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ABSTRACT

We describe specifications, design, and operation of an optical system that couples a high-power copper vapor laser beam into a large core, multimode fiber. The approach used and observations reported are applicable to fiber optic delivery applications.

1. INTRODUCTION

Fiber optic beam delivery systems are replacing conventional mirror delivery systems for many reasons (e.g., system flexibility and redundancy, stability, and ease of alignment). Commercial products are available that use fiber optic delivery for laser surgery[1] and materials processing.[2,3] Also, pump light for dye lasers can be delivered by optical fibers.[4,5,6] Many laser wavelengths have been transported via optical fibers; high power delivery has been reported for argon, Nd:YAG, and excimer. We have been developing fiber optic beam delivery systems for copper vapor laser light; many of the fundamental properties of these systems are applicable to other high power delivery applications.

A key element of fiber optic beam delivery systems is the coupling of laser light into the optical fiber. For our application this optical coupler must be robust to a range of operating parameters and laser characteristics. We have access to a high power copper vapor laser beam that is generated by a master oscillator/power amplifier (MOPA) chain comprised of three amplifiers. The light has a pulse width of 40–50 nsec with a repetition rate of about 4 kHz. The average power (nominal) to be injected into a fiber is 200 W. (We will refer to average power in this paper.) In practice, the laser beam's direction and collimation change with time. These characteristics plus other mechanical and operational constraints make it difficult for our coupler to be opto-mechanically referenced to the laser beam.

The optical design must consider this limitation in addition to requirements for transporting high power with high reliability and without damage to the optical components or the fiber. The nature of the laser beam illumination pattern on the fiber input face is one of the important factors to control.

We describe the optical design for a coupler that injects high-power copper vapor laser light into an optical fiber. The optical fiber is a commercially available, large core (1 mm diameter), all-silica, multimode fiber. We examine features of the design and performance under various laser beam characteristics: sensitivity to misalignment and beam steering, ghost reflections within the coupler, and changes in beam collimation. We also describe design trade-offs between power density on the optical components and overall length of the system.

2. OPTICAL SPECIFICATIONS AND DESIGN

The general optical configuration is shown in Fig. 1. A collimated laser beam illuminates a physical aperture that is placed at the front focal plane of a parabolic mirror (an off-axis section is used). The converging cone of light reflected from the mirror is the input beam to the fiber optic coupler. The function of the coupler is to image the physical aperture onto a large (1 mm diameter), multimode optical fiber. The general optical specifications for the system are listed in Table 1.

We require the optical system to image a physical aperture onto the fiber for several reasons. Chief among these is survivability and protection of the optical fiber from damage. The laser beam direction or pointing may change by up to 1 mrad. To ensure that the fiber face is not damaged, we do not want the irradiance pattern on the silica core of the fiber to move because light would be launched into the silicate cladding. Cladding light will be absorbed in the silicone resin and buffer coating. At high power, this almost always causes damage. In the optical system depicted in Fig. 1, changes in laser beam pointing will cause clipping of the beam at the aperture, which can be water-cooled. The pattern on the fiber does not move, however, only the power transported by the fiber is reduced.

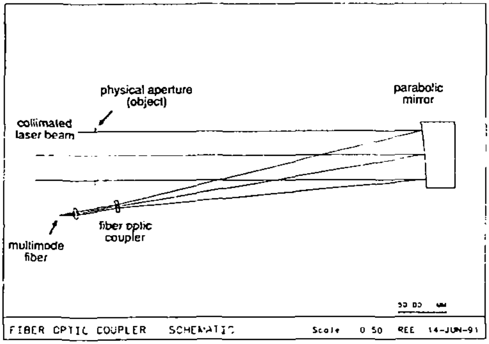

Fig. 1. Schematic diagram of optical configuration.

An additional advantage to such an optical schematic is that the irradiance distribution in the aperture is mapped to the fiber face. The laser beam irradiance profile across the aperture is roughly of uniform; hence, the pattern on the fiber is uniform.

It is standard practice in some applications to focus the laser beam with a lens and place the fiber near the focus. If that approach were used here, the irradiance pattern on the fiber would not be uniform, but would be a diffraction pattern with high and low irradiance points. In addition, such an arrangement would be sensitive to changes in laser beam pointing.

