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Closely spaced mirror pair for reshaping and homogenizing pump beams in laser amplifiers

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ABSTRACT

Channeling a laser beam by multiple reflections between two closely-spaced, parallel or nearly parallel mirrors, serves to reshape and homogenize the beam at the output gap between the mirrors. Application of this device to improve the spatial overlap of a copper laser pump beam with the signal beam in a dye laser amplifier is described.

1. INTRODUCTION

Applications of laser beams may require reformatting the beam shape and smoothing its intensity profile. This is true for laser pumped dye laser amplifiers where the pump beam shape and size must match that of the dye signal beam for efficient amplification with good fidelity and low amplified spontaneous emission (ASE). This is typically done in transversely pumped amplifiers by focusing the pump beam to a line focus at the dye cell using a cylindrical lens. However, the "soft" edges of the focused beam may mean that a significant fraction of the pump light is poorly converted to amplified signal or generates ASE, or that the pump intensity at the focus is too strongly peaked to produce the desired intensity uniformity in the amplified signal beam.

The transversely pumped dye amplifiers used in the copper-laser-pumped, master-oscillator power-ampifier (MOPA) chains of the atomic vapor laser isotope separation (AVLIS) program at Lawrence Livermore National Laboratory (LLNL)[1,2] are designed to produce an output beam of nearly uniform intensity in a well defined, rectangular beam profile with high optical conversion efficiency. This is accomplished by using special optical techniques on both the signal and pump beams. The relationship between the pump beams, the dye signal beam, and the flowing dye solution for one of these amplifiers is

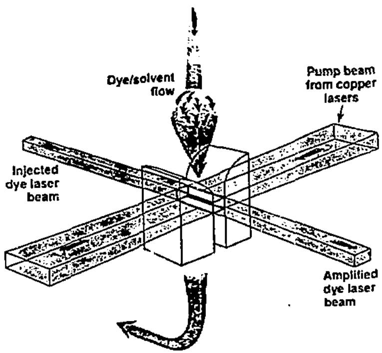


Fig. 1. A schematic representation of a transversely pumped dye amplifier showing the orthogonal relationship of the pump laser beam(s), the dye laser beam, and the dye solution flow. Note the rectangular shape of the dye beam and interaction volume characteristic of the amplifiers in the AVLIS dye MOPA chains at LLNL.

illustrated schematically in Fig. 1. The rectangular shape of the signal beam is achieved by passing the signal beam injected into the chain through a rectangular aperture which forms the entrance pupil for the chain. The image of this pupil is relayed by a series of telescopes to each amplifier in the chain. These telescopes also magnify or demagnify the image so that it maximally fills the flow channel of each amplifier without generating significant diffraction fringes from interactions with the channel walls. This approach minimizes wasted pump light and ASE next to the channel walls.

Efficient utilization of the copper laser pump light with low ASE also requires that the shape and size of the pump beam be well matched to that of the dye beam in the generally rectangular overlap volume of the two beams in the dye cell. The dimension parallel to the flow direction is somewhat more critical than that in the signal beam direction. In addition, intensity uniformity of the amplified beam in the flow direction requires smoothing of both static and radially time dependent spatial intensity variations of the copper laser beams in the overlap volume. (Note that uniformity of the amplified beam in the direction of pump beam propagation is influenced primarily by the spatial dependence of pump beam absorption in the dye solution.) We have built and demonstrated a device using two, closely-spaced, parallel or nearly parallel mirrors, which achieves these requirements in our high average power, copper-laser-pumped dye MOPA chains.[3]

2. DESCRIPTION AND PRINCIPLES OF OPERATION

A schematic diagram of the mirror-pair apparatus used to reformat and homogenize the copper laser pump beams at the dye laser amplifiers is shown in Fig. 2. We assume that the symmetry axes of the beam and the mirror pair are colinear. The reflecting surfaces of the pair are those closest to each other and have highly reflective dielectric coatings designed for high incidence angle S- and P-polarizations at either the yellow or green copper laser wavelengths (these are dichroically separated upstream in the LLNL-AVLIS laser system). An optical device such as a multi-element, anamorphic telescope, or something as simple as a single cylindrical lens or mirror, focuses the incoming circular and collimated copper laser beam to a line focus at the input gap of the mirror pair. While the central segment of the beam passes between the mirror pair without reflection, outer segments will reflect one or more times as the beam expands beyond the line focus. Each segment, or order, exits the mirror pair at a deviation angle which increases with the number of reflections.

