FiberLock: Actively Stabilized Fiber Coupling

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The FiberLock is a simple system for locking free-space laser beams to single-mode fibers. It simplifies the initial coupling, helps with optimizing the coupling efficiency and actively compensates for mechanical drifts.

1 Principles of Fiber Coupling

When laser light exits a single-mode fiber, it forms a divergent cone, and a collimating lens is required to produce a collimated beam. Conversely, if a beam is to be coupled into such a fiber, it must be formed into an equally shaped cone by means of a focussing lens. The exact geometry of the optimal, intensity-maximizing cone is fixed by the properties of the fiber. For optimal coupling efficiency, the incident beam must have maximum spatial overlap with the optimal cone. In a coordinate system (x, y, z), where the z-axis coincides with the optical axis of the fiber, this overlap is determined by six degrees of freedom[1]:

- the angle of convergence of the cone
- the position of the beam waist in z-direction
- the position of the beam waist in x- or y-direction
- rotations of the cone in x- or y-direction

[1] Additional degrees of freedom can be found for example for polarization-maintaining fibers.

An optical setup with optimal alignment is depicted in Figure 1 a).

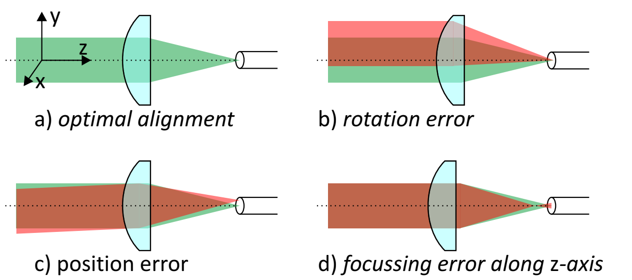

Figure 1: *Different sources of alignment errors in fiber coupling.*

The angle of convergence is determined by the beam diameter and the focal length of the focussing lens. The position of the beam waist in z-direction is addressed by varying the distance between the lens and the tip of the fiber. These two degrees of freedom are depicted in Figure 1d).

To control the remaining four degrees of freedom requires a special fiber mount allowing us to tip, tilt and shift the tip of the fiber. Alternatively, the position (see Figure 1b)) and angle (Figure 1c)) of the incident beam can be varied while focussing lens and fiber mount remain fixed. Either way, the required accuracies are in the sub-micron regime, which means that high-precision mechanical mirror mounts and fiber mounts are necessary. In addition, these parts must be robust against thermal expansion in order to minimize drifts and the resulting deterioration of the coupling efficiency.

The optimization and the long-term stability of the coupling efficiency remain a challenge today, despite the fact that free-space to fiber links are almost ubiquitous in optics laboratories and have wide-spread industrial applications.

2 Active Fiber Coupling

When passive stability is not sufficient, an active stabilization can provide the required performance. It requires an actuator, e.g., a piezo-electrically driven mirror, and a feedback signal.

As shown in Figure 2, TEM Messtechnik's FiberLock uses a single-mirror actuator which is placed in front of the focussing lens. Tilting this mirror changes the position of the beam waist in x- or y-direction. The feedback signal comes from an intensity measurement after the fiber or from inside the fiber using a fiber tap.

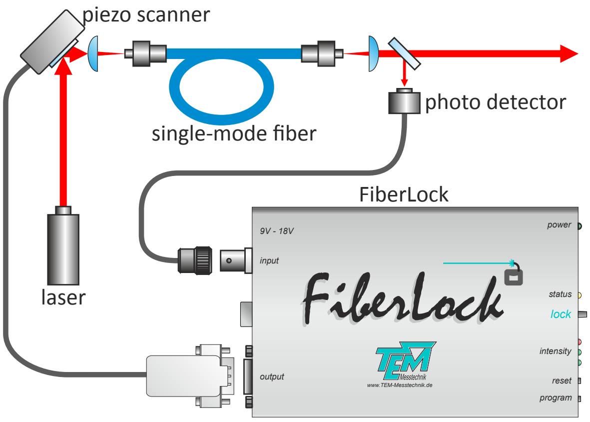

Figure 2: *The FiberLock electronics connect to an active piezo-mirror and to the intensity signal after the fiber, forming a feedback-loop.*

This simple set-up serves three purposes:

1. It aids the initial coupling of light into the fiber,
2. it greatly simplifies the optimization of the coupling efficiency,
3. it stabilizes the coupling, compensating for drifts of the laser beam and of the fiber mount.

In fact, the FiberLock can even compensate for intensity noise of the laser, as described in Chapter 2.4.

2.1 Initial Coupling

When first coupling into a fiber, the different degrees of freedom for alignment have to be scanned "blindly". Only when a detectable amount of light is coupled in do we have a feedback signal to start optimizing.

