NOVEL FOCUSING OPTICS FOR IR LASERS

Paper 1504

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Abstract

Traditional focusing optics for IR lasers are refractive lenses and off-axis reflective mirrors. ZnSe meniscus and plano-convex lenses dominate the refractive lens types in use today for CO_2 laser cutting, welding, marking, and engraving systems, to name a few of the more common applications.

Silicon and copper spherical mirrors that are used near normal incidence and off-axis copper parabolic mirrors dominate the type of reflective mirrors used in very-high-power CO_2 lasers for welding and heat treating. These types of mirrors are made with common polishing and diamond-turning techniques that are well known.

In the last three years, advances in fabrication techniques have allowed optic manufacturers to produce more advanced optical surfaces on metal and refractive materials. This paper will provide details of some of these novel focusing optics for IR laser applications. The paper will include design details of ring-focus off-axis parabolas, focused flat-top generators, toroidal lenses and mirrors, faceted integrators, and long-radius off-axis parabolas. Both design and theoretical performance will be given for the optics. In some cases, laser test data will also be provided.

Introduction

Focusing optics for IR lasers have evolved over the past years from simple lenses to more unique focus shapers. More than 20 years ago, laser users were limited to simple spherical-shaped lenses and mirrors. User control of the focus shape was limited to controlling the diameter only by increasing or decreasing the focal length of the focusing element. Minimum spot size was limited by the laser beam mode and spherical aberrations in the lens element.

As laser applications became more advanced, optics vendors developed diamond-turning techniques for aspherizing optics. Flycutter diamond-turning techniques were used to make flat or plano optic surfaces. Two-axis diamond-turning techniques made it possible to eliminate or minimize spherical aberrations. Adding aspheric lens surfaces allowed diffraction-limited focus spot sizes down to a few times the wavelength.

Creation of off-axis parabolas was also made easy by two-axis diamond-turning techniques. The parabolic mirror is noted for converting collimated light or laser beam into a diffraction-limited focus. Parabolas for use at a 45° angle of incidence are widely used in high-power laser welding applications. Ironically, the off-axis parabola is used in these applications because it does not produce sharp, diffraction-limited foci.

Because of the limited range in focusing optics, users often purchased a laser model because it produced a laser mode that was “good” for their application. System builders constructing laser systems for cutting purchased lasers producing very good modes and used lenses with low aberrations. Welding system builders purchased high-power lasers with high-order modes. These systems produced relatively larger spot sizes desirable for welding applications.

Heat treating and cladding systems quite often use faceted optics. Faceted optics split the beam into segments. The segments are then transmitted to the image plane, where they overlap and produce a roughly flat-top intensity profile. Faceted mirrors and lenses have traditionally been made for quite some time by several different methods. One method for producing mirrors is to make many small, square mirrors and mount them on a curved substrate. But, fabrication, assembly, and alignment of the mirrors is both time consuming and tedious.

Until a few years ago, the two key high-power industrial lasers were the CO_2 and YAG lasers. In recent years, we have seen the growth of high-power diode lasers, disk lasers, and fiber lasers. All of these lasers are capable of multikilowatt operation. New lasers and new applications have placed new demands on optics suppliers.

Fortunately, optic fabrication technology has evolved with laser technology and applications. New techniques in grinding, polishing, and coating optics have been developed over this same time period to keep pace with the demands of the laser industry. High-speed grinding and polishing machines enable the polishing of an optic in minutes, compared with lap polishing techniques that take hours. Some of the newest diamond-turning techniques allow the fabrication of some novel optic surfaces. This paper will discuss some of these new, novel optics for IR lasers.

New Diamond-Turning Machining Methods

In the last few years, new diamond-machining methods have been developed that allow the machining of unusual surface shapes [1,2,3]. These methods have been described previously in literature. Although we will not repeat the description of the technology, we do want to mention here that the most of the optics described in this paper are what we call "free-form" surfaces. By adding a third axis to the diamond-turning machine and synchronizing this axis to the spindle rotation angle, a nonrotationally symmetric optic can be produced.

One such example of a free-form surface is the potato chip surface. This visually descriptive name refers to a toroidal mirror, which has a surface that is the sum of two cylinder curves, with the cylinder axes at 90° to each other. We will discuss a toroidal lens example a little later in the paper.

