Performance characteristics of a high energy, high pulse repetition frequency Krypton Fluoride laser

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ABSTRACT

As applications have evolved out of the research areas, laser beam properties and component lifetimes have become critical to achieving low operating cost in a manufacturing environment.

We will discuss the development of a 110 watt KrF laser using an all solid-state pulsed power system. Solid State pulsed power enables a significant reduction in system operating cost by greatly extending the exchange interval of the pulsed power and discharge chamber modules.

Beam properties of the laser using both stable and unstable resonator configurations will be discussed.

Keywords: excimer laser, KrF, solid state pulsed power, unstable resonator, beam properties

1. INTRODUCTION

Due to their combination of short wavelength, high peak intensity, good efficiency, and power scalability, Krypton Fluoride (KrF) excimer lasers have gained interest for many developing industrial applications. These include deep UV (DUV) photolithography[1], ablation of vias for MCM's[2], ablative drilling of inkjet nozzles[3], and annealing of silicon flat panel displays[4].

In the past, excimer lasers were notorious for their lack of reliability and the fact that their beam properties change from pulse to pulse and with time. However, the marketplace for DUV photolithography excimer laser tools has provided the impetus and resources required for development of robust excimer laser tools over the past decade. Today, the operational characteristics of commercially available KrF excimer lasers are generally acceptable for manufacturing process development in many of these evolving applications. However, improvements in the consistency of the output beam and in Cost of Ownership (CoO) are required before these tools will be sufficiently cost-competitive to gain widespread acceptance in manufacturing environments.

The motivation for reducing system CoO is obvious. As shown in Figure 1, the discharge chamber and pulsed power module account for over 86% of the operating cost for CYMER's Model HPL-110K laser, so improvements in the lifetimes of these modules will have the most significant effect of any laser contribution on system CoO reduction.

The impact of output beam consistency is also directly related to cost. This is because for most laser manufacturing processes, the manufacturing yield is directly related to the stability of the laser output[5]. In this context, stability refers not only to energy, but also beam uniformity, beam pointing, and pulse duration (intensity).

In this paper, we describe the results of our efforts to improve the performance characteristics of a 100 watt class KrF excimer laser while simultaneously reducing its CoO by making significant improvements in the lifetimes of the discharge chamber and pulsed power module. These improvements are largely traceable to the development of an optimized all solid state pulsed power module (SSPPM).

2. SSPPM DEVELOPMENT

The operating principles of an SSPPM have been described in detail elsewhere[6]. A simplified schematic of the electrical circuit is shown in Figure 2.

In this topology, a low voltage (1 kV) SCR replaces the thyratron switch used traditionally in excimer laser designs. A series of LC compression circuits then steps up the voltage and reduces the current pulse duration to one which is optimally matched to the requirements of the laser discharge. The increased complexity of the SSPPM is more than compensated by its advantages over conventional thyratron pulsed power designs, which include:

a) The costly and short-lived thyratron switch is totally eliminated. By suitable selection of design parameters, it is possible to operate the SCR's in a regime where their lifetimes are virtually infinite. In addition, all of the other switching elements in the circuit are passive devices with extremely high reliability.

b) The occasional misfires or prefires (about 1 per million pulses on the average) associated with thyratron discharges are completed eliminated by the use of SCR switching. This effect can be quite important in scanning applications such as DUV photolithography or flat panel annealing where a single bad laser pulse can result in the loss of an entire part.

c) Because the switching function is completely separated from any requirements posed by the laser discharge, the circuit can be quite finely tuned to match the impedance characteristics of the laser discharge. This can lead to substantially less wasted energy being deposited into the laser discharge on a per pulse basis, resulting in extended lifetime of the discharge electrodes and therefore the chamber.

The solid state pulsed power module developed for these experiments is shown in Figure 3. The Commutation Module contains the SCR switch, first stages of compression, and step-up transformer. The Compression Head contains the final stages of compression and mates to the peaking capacitors which are mounted on the discharge chamber.