There are other constraints on the optical design. The aperture and parabolic mirror configuration is determined by characteristics of the overall laser system. The fiber coupler must be at least 275 mm away from the parabolic mirror. It is desirable that the coupler be as compact as possible. The trade-off for shortening the overall length of the coupler is to accept higher power density on the components of the coupler. This is described in more detail later. We established a design requirement that the nominal power density on any component within the coupler should be ≤ 1–2 kW/cm^2.

The optical fiber used is a commercially available, all-silica, multimode fiber. We use a 1 mm diameter fiber (NA = 0.18) and illuminate it with an irradiance pattern 0.9 mm in diameter. Undersizing the image on the fiber gives a reasonable tolerance on initial alignment of the components and the fiber. For the case considered here, the fiber must carry 200 W average power; based on our experience, this is a comfortable power level for a 1 mm fiber.

Table 1
General Optical Specifications

Parameter	Specification
Object size	51.3 mm
Object location	at front focal plane of a parabolic reflector with efl = 350 mm
Image size	0.9 mm
Image distortion	< 15%
Wavelength	578.2 nm
Numerical aperture (object space)	275 µrad (20 times diffraction limited)
Entrance pupil	telecentric (collimated laser beam)
Numerical aperture (NA)	< 0.18

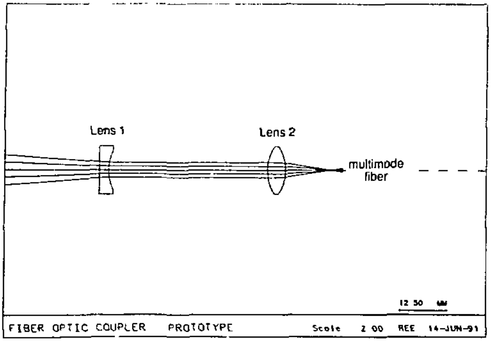

Fig. 2. Optical layout of prototype coupler.

The optical layout of a prototype coupler is shown in Fig. 2. The overall length of the coupler (lens 1 to fiber) is 2-1/2". The coupler comprises two lenses of focal length –25 and 12.5 mm (both are 1/2" in diameter); the substrates used are fused silica. The image distortion for a well-centered laser beam is 19%. The nominal power density incident on the two lenses is 1.5 kW/cm^2.

By placing the aperture at the front focal plane of the parabolic mirror, the object, as seen by the coupler, is at infinity. Therefore, the image is located at the back focal plane of the coupler optical system. Changing the lens 1 to lens 2 spacing changes the effective focal length of the combination and hence the image size. Changing the mirror to lens 1 spacing (holding other spacings fixed) changes only the NA. This is a useful feature during alignment because the correct image size and NA can be obtained independently.

3. GHOST REFLECTIONS AND OPTICAL DAMAGE

When we tested the coupler at high power (50–100 W), the second lens damaged catastrophically. Subsequent analysis of the optical design suggested strongly that a ghost reflection from side 2 of lens 2 was nearly focusing on side 1 of lens 2. A poor quality anti-reflection coating (reflectivity ≈ 2–3%) contributed to the problem. This ghost reflection power density at the surface may have exceeded 50–100 kW/cm^2. The damage was characterized by a small crater (≈ 2 mm diameter) on side 1 plus a small hole (≈ 0.4 mm diameter) drilled through the substrate.

We modified the optical design to greatly reduce this ghost reflection problem. The distortion was also reduced to 14%. The shape of lens 2 was changed to be nearly best-form for infinite conjugates. The first order properties and mechanical dimensions are basically the same, but the ghost reflection from side 2 is under control. In Fig. 3 we show a close-up view of the ghost reflections within lens 2. The primary ghost reflection from side 2 comes to focus well outside the substrate. There is a secondary ghost reflection from surface 1 that comes to a focus inside the substrate. We feel that the power in this secondary reflection is low enough to not be a problem. For an uncoated surface 2 (reflectivity ≈ 4%), the ghost reflection power density on surface 1 is < 800 W/cm^2.

