Opto-mechanics for demanding fiber optic applications

Titanium components ensure long-term stable fiber coupling at short wavelengths.

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A stabile measurement setup is fundamental for the success of an experiment, e.g. in quantum optics. A major cause of frustration and error is the need to continuously readjust opto-mechanical equipment. By using fiber optics, both stability and convenience are significantly increased compared with standard breadboard setups. A fiber port cluster (Fig. 1), for example, can split the radiation from one or more light sources and distribute it on several polarization-maintaining output fibers with high efficiency. The assurance of stability in the opto-mechanics means that the full focus can be set on the experiment (and not the equipment).

Fiber optics can serve as a defined interface between a laser source and the more sensitive environment of the experiment. A physical separation between these parts of the setup enables a mechanical and thermal decoupling, avoiding any negative mutual impacts.

Fiber port clusters are compact opto-mechanical units that split the radiation from one or more polarization-maintaining (PM) fibers into one or multiple output polarization-maintaining fiber cables with high efficiency and variable splitting ratio. The beam delivery system consists of compact, modular opto-mechanic units. The modularity ensures that almost any desired system can be assembled that is compact and sealed. Because of the polarization sensitive properties of the optical components within the fiber port cluster, PM fibers are used to transport the light to the cluster with defined linear polarization. The fibers used here have a polarization extinction ratio of more than 32 dB (measured at 405 nm).

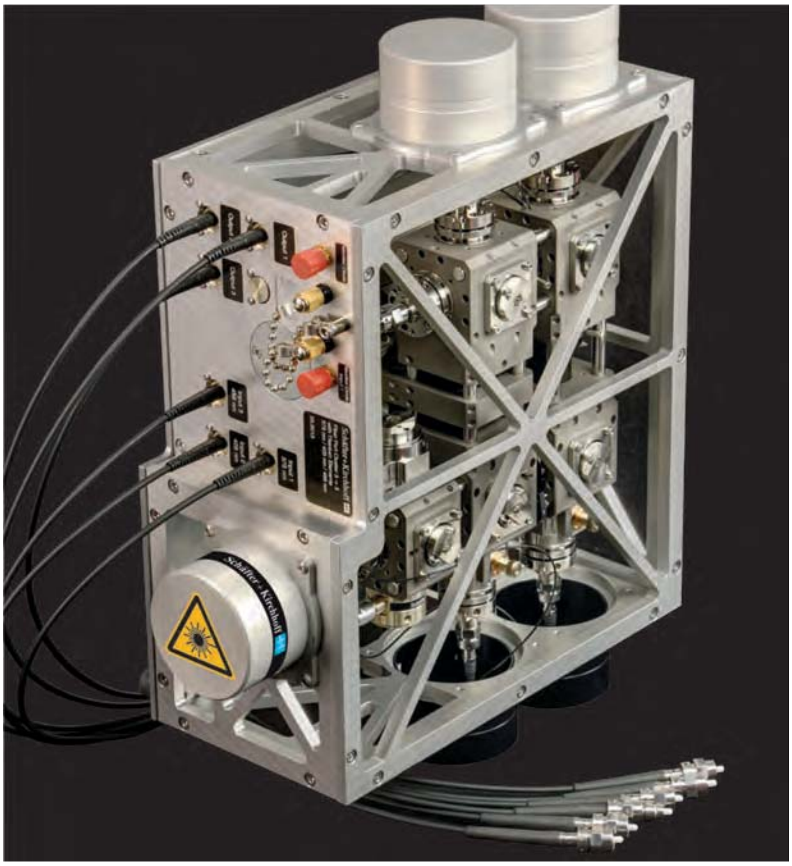

Fig. 1 Fiber Port Cluster made from titanium components for use in demanding environments, e.g. for wavelengths below 400 nm. To protect the system against outside influences during transport or when the fiber port cluster is handled in the laboratory, the whole system can be enclosed in a protective, sealed housing. Thermal influences for the whole system can be reduced by using titanium laser beam couplers and titanium fiber port cluster elements. Fiber collimators with integrated quarter-wave plate can be used to transform the output radiation into circularly polarized light.