3. LIFETIME IMPROVEMENTS RELATED TO SSPPM

Other investigators have demonstrated over 30B pulse lifetime with SSPPM technology[7]. To date, our longest SSPPM lifetest is 6B pulses without failure on a line-narrowed lithography laser[5]. The SSPPM unit shown in Figure 4, which was developed for our 100 Watt laser experiments, has been operated for over 1B shots to date. Based upon our results with the lower power unit and the similarity in design, we estimate the lifetime at > 10B shots.

In addition to the lifetime improvement inherent in the design of the SSPPM, its utilization has led to significant improvements in the projected chamber lifetime. This has manifested itself in two important ways.

First, the ability of SSPPM technology to be finely tuned allows for precise matching between the pulsed power and discharge chamber modules, resulting in reduced electrode erosion and longer chamber lifetime. As the laser operates, streamers resulting from discharge instabilities lead to vaporization of a small amount of discharge electrode material on each laser pulse. This vapor immediately reacts with fluorine in the gas stream to form a combination of metal fluoride compounds. This reaction between the fluorine gas and electrode vapor is the predominant mode of fluorine depletion in modern excimer lasers, and so the rate of this depletion is a prime indicator of electrode lifetime. Using the prototype SSPPM shown in Figure 4, we have demonstrated a reduction of 35% in fluorine consumption, which translates to an equivalent increase in chamber lifetime. Quantification of the actual lifetimes of the SSPPM and discharge chamber will be the subject of a future lifetest study.

4. OPTICAL PERFORMANCE WITH STANDARD RESONATOR

New laser applications require increasingly precise control of output beam properties such as beam shape and size, beam pointing, beam divergence and beam energy/intensity stability. We have measured several of these parameters at the 110W power level to characterize the laser's stability. Some of these results are shown in Figure 4.

Although, in general the stability over time is quite good, most beam properties exhibit some transient variation when the laser is operated in burst mode. This is due to the gasdynamic instability which is induced when the laser firing is paused for some time and then re-started. An example of this is beam pointing, whose evolution in the direction transverse to the direction of the discharge is shown in Figure 5. Designers of excimer laser systems, particularly ones in which the laser beam is scanned, must be aware of these transient burst phenomena. Potential solutions are to start the scan from beyond the perimeter of the part to be processed, or to use real-time beam correction. Another form of instability results from the gradual depletion of fluorine in the laser chamber. As $[F_2]$ changes, so do most laser beam properties, though the dependency is typically quite small. Modern lasers automatically replenish the fluorine at periodic intervals via a gas "injection." As shown in Figures 4C and 4D, these injections can lead to momentary instabilities in the laser beam output. We have made significant reductions in these instabilities by increasing the frequency of injections and reducing the amount of gas injected per injection. This is an important development, because if the instabilities created during gas injections are sufficient to cause the laser to go out of specification, the user is forced to pause manufacturing during this period, thereby reducing throughput and increasing CoO.

5. OPTICAL PERFORMANCE WITH UNSTABLE RESONATOR

Some evolving excimer laser applications utilizing novel mask technologies require a beam with very uniform beam intensity and/or high spatial coherence. Because of this interest, and the low spatial coherence exhibited by high power excimer lasers using stable resonator geometries, we have performed a series of measurements on this laser with unstable resonator designs of magnifications ranging from 4-7. Figure 6 illustrates both "hole-coupled" and "edge-coupled" unstable resonator designs and for these experiments an edge-coupled design was chosen. This choice was made because the resulting square output beam is much easier for a standard beam delivery system to handle.

As illustrated in Figure 7, the primary variable in developing an unstable resonator design is the magnification, M. Increasing magnification leads to lower beam divergence, which was a chief objective of these studies. This is because the geometric losses increase faster in a resonator with higher magnification (Figure 7b), thereby producing a less divergent output beam at any given point in time. To confirm this behavior, we performed an experiment in which we measured the temporal profile of the entire beam and compared this to the temporal profile for the portion of the beam contained within a 0.1 mrad circle. The result is shown in Figure 8, which confirms that this highly spatially coherent portion of the beam develops only after at least 2-3 cavity roundtrips.

