Double-pass acousto-optic modulator system

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A cat's eye retro-reflector, composed of a lens and mirror at its focus, was used to sharply reduce beam deflection when scanning the frequency of a double-pass acousto-optic modulator. The efficacy was determined by measuring coupling efficiency into an optical fiber after retro-reflection. The system has been implemented in a Sisyphus cooling scheme.

I. INTRODUCTION

An acousto-optic modulator (AOM) is an optical element that modulates the frequency of light by an applied signal, usually in the RF range. The modulation is a result of Bragg diffraction caused by the light wave interacting with a sound wave created by the transducer of the AOM. The modulated light is deflected at a small angle due to the diffraction. The angle of deflection is a function of modulation frequency to satisfy the Bragg condition.

This deflection angle in the modulated light causes many alignment difficulties, this is especially true when changing the modulation frequency. Since light must enter the AOM at a small angle, when double passing the AOM (reflecting the modulated light back through the AOM) alignment is critical in maintaining high efficiency. Varying the modulation frequency without a means of correction drastically affects the efficiency of the second pass.

The inspiration for this project came from a need to maintain optical system efficiency as the frequency of a double-passed AOM was varied. This involves maintaining high double pass efficiency in the AOM, and more critically, high fiber coupling efficiency across a 20 MHz range. A method described in Rev. Sci. Instrum. 76, 063112 suggests that using a cat's eye setup can dramatically improve AOM double pass efficiency and fiber coupling efficiency as AOM frequency is modulated.

II. CAT'S EYE RETRO-REFLECTOR

A cat's eye retro-reflector, shown in figure 1, consists of a lens with a mirror at its focus. When properly aligned, collimated light entering the lens will be focused to the mirror. This focused beam will be reflected back to the lens and leave parallel. The parallel ray of light will trace the same path upon reflection only if the focused ray strikes the mirror perpendicularly, in all other cases the reflected light will acquire some small displacement from the original path. If the mirror is not at the focus of the lens, parallel rays of light will be reflected and acquire some angular change.

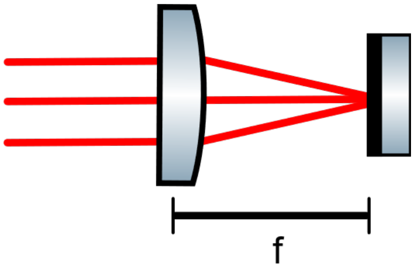

Figure 1. *A cat's eye retro-reflector. Light entering the lens parallel gets focused to the mirror and then reflected back out parallel.*

In terms of maintaining consistent efficiencies, the angle needs to be preserved on the double pass to meet the Bragg condition on the second pass. Additionally, if the angle is off on the retro-reflected beam, coupling efficiency will suffer greatly. Since the modulation frequency of the AOM is variable, there is no way to always have the modulated light enter the cat's eye parallel. To fix this issue an alternative approach to the cat's eye is taken.

By placing the AOM at the focus of the lens, any light that enters the lens from the AOM will exit the lens parallel to the unmodulated beam (see figure 2). This modulated light will then be retro-reflected and focused back into the AOM at the angle it left. In this setup the position of the mirror becomes somewhat arbitrary and the orientation is fixed to be normal to all beams.

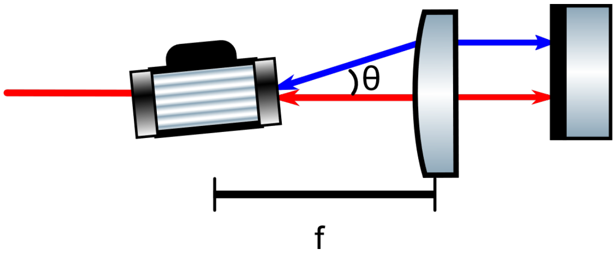

Figure 2. *Light leaving the AOM comes from the focus of the lens and leaves the lens parallel to the original beam. The reflected beams are refocused to the center of the AOM.*

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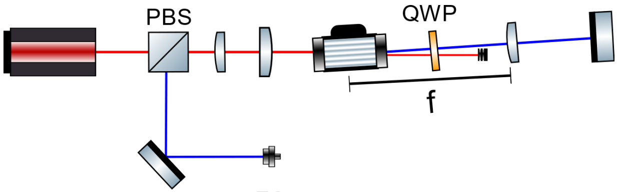

Figure 3. *Schematic drawing of the setup. PBS = polarizing beam splitter, FC = fiber coupler. A beam block is placed before the cat's eye lens to block the unmodulated light.*

III. SETUP

Two setups were built: one as a prototype to measure the efficacy of the cat's eye, and the other to be used in an experiment as part of a Sisyphus cooling scheme in the lab of Eden Figueroa after testing. Many properties were explored when designing the first setup to maximize both AOM efficiency and coupling efficiency for both static and scanned modulation frequency. A diagram of the prototype is shown in figure 3.

