Integrated double-pass AOM systems

Versatile light modulation with highest thermal stability

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As quantum technologies transition from laboratory-based demonstrations to robust, deployable systems, ultracold atom and ion platforms face increasingly stringent demands on the stability and reliability of their optical infrastructure. Inparticular, the opto-mechanical units used to control, modulate, and distribute laser light must deliver stable performance under thermal and mechanical perturbations, while minimizing alignment effort and overall system complexity.

Double-pass acousto-optic modulator (DP AOM) systems represent a well-established approach for precise frequency control and intensity modulation of laser light and are widely employed in quantum optics applications such as quantum gas preparation, spectroscopy, and the control of atoms, ions or molecules. When implemented in a compact and mechanically stable architecture, double-pass systems form robust and well-defined building blocks with reproducible systemlevel performance. Here, we present broadly tunable double-pass AOM systems as integrated product solutions within the rugged, modular, and compact multicube™ platform. In combination with the established Fiber Port Clusters [1], these systems enable the transfer of complex light conditioning assemblies into a standardized and mechanically stable form factor. This approach provides a

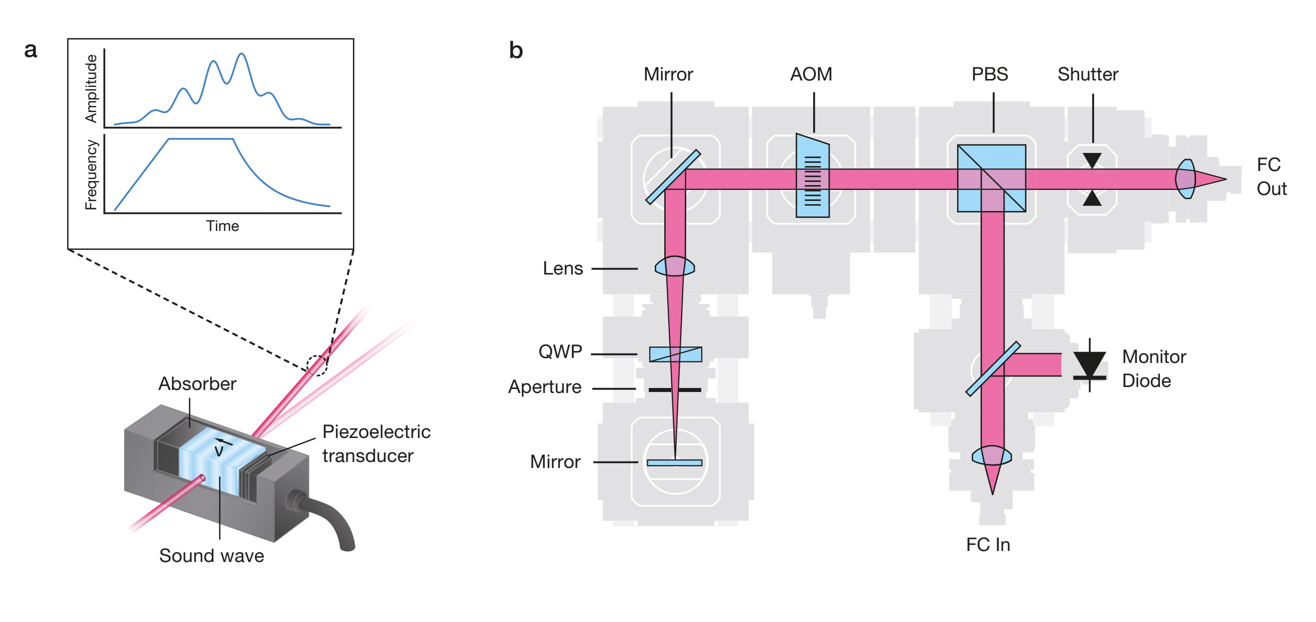

Figure 1 Double-pass AOM setup for amplitude modulation and frequency shifting.

scalable path toward robust solutions for quantum technology applications, supporting the transition from laboratory setups to reliable, application-ready optical systems.

Double-pass AOM

In laser-based quantum technologies, light modulation and frequency shifting are typically achieved using acousto-optic modulators (**Fig. 1a**). These devices use a piezoelectric transducer driven by a radio frequency (RF) signal of frequency f_{RF} to induce a longitudinal, compressional sound wave that propagates through the optical crystal (e.g., TeO_2). The incident light is diffracted by the resulting density grating into different diffraction orders n. These orders have a light frequency of $fd = f_0 + n \times f_{RF}$ shifted by multiples of the radio frequency. When operating in the Bragg regime, most of the incident light is diffracted into the first (or minus first) order. After separation from the zeroth order, the diffracted light can be used with amplitude and frequency control via the applied RF signal.

