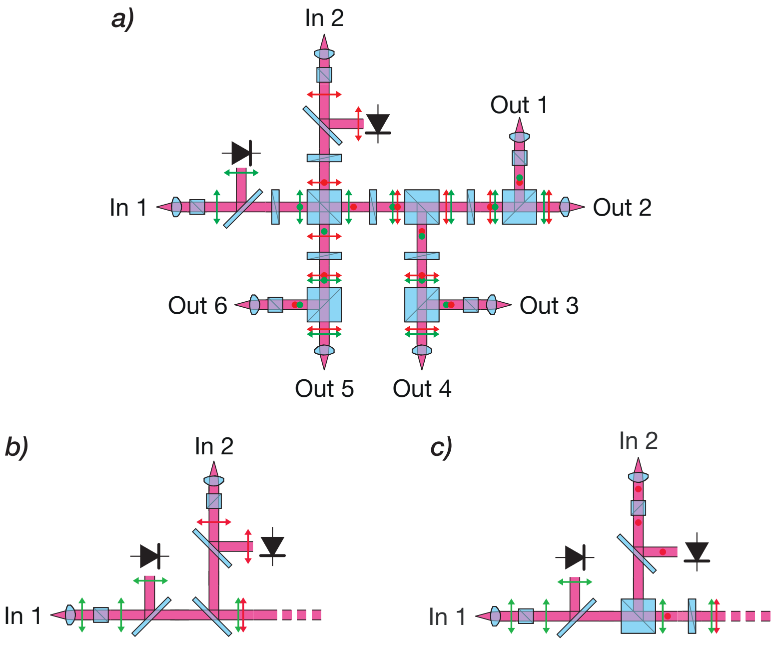


Fig. 6:

a) Optical scheme of a fiber port cluster 2-6. The arrows and the dots denote the state of polarization.

b) Input group for combining of two wavelengths with a dichroic beam combiner (with two power monitors).

c) Scheme of combining of two wavelengths by means of a polarization beam combiner followed by a dichroic wave plate. Input group with two power monitors.

splitters. Integrated elements, such as photodiodes, provide useful input power monitoring. The inputs and/or outputs can be equipped with electromagnetic shutters. Through the use of the rotating half-wave plates, it is possible to achieve almost any desired beam splitting ratio. Various experiments [2] and [3] have demonstrated the high stability and robustness of standard fiber port clusters.

Schäfter+Kirchhoff also offers fiber port clusters with two input ports, e.g. for the cool and repump frequency for a MOT at 780 nm (Fig. 6a).

It is also possible to combine beams of different wavelengths at the input port of a fiber port cluster for subsequent splitting of both components equally, as required for a dual-species MOT, for example. When using multiple wavelength inputs, the wavelength difference between the input ports determines how the combination can be achieved. For two laser sources with a large wavelength difference, a dichroic beam combiner is used (Fig. 6b). If the wavelength difference is too small for a dichroic beam combination, a polarization beam splitter and a subsequent dichroic waveplates allows multiplexing (Fig. 6c).

Fiber collimators are then used to collimate the light exiting the PM fibers attached to the output ports of the fiber port clusters. For cases where the wavelength difference of the two lasers is too large to be guided in a common single-mode fiber, Schäfter+Kirchhoff has developed special fiber collimators with an integrated dichroic beam combiner that have two separate input ports for the two sources. If circularly polarized light is required, fiber collimators with directly integrated quarter-wave plates can be used.

Analyzing the Polarization

For quantum platforms such as ultracold atoms or ionic systems, control over the state of polarization and its analysis is essential. It is also important for the PM fiber coupling process. The polarization analyzer described here has two main applications: One is to monitor the alignment of the polarization-maintaining fibers with the polarization axis of the source; the other is to determine the state of polarization in general and its defined setting according to the requirements. More details can be found here [4].

The polarization is determined by evaluating the light arriving at a photodiode after passing through a rotating quarter-wave plate and a static polarizer. The Stokes parameters are obtained from a detailed analysis of the photodiode signal and the time/position information of the quarter-wave plate. The polarization state is then plotted on the Poincaré sphere, where any change in the polarization state as well as the sense of rotation (plotted on the northern or southern hemisphere) is easily visible.

For fast and accurate alignment of PM fibers with linearly polarized light sources, it is essential to efficiently determine and display the polarization extinction ratio (PER). The polarization of linearly polarized light that is not fully coupled into one of the polarization axes is not maintained, and the polarization changes with temperature and strain variations. This is visualized on the Poincaré sphere by carefully and purposefully introducing environmental changes, such as temperature variation or slow bending of the fiber, which causes a data circle to be formed on the Poincaré sphere resulting from the induced phase shift between the two principal polarization states.

This circle represents all possible polarization states for the current alignment, with the center representing the mean polarization extinction ratio. For an ideal polarization-maintaining fiber, the mean polarization extinction ratio should be located at the equator. The data point farthest from the equator shows the worst possible polarization extinction ratio for the current alignment.

When adjusting the fiber coupling, the radius of the circle on the Poincaré sphere is an indication of the quality of the alignment, since it shows the angular deviation between the fiber polarization axis and the source polarization axis. Assuming an ideal linearly polarized source, the radius of the circle is large for poorly aligned fibers-the polarization varies greatly with ambient conditions-and small for precisely aligned fibers.

For an optimally aligned ideal fiber, the data circle converges to a single point on the equator of the Poincaré sphere. When adjusting the fiber coupling, a series of measurement points are taken while changing the temperature or carefully bending the fiber to generate a circular trajectory of data points. A circle is automatically fitted to the data points and the mean and minimal PER are displayed (Fig. 7a).

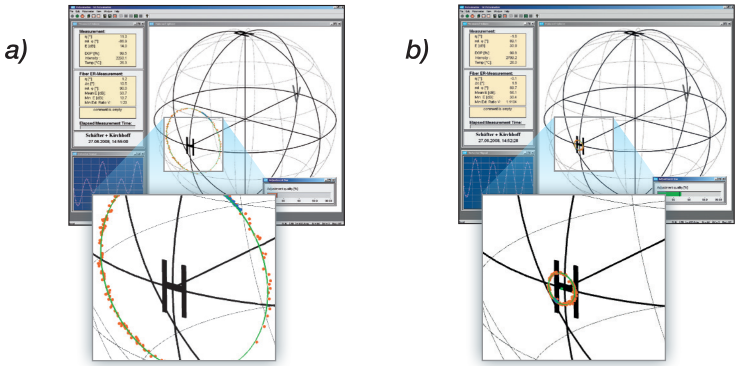


Fig. 7:

Adjustment of a polarization-maintaining fiber with a coherent laser source. Goal of the adjustment is minimizing the data circle radius.

When the fiber polarization axis and the laser polarization axis have a high angular deviation, the state of polarization varies significantly when bending the fiber or when the ambient temperature changes (a).

The better the angular alignment of the fiber, the smaller the change in polarization and the smaller the radius of the data circle (b).

The polarization axis of the fiber can now be rotated with respect to the polarization axis of the source until the radius of the circle reaches a minimum (Fig. 7b). A second measurement then reveals the parameters of the optimized fiber alignment.

Conclusion

Fiber optics has proven to be a powerful tool for quantum experiments for decades. The progress made over the years provides the basis for a variety of so-called quantum technologies, such as quantum cryptography, quantum sensors and quantum computers, which are currently evolving from laboratory experiments to commercial applications. The special requirements for precision, stability and robustness require high-quality components such as polarization-maintaining fiber cables, fiber couplers and collimators, fiber port clusters and polarization analyzers, which are available from UV - IR.

References

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