The various orders of copper light exiting the pair are incident on an optical device which forms an image of the output gap of the mirror pair in the dye amplifier cell. This device could be as simple as a single spherical lens or mirror. The resulting image has a generally rectangular shape defined by the edges of the output gap of the mirror pair along the long dimensions, and by the profile of the incoming, collimated copper beam along the short dimensions. The space between the mirrors at the output is adjusted to achieve a precise match of the image to the short dimension of the dye beam (see Fig. 1), which was noted above to be the most critical dimension for overlap. The long dimension of the image is the same as the

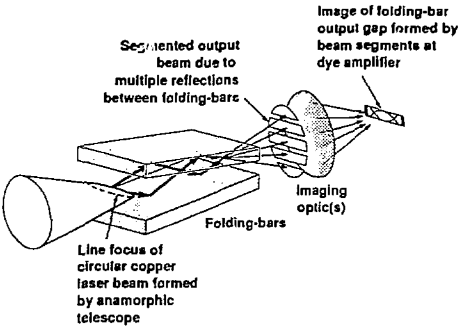


Fig. 2. A schematic representation of the mirror-pair, or folding-bar apparatus used to homogenize and reformat a circular copper laser pump beam into a generally rectangular shape at a dye amplfier for efficient overlap with the dye laser beam.

diameter of the incoming copper beam and is set by upstream optics to be slightly shorter than the length of the dye beam in the amplifier cell to avoid clipping at the interfaces where the dye beam enters and leaves the flow region. Intensity homogeneity along the short dimension (or flow direction) results from mixing the various orders forming the image which originate from different regions of the incident copper laser beam profile.

The effect of the reflections between the mirror pair is the same as if the copper laser beam were sequentially folded like a piece of paper to fit into the output gap. This folded beam is what is imaged at the amplifier cell. Because of this folding effect and the bar-like appearance of the mirrors, we have designated the mirror pair as folding bars and will refer to them as such for the remainder of this report.

The number of orders generated, N, the divergence half-angle of the focused copper input beam, α, the folding-bar wedge half-angle, β, the divergence half-angle of the exiting orders, γ, the folding-bar output gap, h, and the projected height of the copper beam in the plane of the output gap, H, as illustrated in Fig. 3 are related by

$$N = \begin{cases} \mathrm{Int}(H/h) + 1, & \mathrm{Int}(H/h) \text{ even}, \\ \mathrm{Int}(H/h) + 2, & \mathrm{Int}(H/h) \text{ odd}, \end{cases} \tag{1}$$

$$\gamma = \alpha + \beta(N - 1), \tag{2}$$

for the case where the symmetry axes of the incident beam and the folding bars are colinear. Note that N is always odd for this case. Homogenization of the imaged folding-bar output improves as the number of orders increases, but this may also result in greater divergence of the output orders according to Eq. (2).

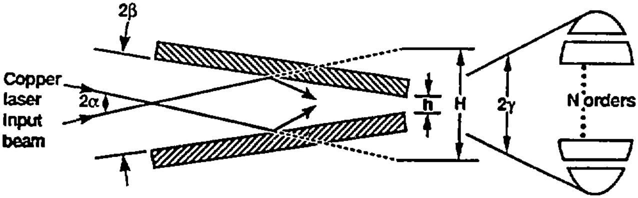


Fig. 3. A general schematic diagram of folding bars showing the divergence half-angle of the focused copper input beam, α, the folding-bar wedge half-angle, β, the projected height of the copper beam in the plane of the output gap, H, the folding-bar output gap, h, the number of orders in the output, N, and the divergence half-angle of the output, γ.

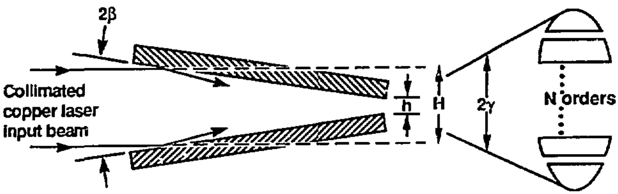


Fig. 4. A schematic diagram of folding bars similar to Fig. 3 but with a collimated copper laser input beam ($\alpha = 0$).