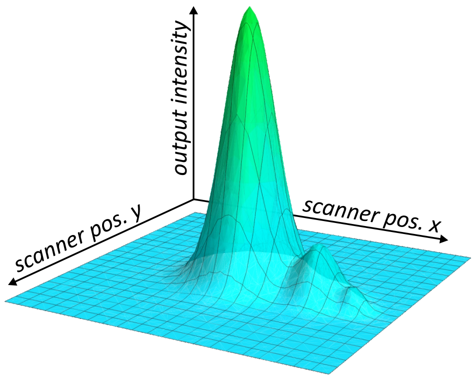

Figure 3: *Scanning the actuator angle provides a three-dimensional visualization of the coupling efficiency.*

With an active piezo-driven mirror, this blind scanning can be done fast enough to deliver live three-dimensional plots of the coupling efficiency versus the mirror position, as shown in Figure 3. Since the scanning range of the actuator is typically one or two orders of magnitude larger than the fiber core diameter, the initial coarse alignment becomes very simple. As a side-effect, we gain information on the beam profile and on artifacts of our set-up such as unwanted ripples in the coupling efficiency.

2.2 Stabilization

Once a maximum in the coupling efficiency has been found, the FiberLock can lock on to it. In lock mode, the active mirror adds small modulations to the x- and y-positions of the beam waist. The output intensity after the fiber provides the necessary feedback: If the modulations show in the intensity, the beam waist is not aligned to the fiber core, and the active mirror will correct this. Once to beam enters the fiber centrally, the modulations in the output intensity disappear[2].

Any drifts of the fiber tip position or of the incident beam will now be perfectly compensated for. If the lock is ever lost, the FiberLock features a search mode which quickly scans through the actuator's range and changes back to lock mode a soon as the intensity

[2] A one-dimensional lock-in regulator invariably causes modulations on the output signal. In 2D, however, a modulation-free output is possible.

peak is found. Such a scan starts automatically if the Auto-Relock is enabled.

2.3 Optimizing in Lock

In typical optical set-ups, it is not possible to adjust the six degrees of freedom involved in fiber coupling optimization independently. For instance, the focus can be adjusted by moving the focussing lens along the z-axis. However even high-quality sleighs have limited manufacturing precisions and cannot be perfectly aligned with the optical axis. As result, the lens will also move in x- and y-direction, which leads to unwanted shifts of the beam waist position.

Such cross-dependencies make the optimization of fiber coupling very difficult: Instead of optimizing one degree of freedom after the other, they disturb each other and must be optimized iteratively, which takes significantly longer.

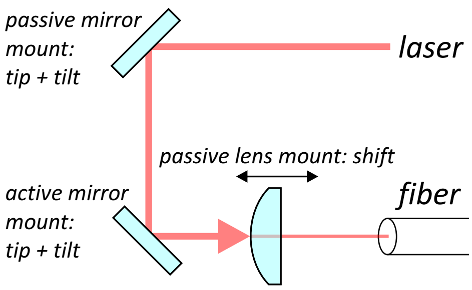

Figure 4: *Optical setup: The active mirror mount controls the position of the beam waist. Other parameters can be adjusted manually.*

Since the FiberLock only stabilizes two degrees of freedom, manual optimization is still required (see Figure 4). This task however is greatly simplified when the FiberLock is active: Firstly, the number of adjustment options is simply reduced. Secondly, the cross-dependencies introduced by imperfect opto-mechanics are now largely removed. For instance, if the fiber tip is moved along the z-axis, unwanted x- and y-shifts are automatically compensated for and the output intensity purely show the effect we are interested in.

The FiberLock's regulator is easily fast enough to follow manual adjustments so that all remaining degrees of freedom can be optimized in an independent, fast and convenient manner.

2.4 Noise-Eater Mode

The ability to control the coupling efficiency opens up an interesting possibility: The FiberLock system can act as a "Noise Eater" if the aim is to keep the intensity in the fiber at a constant, rather than at the maximum value. If, for example, the laser shows intensity fluctuations, the FiberLock can compensate for those by actively tuning the coupling efficiency.

In this way, the combination of a FiberLock and a single-mode fiber can act as a mode-cleaner. Distortions of the beam profile, intensity noise and pointing fluctuations are all removed, at the expense of losing some optical power.

2.5 Summary

In essence, an active fiber coupling works the same way as manual alignments: The fiber output is used as a feedback signal for the adjustment of the opto-mechanics. However, the FiberLock does this much faster, more reliably, and most important, continuously. Once locked, the coupling will remain stable indefinitely. This is crucial for optics experiments which must run several days without interference or for "hands-off" industrial applications such as fiber-coupled lasers. Furthermore, the FiberLock's scan and search functions make it a valuable asset in frequently changing optical set-ups.

A simple but effective user interface on the FiberLock electronics allows the operation without connecting a PC. This becomes necessary only for visualization or access to advanced parameters.

Lastly, the task of optimizing some quality signal by aligning an optical element is a much more general one and has applications as varied as lens positioning in the production of laser diodes or beam alignment in optical parametric amplifiers.

References

[Web-link:] `http://www.tem-messtechnik.de/EN/fiberlock.htm`