Long-Radius Off-Axis Parabolic Mirror

Our first example for discussion is the long-radius off-axis parabolic mirror. Parabolas for high-power IR lasers are usually machined using two-axis diamond-turning methods. Using traditional methods, the parabola must be machined at its off-axis location. For example, to make a 90° off-axis parabola with a working distance of 300 mm, the mirror must be mounted to the diamond-turning spindle at 300 mm from the axis of rotation. Such a mirror would require a spindle face plate of about 650 or 700 mm in diameter.

These large face plates get difficult to spin and mirrors mounted far from the center tend to vibrate and wobble during the machining process. Most commercially available diamond-turning machines today have maximum spindle sizes of about 700 mm. Therefore, the maximum off-axis parabolic working distance that is obtainable with this method is about 300 mm.

If a 1-meter working distance parabola is required (such as in a remote welding application), a diamond-turning machine with a 2.1-meter spindle would be needed using the traditional technology. But, free-form diamond-turning technology allows us to machine these large-radii parabolas by centering them on the spin axis of the diamond-turning machine. Although the surface is not rotationally symmetric, it is easily machinable using a DT machine with three or more precision axes. Parabolas with a wide range of turning angles and radii are easily obtainable. A side benefit of this method is that the mirror undergoes much less vibration and wobble during spinning; this results in better surface figures and surface roughness compared to parabolas machined using the traditional two-axis method.

Ring-Focus Off-Axis Parabola

Free-form machining also allows us to add special terms to the general equation for machining the surface. For example, it is possible to add a conical term to the equation of a parabola. The conical term has the effect of producing a ring focus.

Figure 1 is a drawing of a ring-focus off-axis parabola with an exaggerated conical term. Rays are drawn in the figure to show how this type of parabola produces a focused ring. Figure 2 is an IR image of a focused ring produced by one of these parabolas. The image was captured using a Pyrocam III IR camera manufactured by Spiricon.

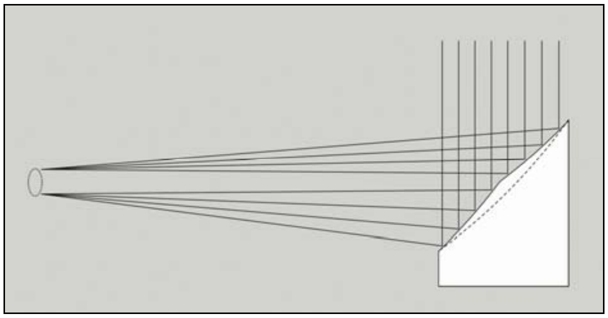

Figure 1 Exaggerated drawing of a parabola and conical component with ray trace.

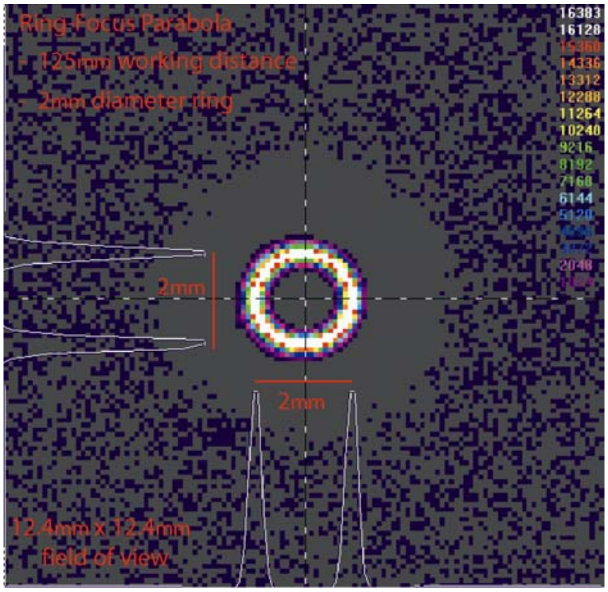

Figure 2 Focused CO2 laser beam with a conical parabola. Focused beam is 2 mm in diameter.

Focused Flat-Top Generator

Generating a flat intensity (flat top) at the focus of a lens has advantages in the drilling industry. For on-axis drilling with low- to medium-power lasers, it is possible to design a single or doublet lens that can produce such a flat top. To test the effectiveness of this type of optic, we designed a flat-top generator that is capable of generating a flat-top intensity of about 100 microns

The basic design is modeled in Figure 3, which shows a cutaway view of the solid model.

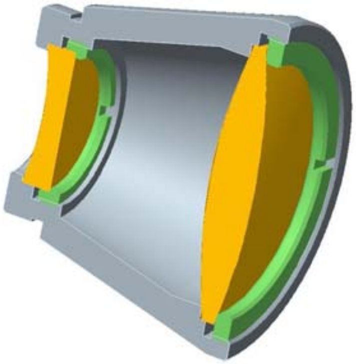

Figure 3 Cutaway view of focused flat-top generating doublet. This model consists of two ZnSe lenses.