When the folding bars are parallel ($\beta = 0$), the various ouput orders do not separate as they propagate. When the folding-bar wedge narrows toward the output gap ($\beta > 0$), the orders will separate as they propagate. Conversely, when the wedgeopens toward the output gap ($\beta < 0$), the orders will first converge and eventually separate as they propagate. With the non-diffraction limited copper laser beams that we use, the input gap of the folding bars was opened the minimum amount required to accept all the copper light at its line focus. This resulted in a wedge which narrowed toward the output.

The folding bars can also be operated in a mode where the input beam is not focused but collimated as shown in Fig. 4. The input gap must then be opened to a size large enough to accept all the light from the collimated input beam. Eqs. (1) and (2) still apply but with $\alpha = 0$.

The photograph of Fig. 5 shows the generation of multiple output orders by folding bars for a slightly expanded and nearly collimated HeNe laser input beam.

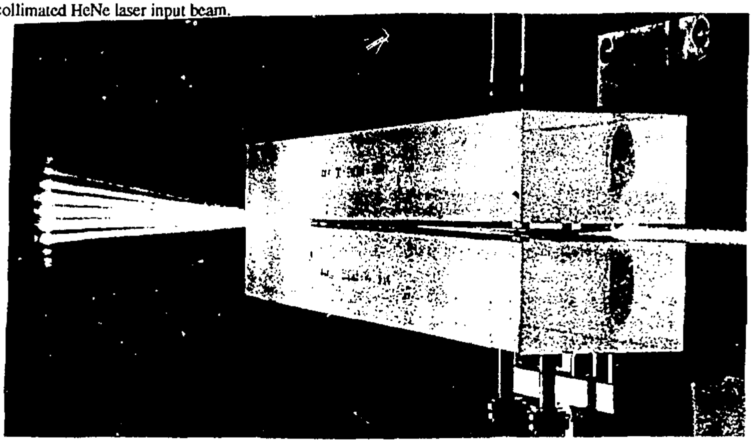


Fig. 5. Photograph showing the formation of multiple output orders by non-parallel folding bars with an expanded, nearly collimated HeNe laser input beam from the right.

A number of factors influence the choice of length and gap sizes for folding bars. These include the number of orders desired, the final image size, the magnification and numerical aperture of the image forming optics, the high angle reflectivity characteristics of the folding bar coatings, heat loading from coating and substrate absorption, the size, divergence, and beam quality of the input beam, and any mechanical or space constraints. To arrive at a final design we typically had to impose some non-critical constraints such as unity magnification of the imaging system, or parallel folding bars, or a particular folding bar length based on available substrate material.

3. FOLDING BAR PERFORMANCE

Folding bars were deployed on 13 dye amplifiers in the AVLIS dye MOPA chains at LLNL. A photograph of folding bars in operation for one of the power amplifiers at low power levels is shown in Fig. 6. Since each amplifier is pumped symmetrically from opposite sides as shown in Fig. 1, a total of 26 folding-bar mirror pairs was used. Pump powers ranged from <100 W delivered to the folding bars of the high gain preamplfiers to ~2.5 kW delivered to those of the largest power amplifier. The input beams contained roughly equal contributions from up to 12 copper laser MOPA chains which had been combined by optical and angular multiplexing based on pupil-relay techniques.[1] The folding-bar lengths varied from a few centimeters for the lower power amplfiers to ~30 cm for higher power amplifiers.

We chose unity magnification for all the imaging optics. A single concave mirror sufficed for the power amplifiers. A symmetric triplet lens was necessary for the lower power amplifiers to correct for spherical aberration. Folding-bar output gaps (the same as image heights for unity magnification) ranged from ~0.5 mm for the low power amplifiers to >2 mm for the power amplifiers.