While higher magnification is beneficial from the standpoint of obtaining high spatial coherence, it cannot be made arbitrarily large because it results in lower laser efficiency and higher fluence on the output coupler. For example, the output coupler reflectivity ($1/M^2$) is 6.25% for $M = 4$, but is only 2.77% for $M = 6$. Also, the energy density is 2.25 ($6^2/4^2$) times greater, which poses a risk to the lifetime of the output coupler coating.

Figure 9 shows some of the optical measurements performed with an optimized unstable resonator design and illustrates that extremely good near- and far-field beam properties can be obtained using such a configuration. The determination of M^2, divergence, and astigmatism utilize experimental and computational techniques developed originally by Siegman[8] and commercialized by Coherent[9]. The following table summarizes the performance specifications which were demonstrated with this laser configuration.

PARAMETER	VALUE
Energy (mJ)	200
Repetition Rate (Hz) ↘	300
Beam Size (typical, H x V, mm)	12 x 13
Pulse Duration (ns, FWHM)	30
Beam Divergence (H x V, mrad)	< 0.4 x 0.4
Astigmatism (cm)	< 5
M^2	< 10

A prime concern in the development of the unstable resonator design was the lifetime of the output coupler, which is subjected to peak fluences as high as 3J/cm^2. To this end, we evaluated optical coatings from several suppliers and selected one supplier for evaluation and lifetesting. With this optical coating, we demonstrated over 500M pulse operation on the output coupler prior to required maintenance. This lifetime is not significantly reduced from the output coupler replacement interval on a stable resonator laser.

6. CONCLUSIONS

These experiments have demonstrated the feasibility of scaling SSPPM technology to 100 W output power KrF excimer lasers. The use of SSPPM promises substantial CoO reduction through anticipated improvements in the lifetimes of the pulsed power and discharge chamber modules. Output beam properties for this laser have been measured using both stable and unstable resonator geometries and provide results which are of interest for industrial applications.

ACKNOWLEDGEMENTS

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REFERENCES

1. W. Andrews; "IBM said to be lead for deep UV development," *Electronic News* **48**, January 23, 1995.
2. R. S. Patel, T. F. Redmond, C. Tessler, D. Tudryn, and D. Pulaski; "Laser Via Ablation Technology for MCM's Thin Film Packaging - Past, Present, and Future at IBM Microelectronics", *Proceedings of ISHM*, 1994.
3. C. Rowan; "Excimer lasers make better holes," *Laser Focus World*, August, 1995.
4. B. Godard, P. Laborde, C. Dutems, S. Prochasson, D. Zahorski, M. Stehle; J. Bonnet, and D. Pigache; "A 52J XeCl laser for single shot excimer laser annealing," *XI International Symposium on Gas Flow and Chemical Lasers*, Edinburgh, Scotland, UK, August 25-30, 1996, and references therein.
5. T. A. Watson and C. Rowan; "Industrial excimer laser beam properties," *Applied Surface Science* **96-98**, pp. 532-536, 1996.
6. William Partlo, Rick Sandstrom, Igor Fomenkov, and Palash Das; "A low cost of ownership KrF Excimer laser using a novel pulse power and chamber configuration," *SPIE Optical/Laser Microlithography VIII* **2440**, pp. 90-100, February, 1995.
7. D. G. Ball, et al; "High average power magnetic modulator for metal vapor lasers," *U.S. Patent #5,315,611*, May, 1994.
8. A. E. Siegman, "New developments in laser resonators," *SPIE Optical Resonators* **1224**, 1990.
9. M. W. Sassnett and T. F. Johnston, Jr., "Beam characterization and measurement of propagation attributes," *SPIE Laser Beam Diagnostics* **1414**, pp. 21-32, 1991.