Figures 4 and 5 are the results of an analysis of this model using the physical optics program, FRED, published by Photon Engineering. FRED was used for all theoretical analyses presented in the remainder of this paper. A Gaussian beam of 12-mm diameter at the e^{-2} intensity points (Figure 4) was passed through the doublet. Figure 5 shows the resulting intensity field at an image plane location for best flat-top intensity. The focus size is about 100 µm. This plane is not necessarily the sharpest focus, but it is instead about 0.150 mm farther from the lens. It should also be noted that the intensity at this plane is about 20 percent of the intensity at the sharpest focus.

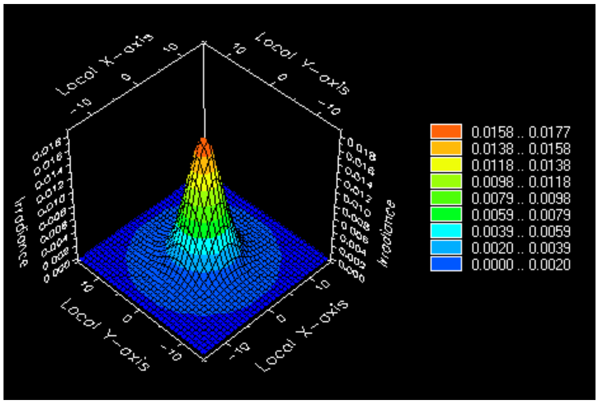

Figure 4 Profile of Gaussian laser beam used in the analysis of flat-top generator optics. The beam input is 12 mm in diameter at the e^{-2} intensity points.

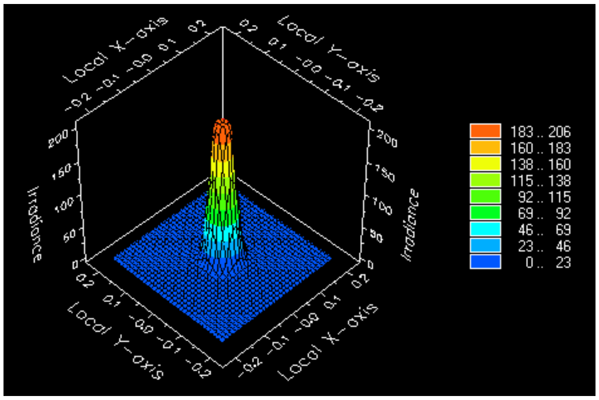

Figure 5 Resulting focused flat-top intensity profile of 100-µm diameter.

Other, more complex, methods are available to produce a flat intensity profile without sacrificing intensity, but these methods usually require more complex optical systems.

Toroidal Lenses and Mirrors

Toroidal surfaces have different radii along mutually perpendicular axes. Applications requiring a line focus or anamorphic beam expansion usually use one or more cylinder lenses. The alignment of cylinder lenses can be difficult and tedious. But, toroidal lenses or mirrors can make this alignment process much quicker and easier. Figure 6 presents the focused beam intensity of a gaussian beam using a simple toroidal lens. In this simulation, an 8-mm diameter gaussian beam is passed through a toroidal lens. The focused beam is 0.2 by 16 mm. Once again, all beam values are provided at the e^{-2} intensity points.

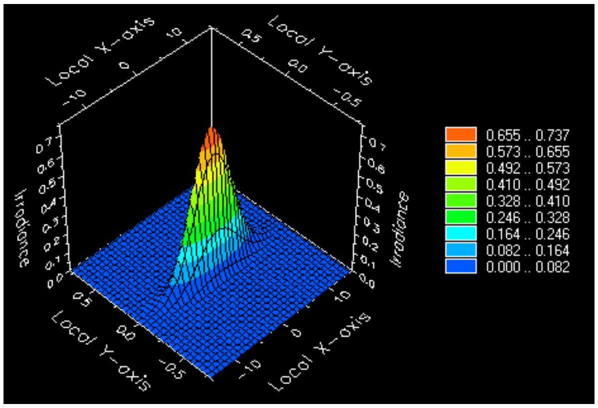

Figure 6 Line shape focus of toroidal lens.

Another possible application for a toroidal mirror would be in high-power CO_2 laser beam delivery systems. These systems often use two spherical mirrors at near normal incidence to slightly expand and reposition the beam waist out to the cutting or welding station. This method adds two additional mirrors to the system. It would be possible to remove both spherical mirrors and replace one of the bend mirrors with a toroidal mirror at some location in the beam path. This toroidal mirror could be designed to reposition the waist to the desired location.