Integrated into rugged, fully fiber-coupled systems, singlepass AOM setups are designed for amplitude modulation and fixed frequency shifting with high efficiency (48-AOM-1xxx). However, because the diffraction angle is proportional to the radio frequency, they are not suitable for dynamic frequency shifting followed by fiber coupling. In a double-pass configuration, the diffraction angles of the forward and backward paths cancel each other. Thus, the beam path becomes independent of the frequency shift within a certain tuning range, enabling subsequent fiber coupling.

Fig. 1b illustrates the integrated double-pass AOM system. The laser light is coupled into the system via a polarization-maintaining input fiber. After collimation, a portion of the light is reflected onto a photodiode to monitor the input laser power. The vertically polarized light is reflected by a polarizing beam splitter (PBS) and then diffracted by an acousto-optic modulator. The diffraction angle of the first (or minus first) order is compensated by a mirror that directs the beam into a cat's-eye retroreflector. The retroreflector consists of a focusing lens, an iris aperture that blocks adjacent diffraction orders, and a retroreflecting mirror located in the focal plane. After passing through the quarter-wave plate (QWP) twice, the polarization becomes horizontal. On the return path, the diffracted light is transmitted by the PBS and can be coupled into an output fiber or split into multiple output ports. Depending on the use case, this setup can include various AOM types from different manufacturers. Additionally, electromagnetic shutters (48EMS-6) can be implemented. The output laser light is shifted in frequency by twice the applied radio frequency relative to the input light, and the output power can be directly controlled by

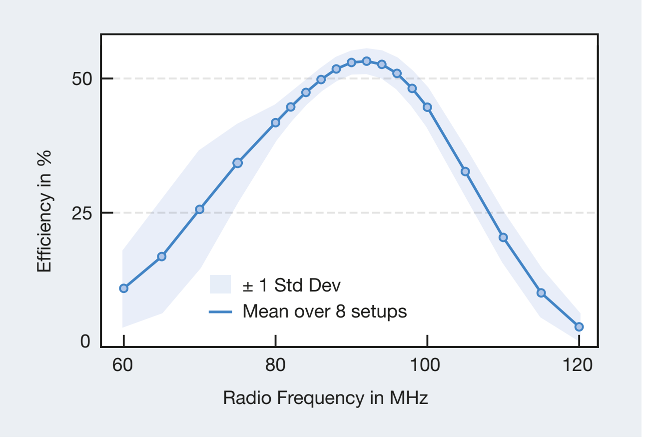

Figure 2

Tuning range of double-pass AOM systems: DP AOM efficiency as a function of the applied radio frequency averaged over eight systems at 561 nm with 90 MHz center frequency.

the RF power. Therefore, double-pass AOM setups constitute a versatile tool for dynamic frequency control and amplitude modulation.

Dynamic detuning of light

The achievable center frequencies, tuning ranges, and diffraction efficiencies depend on the availability and choice of AOMs with the required properties. The optical beam path does not impose additional constraints on these limitations. Typically, various solutions for a single use case can be integrated into the system. When the radio frequency is detuned in a setup optimized for the center frequency, the Bragg condition for optimal diffraction is increasingly violated, reducing the diffraction efficiency.

Fig. 2 shows the system efficiency, averaged over eight DP AOM systems at 561 nm and a center frequency of 90 MHz (G&H AOMO 3080-125) [2], as a function of the applied radio frequency. System efficiency is defined as the ratio of the input power measured after the monitor diode to the output power after the fiber. As with most comparable AOM types, peak efficiency above 50 % is achieved, corresponding to an insertion loss of 3 dB. The FWHM width from 70 MHz to 116 MHz yields a 3 dB tuning range of 140 MHz to 232 MHz for the output light frequency. Using AOM devices designed for broad detuning (e.g., high frequency AOMs in a focused double-pass setup) can further increase the tuning range.

A broadband plug and play tool for light modulation

The ability to support setups with extensive tuning ranges, and thus varying diffraction angles, enables the construction of a unified configuration compatible with multiple wavelengths. The system incorporates broadband optical fibers, chromatically corrected fiber couplers (60SMF) [3, 4], and broadband optics within the double-pass configuration.