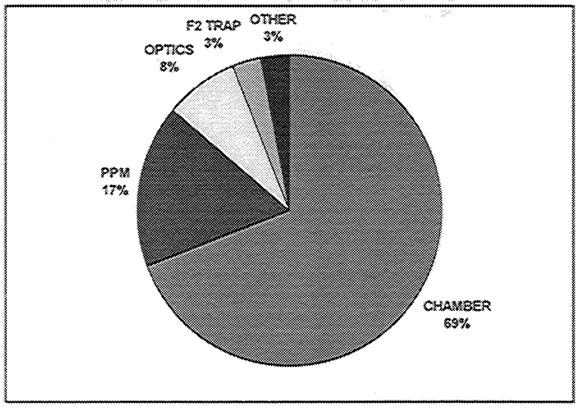


Figure 1. CYMER Model HPL-110K Replacement Parts Costs

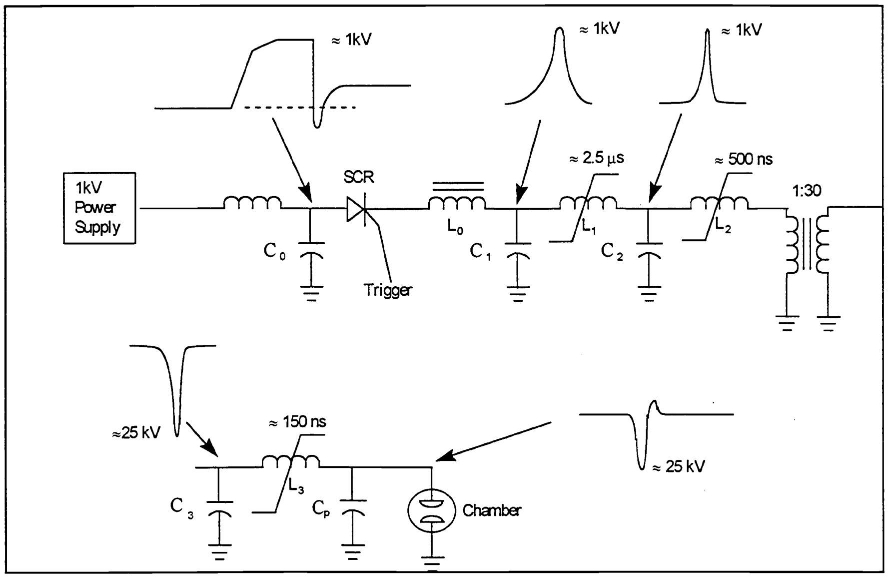


Figure 2. Simplified electrical schematic of the SSPPM

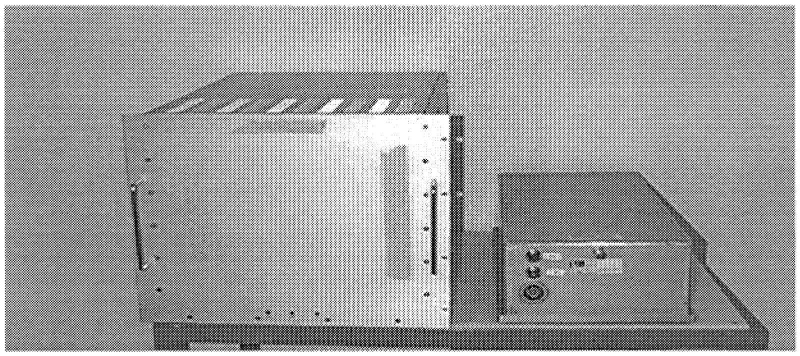


Figure 3. SSPPM. Left: Commutation Module; Right: Compression Head