There are several ways to achieve the beam splitting into several output ports. For fiber port clusters with one input wavelength, radiation splitting is achieved by using a cascade of rotary half-wave plates in combination with polarization beam splitters. Integrated elements, such as photodiodes, allow insightful monitoring of the input powers. By use of the rotary half-wave plates, almost any desired splitting ratio can be realized.

If using several inputs with multiple wavelengths, 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. If the wavelength difference is too small for dichroic beam combination, a polarization beam splitter and subsequent dichroic wave plates allow multiplexing. This can be seen in the exemplary fiber port cluster depicted in **Fig. 2**, with the multiplexing of three input laser sources of 378 nm, 404 nm and 460 nm. The first combina-

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tion is achieved using a polarization beam splitter that transmits the p-polarized 378 nm and the s-polarized 404 nm radiation. A dichroic wave plate then rotates the polarization axis of the p-polarized 378 nm while maintaining the s-polarization of the 404 nm so that both can be combined with an s-polarized 460 nm source. Because of the rather large wavelength difference this is achieved by use of a dichroic beam splitter. The light is then distributed to three output ports with variable splitting ratio using a cascade of half wave plates (adequate for all three wavelengths) and polarization beam splitters. Fiber collimators with an integrated quarter-wave plate can then be used to transform the linear output radiation into circularly polarized light for use in, for example, magneto-optical traps.

Stable fiber coupling at short wavelengths

A fundamental component of a fiber port cluster is the laser beam coupler, which is the input into the opto-mechanic unit collimating the input radiation and, finally, couples the radiation back into the polarization-maintaining fibers. The basis of the stability of the total fiber port cluster is the stability of the laser beam coupler.

When coupling back into the polarization-maintaining fibers, the laser beam couplers produce a diffraction-limited spot that matches the mode field diameter and the numerical aperture of the fiber. It is only when this condition is met that fiber coupling with high coupling efficiencies of up to 80 % are achieved. The mode field of a fiber is wavelength dependent and inversely proportional to the numerical aperture NA. Typical mode field diameters range from 3 µm (405 nm, NA 0.12) to 5 µm (780 nm, NA 0.12). The required pointing stability of the laser beam coupler when coupling a free beam into a polarization-maintaining fiber can be visualized with an example: For a focal length of 5 mm, an angular misalignment of the coupler of a mere 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. A displacement of 0.4 µm alone at λ = 400 nm and NA 0.12 is enough to decrease coupling efficiency by as much as 10 %. Thus, for high coupling efficiencies and long-term stability, a sub-micron precision and pointing stability of the coupling optics is required, especially in the ultraviolet range.

In order to demonstrate the stability of the laser beam coupler, temperature-stability tests are performed using different focal lengths and wavelengths. The laser beam couplers are made from standard nickel silver. The test setup is depicted in **Fig. 3a**. The light emitted by the temperature-stabilized laser diode beam source 48TE is guided to the experiment via a polarization-maintaining fiber, collimated by a laser beam coupler and then coupled back into a polarization-maintaining fiber with a second laser beam coupler. Both couplers are placed at the opposing ends of a multicube element, about 12 mm apart. The power guided through the test setup is monitored using a photo detector. In order to minimize any temperature impact on the measurement equipment, the laser source, the photo detector and the data logger are all placed on a thermo-controlled plate holding a constant temperature of 25 °C.

The coupling system itself is placed on another thermo-controlled plate. The temperature of the coupling system is monitored by placing a temperature sensor on one of the laser beam couplers. This thermo-controlled plate is used to vary the temperature of the coupling system between 15 °C and 35 °C in successive cycles with a rate of 0.5 °C/minute.