The double-pass is aligned for a single wavelength of 561 nm at a center frequency of 80 MHz and the optimal RF power for each wavelength is measured. The system can then be used for wavelengths from 450 nm to 685 nm without realignment by simply adjusting the RF power.

Fig. 3 shows the DP AOM system's efficiency as a function of the applied radio frequency for wavelengths from 457 nm to 685 nm. A peak efficiency of over 40 % is achieved for each wavelength, with the peaks shifting to higher frequencies for shorter wavelengths, as expected from the Bragg condition.

Schäfter + Kirchhoff 's established expertise in broadband fiber optics enables the provision of a multicolor acousto-optic modulator that supports plug and play use without the need for additional adjustment or maintenance.

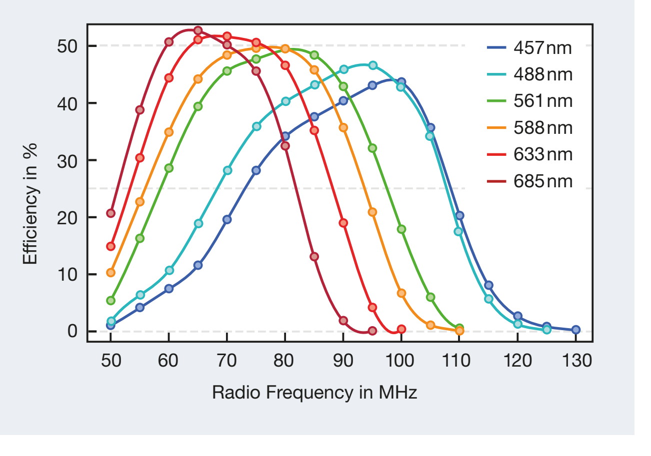

Figure 3

Tuning range of RGB doublepass AOM system (G&H AOMO 3080-125). Efficiency for different wavelengths from 457 nm to 685 nm as a function of the RF power without re-alignment.

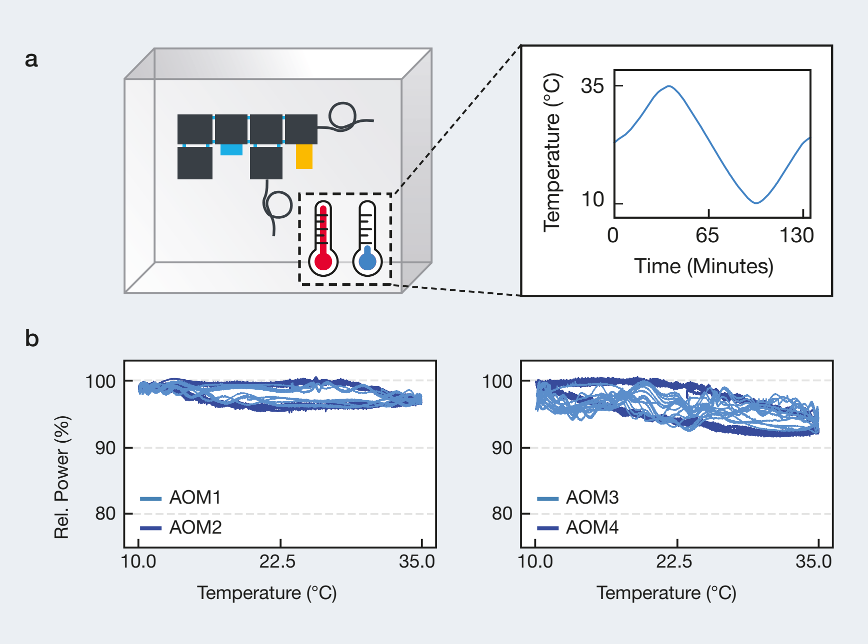

Figure 4

Thermal stability measurements for individual double-pass AOM systems (G&H AOMO 3080-125): Thermal stability measurements for individual double-pass AOM systems (G&H AOMO 3080-125):

(a) The systems are exposed to a series of dynamical temperature cycles between 10 °C – 35 °C inside a climate chamber.

(b) Measured relative output power of the individual systems during seven consecutive thermocycles

Building blocks for quantum technologies

The multicube™ series integrates optical setups into a compact optomechanical framework with exceptional mechanical and thermal stability, meeting the needs of the quantum industry as it transitions from laboratory research to commercial applications. To ensure and verify the thermal stability of multicube™ systems, we repeatedly expose the respective setups to harsh thermal cycles after adjustment. During these cycles, the temperature is varied between 10 and 35 °C over a period of 130 minutes (**Fig. 4a**). This process relieves mechanical stress, eliminating residual drifts that would otherwise compromise long-term fiber-coupling stability.