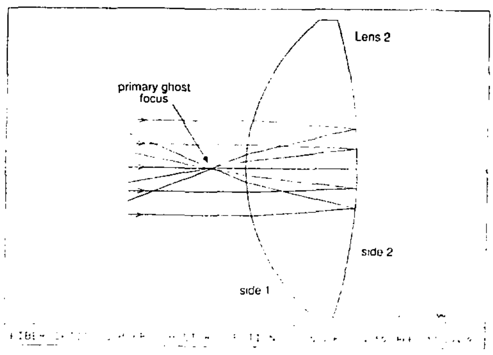

Fig. 3. Ray trace of ghost reflection from side 2 of lens 2. Light is incident from the left onto the reshaped lens.

4. LASER BEAM FOCUSING EFFECTS

When we tested the modified lens (uncoated) at high power (50–100 W), again, it damaged catastrophically. The cause was eventually traced to the procedure used to align and adjust the fiber coupler. The optical damage indicated the importance of understanding the character of the laser beam (described below).

We show the fiber coupler test configuration schematically in Fig. 4. The copper vapor laser chain is separated from the test area by an 18 meter air path (conventional beam delivery). In the test area, the laser beam impinges on the physical aperture and parabolic mirror and enters the fiber coupler.

Initial alignment of the fiber coupler was performed off-line with a low power HeNe laser beam. The lens spacing was adjusted to produce the correct image size and the relative position of lens 1 with respect to the parabolic mirror was adjusted to produce the desired NA. (Note, this corresponds to the case where light is collimated between lens 1 and lens 2; hence the laser beam spots are the same on both lenses.) The assembly was then transported to high power test area.

To safely align the fiber coupler coaxial to the laser beam (i.e., to center the beam on the lenses), the high power copper vapor laser beam was attenuated. We did this in two ways. A Hartmann mask (solid plate with 5 small holes) was inserted in the beam near the output of the chain. The achieved attenuation is equal to the ratio of the area of the small holes in the mask to the entire beam diameter. Additionally, the copper vapor laser chain was mistimed. This reduced the end-of-chain power because the pulses in successive amplifiers do not overlap completely. At some point, the mistiming is great enough that the copper vapor laser chain no longer acts like a laser. The light is primarily ASE generated at a point roughly 18 meters from the test area.

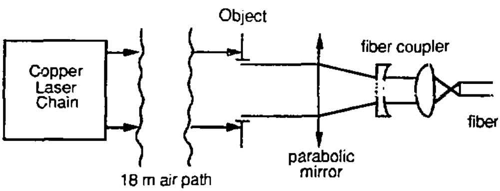

Fig. 4. Schematic diagram of high power test configuration.

Therefore, in this 'low power' state, the beam entering the test area was not collimated; it appeared to be diverging from a point 18 meters away. Diverging light incident on the aperture will illuminate the fiber at a higher NA than for collimated light incident. For the case of 18 m of divergence, the NA exceeds the acceptance cone of the fiber. The NA is directly related to the spot sizes on the lenses. For a divergence of 18 m, the spot size on lens 2 increases by 70%. A ray trace analysis showed that the distortion increases to > 80%. This was observed experimentally when the fiber coupler was transported to the test area. Mistakenly, the mirror to lens 1 spacing was adjusted (i.e., increased) in the field to compensate for this observed distortion. Now, when the laser was retimed and the Hartmann mask removed, the incoming beam was collimated. The result, however, was that the spot on lens 2 shrunk to one-fourth the design value; the nominal power density on the lens was exceeded by a factor of 16. In addition, the ghost reflection that should have been under control was nearly focussed on side 1.

Subsequent discipline in trusting the off-line, low power alignment produced successful results. The design goal of 200 W average power has been injected into the fiber without damage and for long periods of time. This experience indicates a sensitivity of the fiber optic coupler to laser beam collimation.

5. DESIGN TRADE-OFFS

We decided to develop a more conservative design, that is, decrease the power density on the lenses. The main trade-off was in overall length of the fiber coupler. A map of first-order design space parameterized to the power densities on the lenses was generated using a spreadsheet program. In Fig. 5 we show the first-order design space surveyed. A family of curves for constant overall length is shown in solid lines; a family of curves for constant focal length of lens 1 is shown in dashed lines. We decided to reduce the power density on lens 2 by 5–6x and to lower the power density on lens 1 to below 1 kW/cm^2. A first-order design was chosen as a starting point (indicated in the figure). The overall length increased to 10".