A. Prototype

The prototype went through several iterations before any real results were achieved; each iteration attempted to improve on a single aspect of the system and many AOM qualities were investigated. Through trail and error it was determined that beam waist, beam quality, modulation signal power, and precise lens control were the strongest factors in determining system efficiency.

According to Rev. Sci. Instrum. 76, 063112, the amount of light that gets modulated (diffraction efficiency) is strongly determined by the matching of the waist to the effective aperture of the AOM. This is somewhat intuitive because a larger waist gives a greater interaction area with the sound wave, but too large of a waist causes interaction with inhomogeneous parts of the sound wave (edge effects) or even clipping in the crystal. To more appropriately match the effective aperture, a telescope was installed before the AOM. This improved our diffraction efficiency by a factor of 1.3.

The original laser used in our prototype setup was found to be producing mixed modes and not the desired TEM_{00} mode. Multi-mode beams suffer great losses when coupled into single mode fibers, so it was sensible to switch to a cleaner mode producing laser. To investigate whether or not this was affecting the diffraction efficiency as well, the original laser's efficiency was compared to the new laser and found to have markedly worse diffraction efficiency (55% compared to 72%). This may have been conflated with the fact that the waists of the lasers were different; the second laser no longer required a telescope and may have matched the aperture better than the original setup. Regardless, for our purposes of coupling into a single mode fiber, total system efficiency is maximized with a TEM_{00} laser output.

The rf amplifier driving the AOM for our system had a highly variable gain curve (figure 4) over the frequency range we were interested in. This meant that the RF power supplied to the AOM varied strongly as a function of modulation frequency. Diffraction efficiency has a nonlinear relationship to input power, and since diffraction efficiency is a function of modulation frequency, this presented a large problem for maintaining constant efficiency in the system. This problem could be fixed with constant gain amplifiers. The advent of this issue made us move to studying primarily the geometric effectiveness of the cat's eye by measuring fiber coupling efficiency instead of total efficiency. The justification for this change in metric of efficacy came from the only constant between our two setups being the cat's eye. The true setup had a different RF power supply and amplifier to give more constant power, and a different AOM with a different diffraction efficiency/frequency relationship.

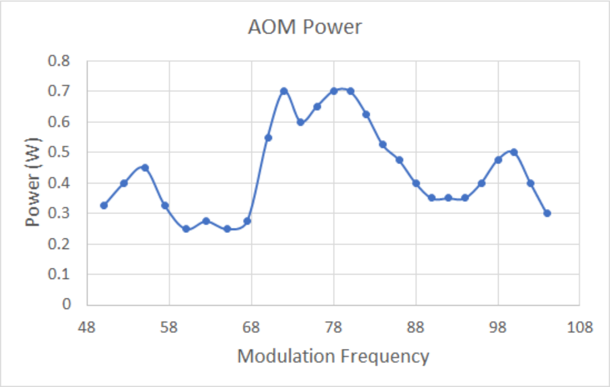

Figure 4. *A plot of power supplied to the AOM vs. modulation frequency for the first setup.*

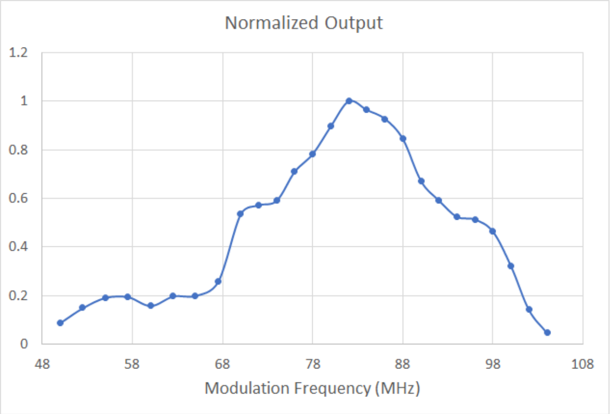

Figure 5. *A plot of output power vs. modulation frequency for the first setup. Output power is a convolution of coupling efficiency and AOM power.*

In using coupling efficiency as our metric of efficacy the most crucial quality found was the position of the lens relative to the AOM. Beam quality and waist both affect coupling efficiency in terms of mode matching so these factors were both maximized before taking any measurements of coupling efficiency due to lens position. Finding the correct lens position was the final step in getting significant results from the cat's eye. The critical position of the lens was found to be such that its focus lies in the center of the AOM crystal. This position was found by moving the lens fractions of millimeters about the nominal focal point and sweeping the modulation frequency until the widest coupling efficiency peak was found. Before the cat's eye was put in and aligned, the coupling efficiency would drop to 0 within the smallest interval we could tune modulation frequency. Considering the size of our peak as the full width at half max, we have a peak width change from less than .1Mhz to over the 54MHz range that was scanned.