After this procedure, four individual double-pass AOM systems were characterized in terms of thermal stability by measuring their output power over seven thermal cycles. **Figure 4b** shows the output power as a function of temperature. These double-pass units are optimized for a wavelength of 561 nm and a center radio frequency of 90 MHz. The output power of all four systems forms closed contours, indicating the absence of drift in fiber-coupling efficiency. All setups achieve more than 90 % of the maximum output power measured under thermally stable conditions, with a maximum deviation of ±4.5 %. Thus, the DP AOM systems exhibit the high thermal stability typical of Fiber Port Clusters – above 85 % of maximum output power – since fiber coupling is the most thermally sensitive component.

Following this procedure, the integrated single- and double-pass systems become maintenance free building blocks for light modulation that can be used in non climatized environments. These systems can be equipped with a variety of acousto-optic modulators as well as other multicube™ components such as electromagnetic shutters and monitor diodes. They can also be connected to beam-distribution systems with multiple output ports and to combination units.

Stable light conditioning systems of increasing complexity

Integrated AOM systems can be combined with the well-established Fiber Port Clusters via direct attachment or fiber links. This makes it possible to integrate complex light conditioning systems into the stable multicube™ platform and build highly customized solutions.

Figure 5a illustrates such a cascaded light-conditioning system that distributes light to multiple output ports, enabling individual amplitude modulation and dynamic frequency shifting. The system consists of a Fiber Port Cluster withfour output ports, each connected to a DP AOM via a fiber link. The system was built for a wavelength of 561 nm with a central radio frequency of 90 MHz.

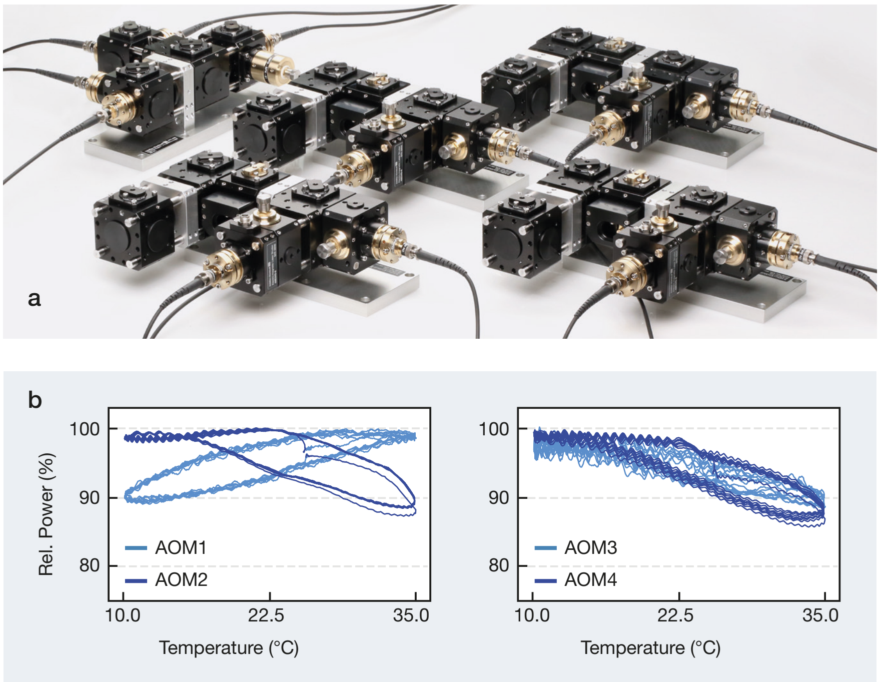

Figure 5

Thermal stability measurements for cascaded multicubeTM systems:

(a) Example photograph of a 1->4 Fiber Port Cluster with double-pass AOMs at each output (G&H AOMO 3080-125),

(b) measured relative output power of the system during thermocycling.

To test the thermal stability of these compound systems, we exposed them to the same thermal cycle as described above. **Figure 5b** shows the output power of each of the four ports as a function of temperature. Although thermal instabilities of successive multicube^{TM} systems could accumulate, the entire system achieves over 85 % thermal stability throughout the cycle, with a maximum deviation of ±7.1 %. This qualifies the system for use in non-climatized environments.