Fig. 3b shows typical results of the relative power that is transmitted through the system using a focal length of 4.5 mm and a wavelength of 405 nm over 5 measurement cycles. The power is normalized with respect to the mean power acquired over all measurement cycles for a total measurement time of about 800 min. The deviation from the mean power is ±1.5 %. The repeating pattern in the relative power arising from the temperature cycling is demonstrated more clearly in **Fig. 3c**, in which the relative power (this time normalized to the maximum) is plotted against the temperature of the laser beam couplers. A maximum coupling efficiency is reached a little above 25 °C that decreases towards 15 °C, but less so at higher temperatures, with a small slope near the required operating point (25 °C). The relative power curves for each measurement cycle are almost located on top of each other and the power variation at points with equal temperatures is < 1 %, which shows the reproducibility of the pointing stability during temperature cycling and the long-term stability.

Maximum deviation with respect to the maximum power here is 3 %.

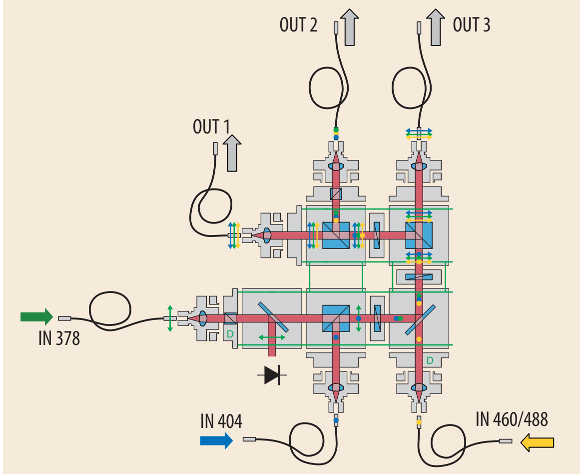

Fig. 2 Optical scheme of a fiber port cluster for the multiplexing of p-polarized 378 nm (green arrows), s-polarized 404 nm (blue dots) and s-polarized 460 nm (yellow dots) radiation. The first two beams are combined using a polarization beam splitter, the third beam is added by use of a dichroic beam splitter and distributed to three output ports using a cascade of halfwave plates and polarization beam splitters.

Enhanced stability of the fiber port cluster

The high stability and ruggedness of standard fiber port clusters has been proven in very harsh environments including zero-G experiments, either on an airplane performing parabolic flights [1] or even using a drop tower [2]. The