Fig. 6. Photograph showing the two folding-bar pairs used to reformat copper laser light pumping a dye power amplifier from above and below. The amplifier is the object with the conical shape and four-way dye flow piping in the center of the photo. The laser interaction volume inside the amplifier cannot be seen. The 5 output orders of copper light generated by the lower folding bars can be seen on the upward facing mirror at the bottom of the photo. This mirror is concave and forms the image of the folding-bar output gap in the amplifier.

The input gaps for the power amplifiers were opened to values several times that of the output gaps in order to accept the focused input copper laser beams which ranged from ~20 to >40 times diffraction limit. It was possible to use a parallel folding-bar configuration for the lower power amplifiers because of faster focusing optics used there. Three-element, reflective, anamorphic telescopes were used to focus the beams into the folding bars of the power amplifiers while single, cylindrical focusing lenses were used for the lower power amplifiers. The three-element telescopes, although not essential to the use of folding bars, were convenient to use because they were already present in the system prior to the introduction of the folding bars. They allowed placement of the pupil at the folding-bar output while controlling its size to produce the desired number of orders.

The folding-bar systems were originally designed to generate 5 output orders. In some instances additional factors dictated deviations from the original design resulting in up to ~9 orders with no noticeable degradation of amplifier performance.

Folding-bar transmissions were measured both at low and high power levels. The high power measurements could not be made directly at the folding-bar input and output and involved other optics in the system. Nevertheless, most measurements were above 95% with some indicating transmissions in excess of 98%. The primary cause of reduced transmission appeared to be loss of light at the input due to highly non-diffraction-limited beams, or poor overlap of the multiplexed laser beams. Coating reflectivity by comparison appeared to be a small contributor to transmission loss.

Alignment of the copper laser beams through the folding bars is maintained by observing the beam profile of the folding-bar output on the imaging optics. A video monitor is used to view these optics remotely during actual system operation at high powers. Two remotely controlled, motorized, upstream mirrors permit control of beam pointing and centering through the folding bars. Alignment along the symmetry axis of the folding bars is indicated by a profile where the orders are symmetric and evenly spaced as shown by the video photos in Fig. 7.

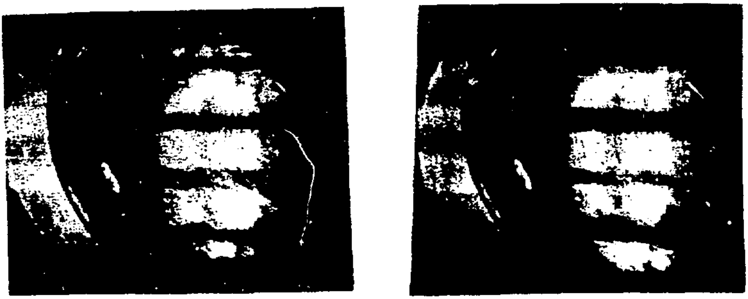
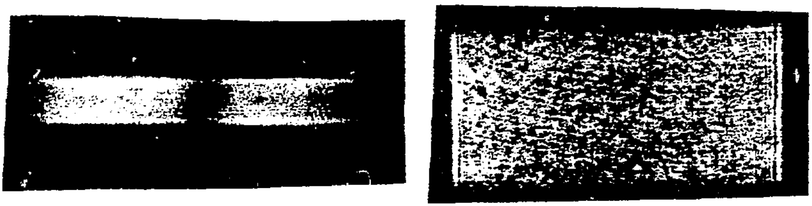


Fig. 7. Video photographs showing the output orders from folding bars as monitored on an imaging mirror to a dye amplifier. The more symmetric and evenly spaced pattern on the left indicates that the input copper laser beam is aligned along the symmetry axis of the folding bars, while the unevenly spaced pattern on the right indicates misalignment.

The nearly rectangular profile o. the imaged folding-bar output gap in a dye amplifier is shown in Fig. 8a. It is generated by a video monitor viewing fluorescence light from the pumped volume through one of the pump windows. The nearly flat intensity profile along the dye flow direction (short axis of rectangle) results from the homogenizing effects of the folding bars. This diagnostic is useful for maintaining overlap of the pump beams from opposite sides of the amplifiers with each other and the dye laser beam.