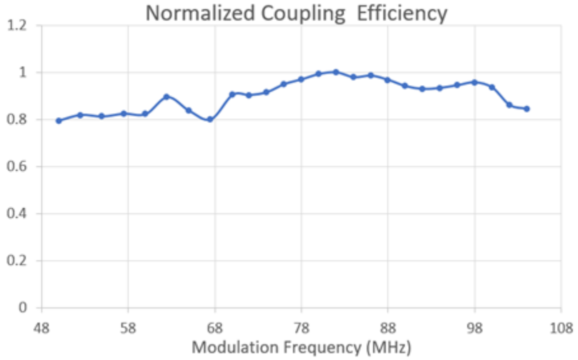

Figure 6. *The final coupling efficiency results of the first setup. From 70-90MHz coupling efficiency never drops below 90% of the original.*

B. Implementation

After the success of the prototype, a more compact version was placed within a laser cooling setup. The 100mm lens of the prototype was swapped for a 75mm focal length lens to make the setup as short as possible while still maintaining ease of alignment. The change in lens did not have any noticeable effect on performance and the cat's eye performed similarly to the prototype. Initially there was an asymmetry in the coupling efficiency curve much like in the prototype. This was attributed to alignment issues, however it was discovered that in aligning the unmodulated light to the center of the cat's eye lens, translating the lens causes the motion in other dimensions for the modulated light. This would cause the modulated light to be closest to the center of the lens at the lowest frequency and likely an asymmetry in coupling efficiency. To fix this issue, the modulated light was aligned to pass through the center of the lens at the center frequency. This allows for the light to be symmetrically away from the center of the lens at the frequency extremes. This resulted in a much flatter coupling efficiency curve than the prototype.

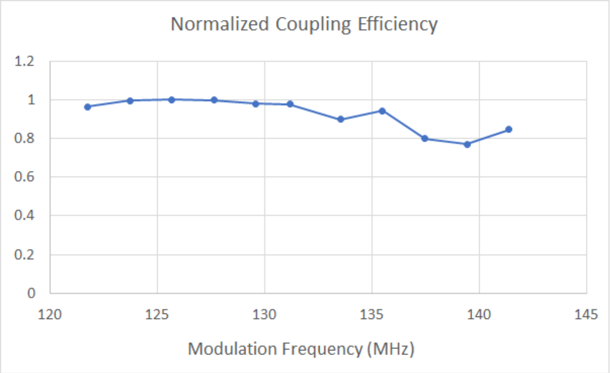

Figure 7. *A plot of coupling efficiency using the new alignment technique. The asymmetry implies a misalignment but efficiency is very constant for lower frequencies.*

Since there is nearly 100% of the original coupling efficiency in the low frequency range, this new alignment method is clearly much better. The center of this curve could be increased such that the high efficiency covers the center of the range better by aligning the system better. Due to time constraints in the lab, this curve was deemed sufficiently good and no more formal measurements could be taken.

IV. FUTURE WORK

The original goal of the project was to be able to maintain a constant output with a goal of ±10%. Due to the efficiency curve of the AOM, this goal was not met. The next step for this project is to create a feed-forward system that varies the power supplied to the AOM to give a more constant fiber output across our frequency range.

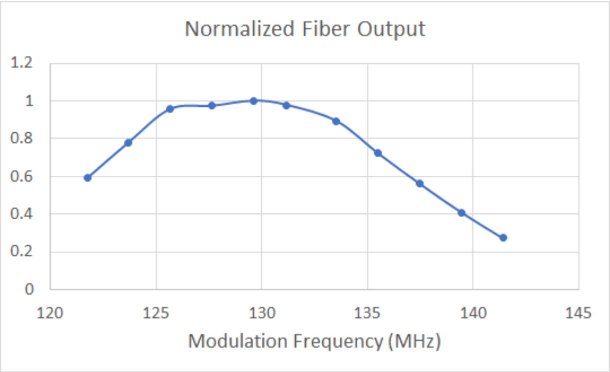

Figure 8. *The output of the fiber is not constant within the ±10% goal.*

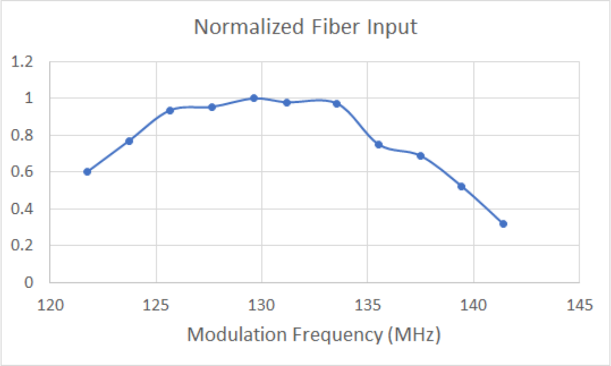

Figure 9. *The input of the fiber is not constant within* 10%*, causing output to vary more than* 10%*.*

ACKNOWLEDGMENTS

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