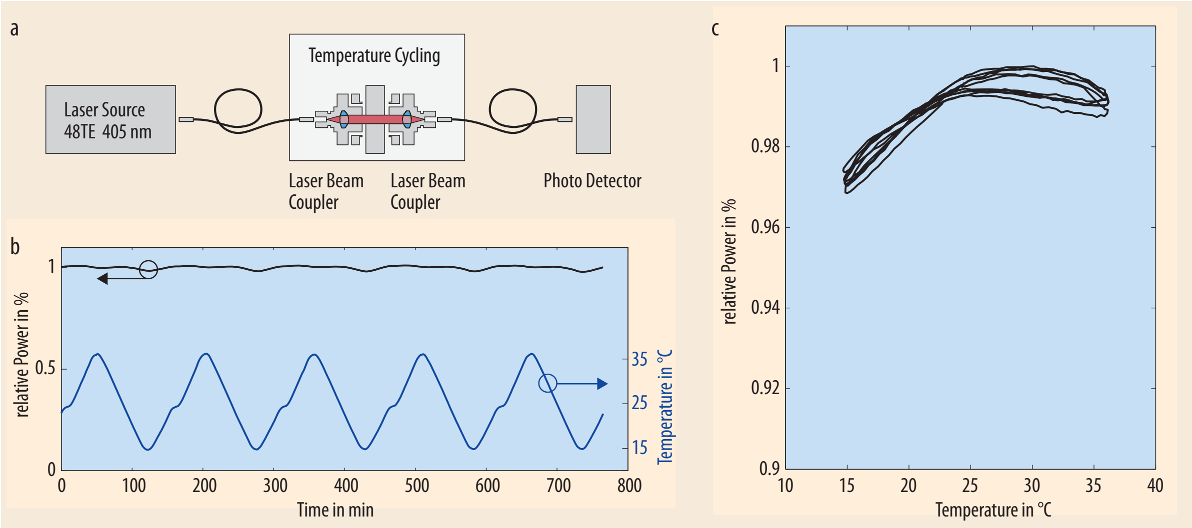

Fig. 3 Test setup for measuring the stability of two laser beam couplers (f = 4.5 mm, λ = 405 nm) during successive temperature cycling between 15 °C and 35 °C (a). The relative power (normalized with respect to the mean power) over time is depicted in (b). It shows a repeating pattern following the temperature (below) and has a maximum deviation of ±1.5 %. A detailed analysis of the relative power (now normalized with respect to the maximum power) reveals that the curves are almost located on top of each other, showing the high reproducibility of the pointing stability during temperature cycling (c). Maximum deviation is only 3 %.

fiber port cluster elements are made from aluminum. In order to protect the system from outside influences, during transport or when the fiber port cluster is handled in the laboratory, the whole system can be enclosed in a protective, sealed housing (see **Fig. 1**). The most sensitive parts of the cluster, the input and output laser beam couplers are then protected from major mechanical influences. The cluster is shipped prealigned and fully assembled and the opto-mechanical units can be protected from any shock e. g. during transport by placing the unit on anti-vibration bearings.

The mechanical stability of the fiber port cluster can be further enhanced, where necessary, by using titanium components. Standard fiber port clusters, as used e. g. in zero-G experiments are already very stable and rugged against outside influences. Very short wavelengths below 400 nm however require increased stability to ensure a high coupling efficiency.

The laser beam couplers characterized in **Fig. 3** are made from nickel-silver with a coefficient of thermal expansion of about 19.5×10^{-6}/K. Pointing stability can be enhanced by using titanium for the laser beam couplers. Titanium has the highest strength-to-weight ratio of any metal and a low coefficient of expansion of 10.8×10^{-6}/K. It is corrosion resistant and also amagnetic, so that titanium components can be used in environments that require very defined magnetic fields.

For a planar system with parallel collimated beams, the thermal expansion of the mechanical components during transport or with changing ambient conditions in the laboratory alone is not so critical. Standard aluminum components have a coefficient of thermal expansion of 23×10^{-6}/K and are combined using 4 rods from stainless steel (coefficient of thermal expansion: 10.5×10^{-6}/K). In order to compensate thermal influences in the fiber port cluster to an even higher degree the whole system can be made of components with similar coefficients of thermal expansion. The coefficient of thermal expansion for the optic glass N-BK7, for example, is 7.1×10^{-6}/K [3] – close to that of titanium. Thermal influences for the whole system can thus be reduced by using titanium laser beam couplers and titanium fiber port cluster elements.

Conclusion

Fiber optics can significantly increase the stability and convenience of measurement setups. Fiber port clusters are compact modular units that can be used to split radiation into multiple polarization-maintaining fibers. Large breadboard setups can be replaced by stable, compact, transportable, sealed fiber-optic systems.

The stability of any fiber port cluster is dependent on the stability of the laser beam couplers used for collimation at the input and for coupling the radiation into the output PM fibers. Power stability during temperature cycling with a typical maximum deviation of 3 % is achieved in a test setup for a focal length of 4.5 mm at 405 nm. This high stability is fundamental for the successful use of fiber-optic equipment.

As a protection against shock and mechanical influences, the cluster can be placed on anti-vibration bearings in a sealed protective housing. In order to further compensate thermal influences titanium cluster elements and laser beam couplers can be used.

References

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