(a) (b)

Fig. 8. (a) Video photograph from fluorescence light showing the nearly rectangular image of the folding-bar output gap in a dye amplfier. Intensity uniformity along the dye flow direction, or short axis of the rectangle, results from the homogenizing effects of the folding bars. The darker region at the center of the profile is an artifact of the copper laser beam intensity profile. (b) Video photograph of the near field output beam profile of a dye MOPA chain showing the edges along the pump beam direction (long axis) defined by the images of the folding-bar output gaps in the amplifiers. The edges along the short axis are defined by the flow channel walls created by the pump windows.

Typical efficiencies for the AVLIS dye MOPA chains equipped with folding bars are >50%,[1] and efficiencies of some amplifiers are >60%. The fraction of ASE in the output is a few percent. This indicates the effectiveness of the folding bars in achieving high pump light utilization with low ASE through precise spatial overlap. The rectangular, near-field output beams from the chains as shown in Fig. 8b have edges along the pump beam direction defined by the images of the folding-bar output gaps in the amplifiers. Stable operation of the chains for periods >100 hours and output powers >1500 W is regularly achieved. Alignment corrections of the beams through the folding bars are made periodically during high power operation.

4. INTERFERENCE EFFECTS

Interference occurs between the orders of the folding-bar output where they overlap in the vicinity of the output gap. This results in interference fringes in the image of the output gap in the dye amplifiers. These fringes, which are parallel to the folding-bar gap edges, are shown in the video photo of Fig. 9 taken at the image formed by light from a single copper laser leaked through one of the turning mirrors following the image forming optics of a power amplifier.

Fig. 9. A portion of the image of a folding-bar output gap showing interference fringes formed by the central 3 orders in the output of the folding bars. The photo was made with copper laser light leaked through a turning mirror following the image forming mirror of a power amplifier.

The interference can be regarded as being generated by a series of N-1 coherent, virtual line sources formed by the folding-bar reflections together with the real line focus. These sources lie near the input plane of the folding bars. In general the interference fringes tended to wash out when multiple copper lasers or numerous orders are present. Observations with a single single copper laser and a limited number of orders (see Fig. 9) show that fringe contrast is highest at the edges of the of the folding-bar gap. This is expected since these are produced by adjacent regions of the beam where it is folded by a single refelection. The reduction of fringe contrast evident in Fig. 9 away from the edges is attributed to loss of coherence between separated parts of the copper beam profile. A complete analysis of the formation of interference fringes by folding bars has shown that there are periodic locations of the input line focus where high fringe contrast occurs with all orders present.[4]

Generally, the effects of the interference fringes produced by the folding bars has not been evident in the output beam profiles of the dye MOPA chains. There are probably many factors contributing to this such as averaging from multiple copper lasers and dye amplifiers, imprecise alignment of the fringe pattern with the dye beam, and the presence of multiple orders. However, we were able on one occasion to generate observable effects from the interference fringes in a single dye amplifier for a particular alignment of the copper lasers into the folding bars. We were unable to reproduce the effect and attributed the observation to a condition where the input line focus happened to be located for high contrast, sharp fringes from all the orders present simultaneously as discussed above. There may be other potential effects of the interference fringes on the dye MOPA chains besides intensity structure on the output beams, but they do not appear to be significant since chain performance has been equivalent or superior to that achieved with more conventional optical formatting techniques for the pump beams.

5. SUMMARY

We have designed, characterized, and deployed an optical system consisting of a closely spaced mirror pair, designated folding bars, and associated input and output optics for reformatting a pump laser beam to precisely overlap it with the dye signal beam in a transversely pumped dye amplifier. Multiple reflections of the pump beam between the folding bars homogenizes the beam in their output gap and generates several beams, or orders, in their output corresponding to different segments of the input beam. Imaging the output gap in the dye amplifier produces the nearly rectangular profile needed for precise overlap with the dye beam. Performance of the AVLIS dye MOPA chains at LLNL has demonstrated the effectiveness of folding bars in highly efficient utilization of pump light in dye amplifiers. Interference fringes between the output orders of the folding bars did not produce observable effects on the output beams of the dye chains. The folding-bar technique could find uses in other illumination applications where reshaping and homogenizing laser or non-laser light beams is required. Folding-bar type devices could also conceivably be used as interferometers to measure laser beam wavefront or coherence properties.

6. ACKNOWLEDGEMENTS

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