Fast-switching AOM devices with focused beam

A significant parameter for AOM setups is the switching time, which determines the achievable modulation bandwidth. Switching time is proportional to the ratio of beam size to the speed of sound in the AOM crystal. Double-pass AOM devices with collimated beams typically have beam diameters of about one millimeter, resulting

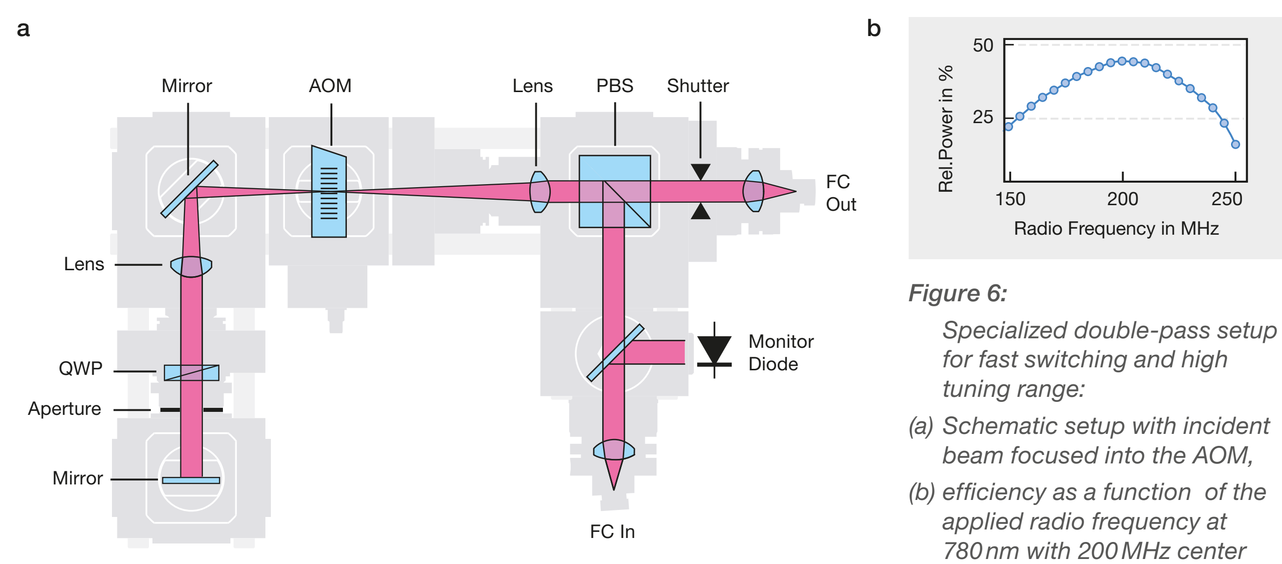

Figure 6:

Specialized double-pass setup for fast switching and high tuning range:

(a) Schematic setup with incident beam focused into the AOM,

(b) efficiency as a function of the applied radio frequency at 780 nm with 200 MHz center frequency (G&H AOMO 3200-124).

in switching times of a few hundred nanoseconds (159 ns per mm for TeO_2). To achieve switching times in the tens of nanoseconds, the light must be focused into an AOM designed for high modulation frequencies.

Figure 6a illustrates a focused AOM setup in which the first lens focuses the beam into the AOM and the second lens re-collimates it. By adjusting the diameter of the incident beam, different waist sizes in the diffraction region can be achieved. These setups are also available in single-pass configurations and for AOM types suited for fast modulation. In addition to modulation bandwidths in the tens of megahertz, AOMs designed for focused operation enable large detuning ranges.

Figure 6b shows the efficiency of a focused double pass system at 780 nm with a center frequency of 200 MHz and a spot size of 70 µm. The integrated system achieves a 3 dB tuning range from 300 MHz to 490 MHz for the output light frequency.

Conclusion

With the integration of AOMs, the multicube™ framework has expanded to the point where complex optical systems for light conditioning can be replaced by robust, scalable building blocks with high thermal stability. The modular system design enables extensive customization to include all necessary functionality. The new setups range from single- and double-pass integrations for various types of modulators to broadband RGB solutions and focused configurations for fast switching and modulation.

Schäfter + Kirchhoff aims to contribute to a robust chain of light transport and conditioning, which is essential for technologies transitioning from the laboratory to non-climatized environments.

References

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