Faceted Lenses and Mirrors

A common mirror used in high-power heat treating and welding applications is the faceted mirror. Figure 7 shows a faceted mirror designed for use at a 45° angle of incidence (AOI). Notice that the facets are rectangular, which will produce a square focus. Square, rectangular, and circular facets can be machined into the surfaces of copper mirrors and lens materials such as ZnSe, Ge, and MultiSpectral ZnS. They can be machined into surfaces for use at normal incidence as well as surfaces designed for other angles of incidence.

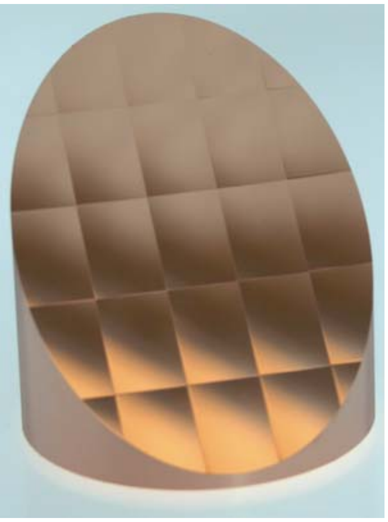

Figure 7 Photo of 45° AOI faceted copper mirror

Usually, faceted mirrors are produced by making small individual mirrors. These mirrors are fabricated to very tight tolerances. Each facet is then attached to a curved substrate, and facets must fit together with a minimum gap between each edge. Making this type of mirror is difficult and time consuming. But, new diamond-turning techniques allow the facets to be machined directly into the surface in one pass using free-form machining techniques.

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The facets are arranged tangentially to a base radius, so the laser power in each facet is sent to the image plane where they overlap. The base radius for the facets determines the working distance of the mirror. The imaged spot has the same dimensions as the facets, factoring in the 45˚ angle of incidence. For very high-power lasers with poor coherence, these mirrors produce a uniform intensity at the image plane and so are sometimes called faceted beam integrators. Faceted mirrors are used for heat treating and cladding, where it is necessary to convert a large, high-order beam mode to a uniform intensity.

Figure 8 is a simulation of the image plane of the faceted mirror shown in Figure 7. For this simulation, the laser beam was assumed to be incoherent. Curiously enough, a coherent laser beam focused with a faceted mirror will produce a focus as shown in Figure 9. Note that the focused beam has strong interference spikes, making it unusable in most systems.

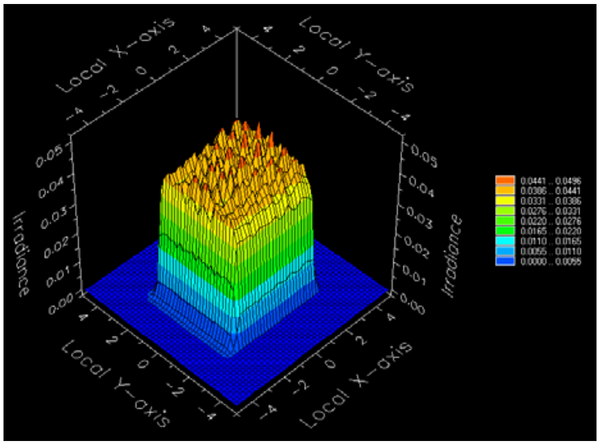

Figure 8 Simulation of a flat-top intensity focus produced by a faceted mirror. Focus is 4 by 4 mm square.

Fortunately, most high-power laser beams have a short coherence length; therefore, faceted integrators produce very good flat-top intensity profiles.

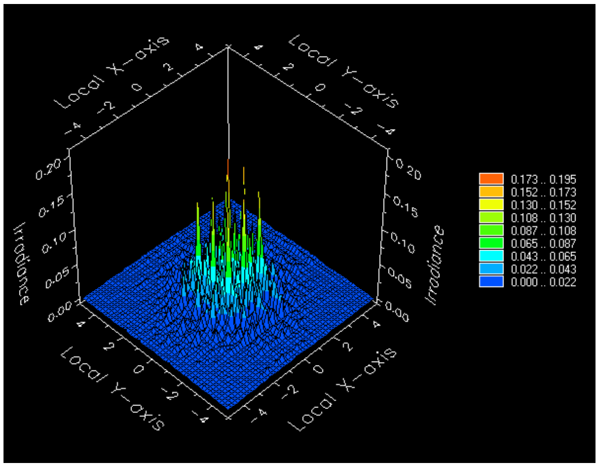

Figure 9 Simulation of the focus of a faceted integrator. A coherent beam was used for this simulation. Note large interference spikes.