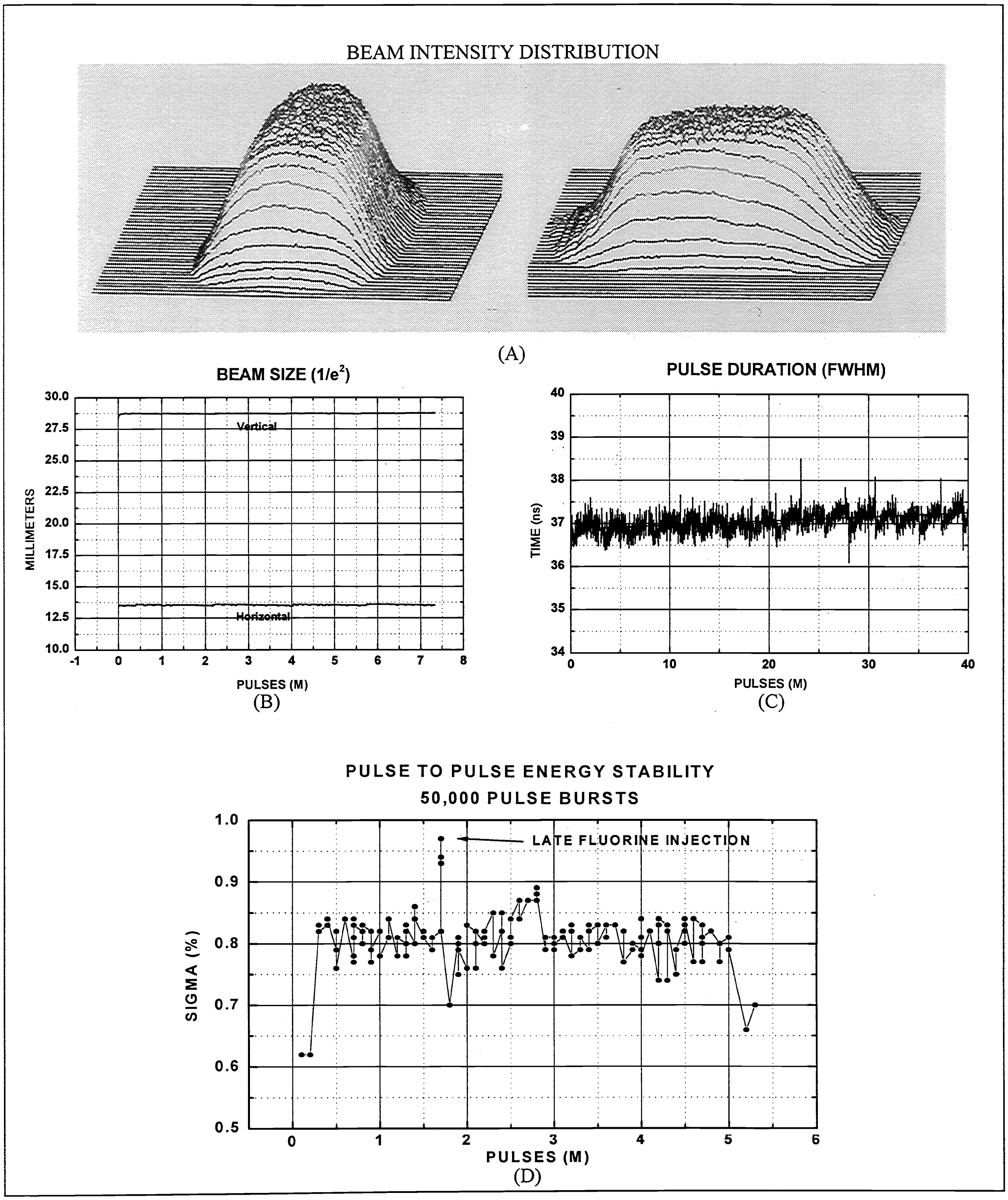


Figure 4. Stable Resonator Optical beam properties measured at 110 watt power level. A) Typical Near-Field Spatial Intensity Distribution; B) Horizontal and Vertical Beam Size stability; C) Pulse Duration stability ; D) Pulse Energy stability