When we performed the higher-order design, we learned that the distortion could not be kept below 15% by using a single element for lens 2. (The spot size on lens 2 was increased to decrease the power density.) Hence, lens 2 was split into two lenses so that the distortion remained below 15% (8% was achieved). In addition, simple shapes for this lens pair (equi-convex and plano-convex) were sufficient to keep the ghost reflections from focusing within the substrates or near the surfaces. An optical layout drawing for this fiber coupler is shown in Fig. 6. Lens 1 has focal length –33 mm, lens 2 has focal length 85 mm, and lens 3 has focal length 63 mm. The diameter of lenses 2 and 3 was increased to 1" to accommodate the larger beam size.

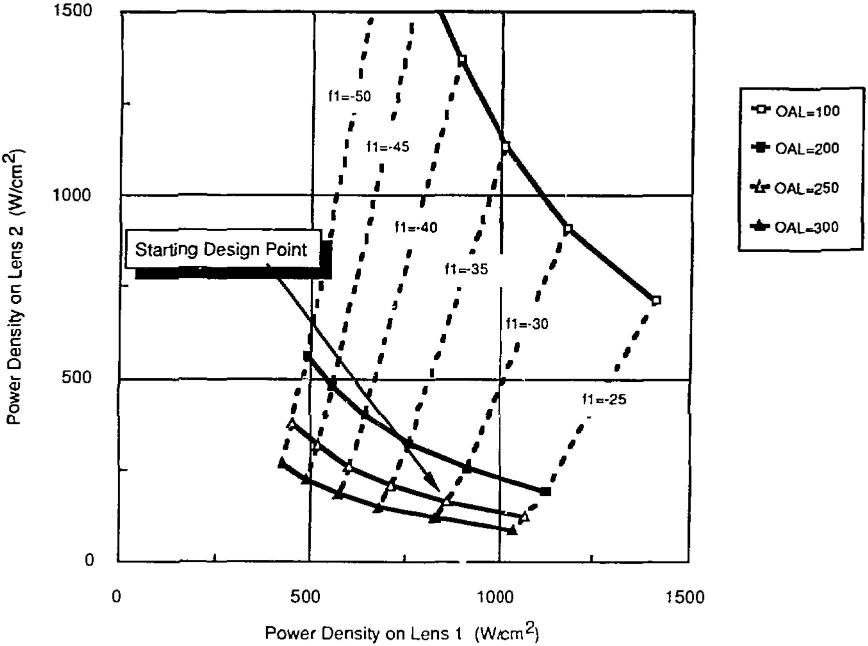

Fig. 5. First-order design map (OAL = overall length, lens 1 to fiber; f1 = focal length of Lens 1).

6. CONCLUSIONS

We have described several considerations in the design and adjustment of an optical system that couples high average power from a copper vapor laser into a large core, multimode fiber. By imaging a physical aperture onto the fiber, sensitivity to damage caused by beam pointing is reduced. The operation of the fiber coupler at high power is sensitive to ghost reflections; these can be controlled by shaping the lens appropriately. Laser beam collimation affects the power density on lenses within the coupler and adjustment of the optical system must be performed under controlled conditions. Finally, the design can be modified so that the power density on the lenses is reduced, but the overall length of the system is increased.

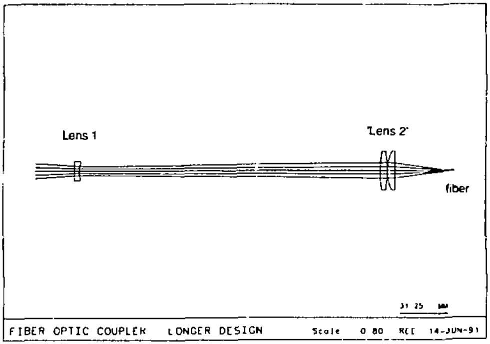

Fig. 6. Optical layout of longer fiber coupler.

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