Spiral or Vortex Lens

A spiral lens is sometimes called a vortex lens. Free-form machining allows us to add a spiral-step term to the surface of a lens or mirror. The spiral lens has, as its name implies, one or more spiral steps machined into the surface. These spiral steps are generally one optical wave deep. Figure 10 is a photo of a spiral lens we produced for experimentation. Note that the surface has five spiral arms, with each arm rotating about 270˚.

Figure 10 Photograph of spiral or vortex lens made by II-VI Inc. This lens has five spiral arms.

Figure 11 is a simulation of the phase profile near the focus of a spiral lens. The phase is, as would be expected, spiraling through space. This spiraling phase front produces a null intensity field (or vortex) at the center of the focal plane [4]. In other words, the focus spot has a hole in it. Figure 12 shows the beam caustic through focus. Note that there is no power along the optic axis throughout focus. The ring diameter at the most intense focus is about 0.2 mm. Spiral lenses can be used to produce very small ring focus.

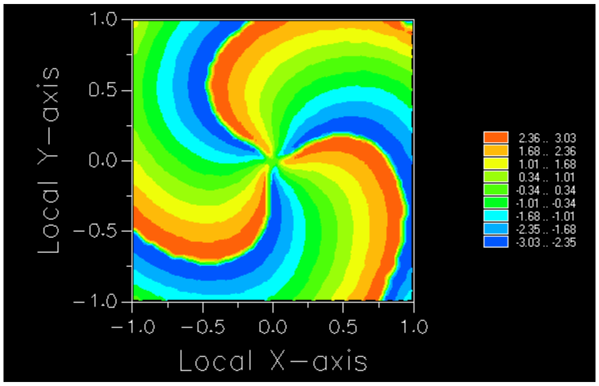

Figure 11 Simulation of spiral phase at the focus of the spiral or vortex lens.

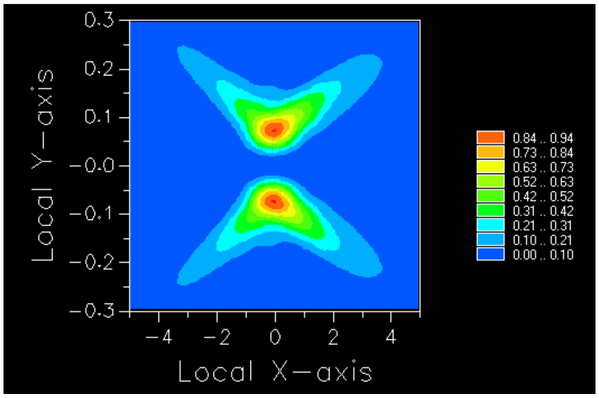

Figure 12 Caustic profile for the spiral lens. Note the null intensity throughout focus. Intensity information is provided by the false color.

Summary

Currently, focusing optics produce three types of focused spots: (1) Gaussian distribution from a low-order-mode laser beam, (2) airy disc distribution from a high-order-mode laser beam, or (3) a flat-top intensity. The flat-top intensity distribution can be generated using special aspheric optics or by simply re-imaging the end of a fiber. All of these types use standard spherical or aspherical lenses and mirrors.

Free-form machining techniques produce some new and interesting optic surfaces. Toroids, cones on 45° surfaces, facets, and spirals are just a few of the geometries that can now be machined directly into an optic surface. This new fabrication technique opens up new opportunities for special optics that were not possible just a few short years ago. And, it gives laser process and optical engineers a new way to solve problems.

References

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Meet the Authors

Gary Herrit has worked for II-VI Incorporated for 25 years, initially as a laser test engineer developing laser tests for IR optics. Currently he is part of the engineering staff with responsibilities that include technical support of IR optics and components, new product development, and optical design.

Herman Reedy has been employed by the company since 1977 and has been Executive Vice President, Infrared Optics, since February 2003. Previously, Mr. Reedy held positions at the company as Vice President and General Manager of Quality and Engineering, Manager of Quality, and Manager of Components.

Alan R. Hedges obtained his Doctorate Degree in Applied Physics from the Imperial College of Science and Technology in London, England, in 1987. He joined II-VI Incorporated in 1993 and, as Manager of Precision Machining, he has worked within II-VI to build up an extensive diamond-turning capability.