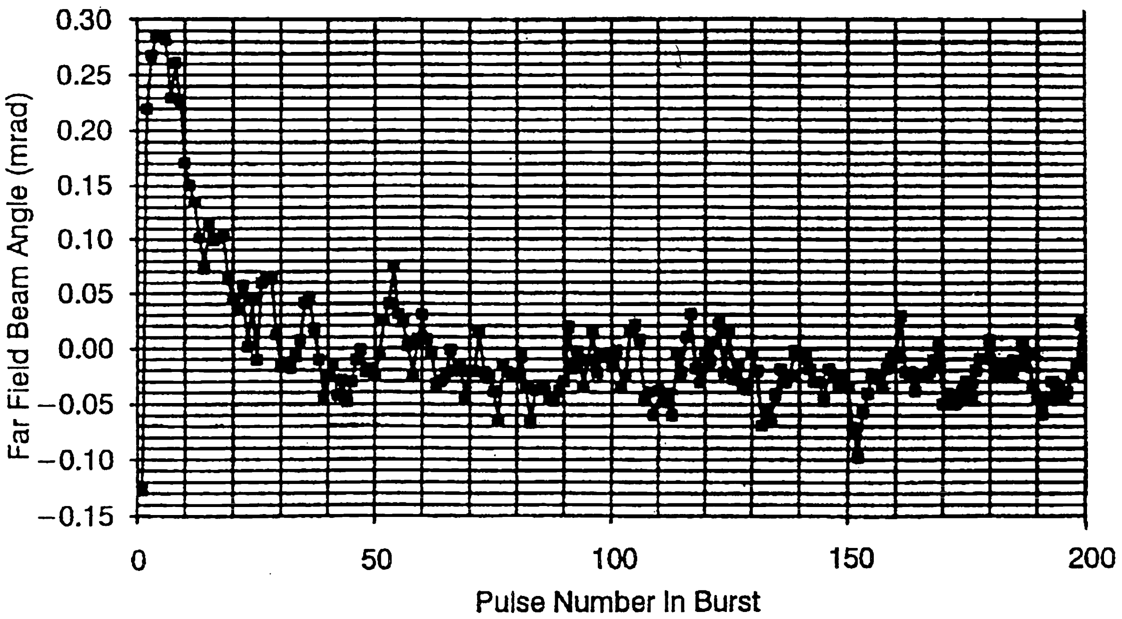


Figure 5. Transient horizontal beam pointing shift in the beginning of a burst.

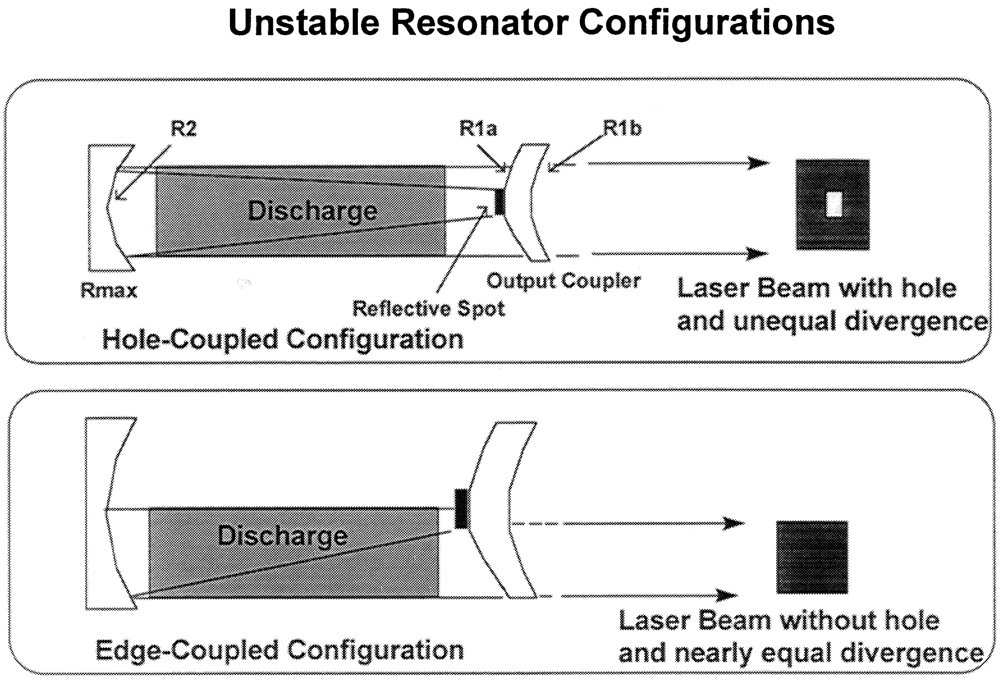
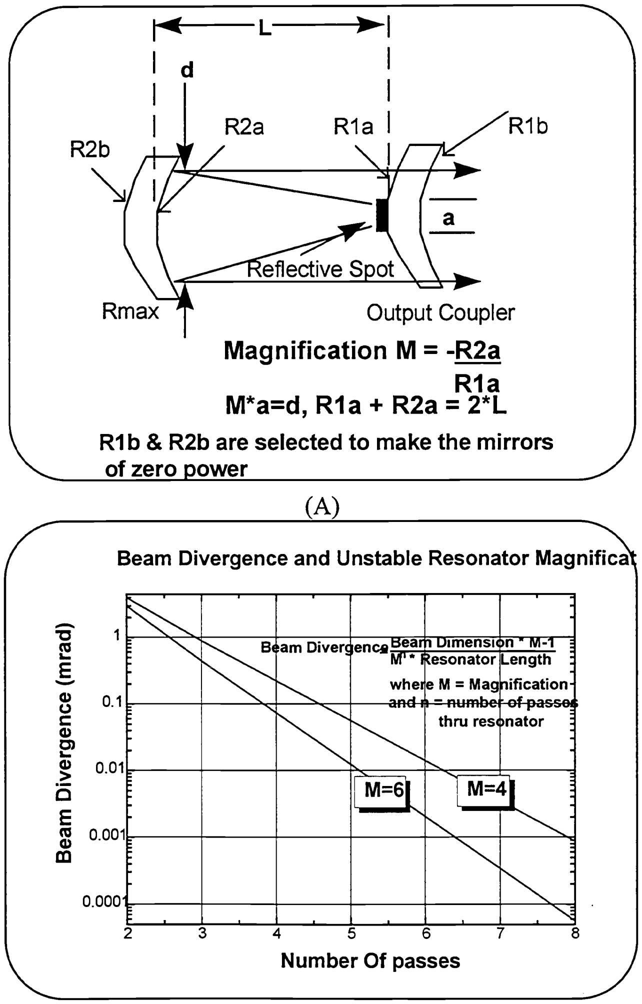


Figure 6. Unstable resonator geometries. The bottom configuration was used for our experiments.



(A)

(B)

Figure 7. Unstable resonator optimization. A) Basic resonator layout; B) Time-dependence of laser beam divergence as a function of resonator magnification.

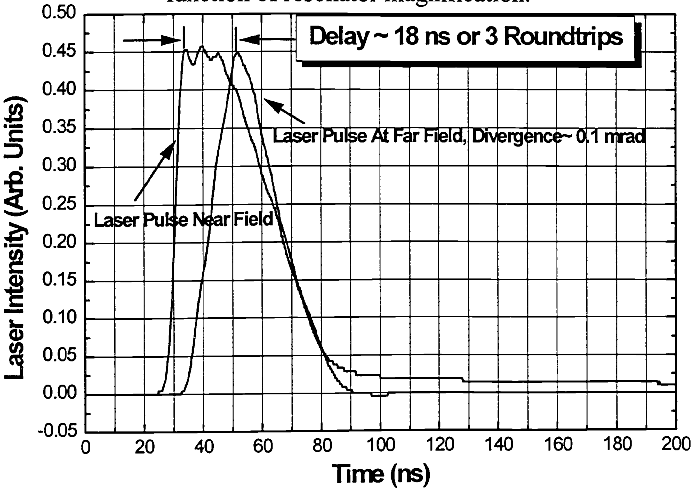


Figure 8. Temporal behavior of unstable resonator output beam in the near and far field.

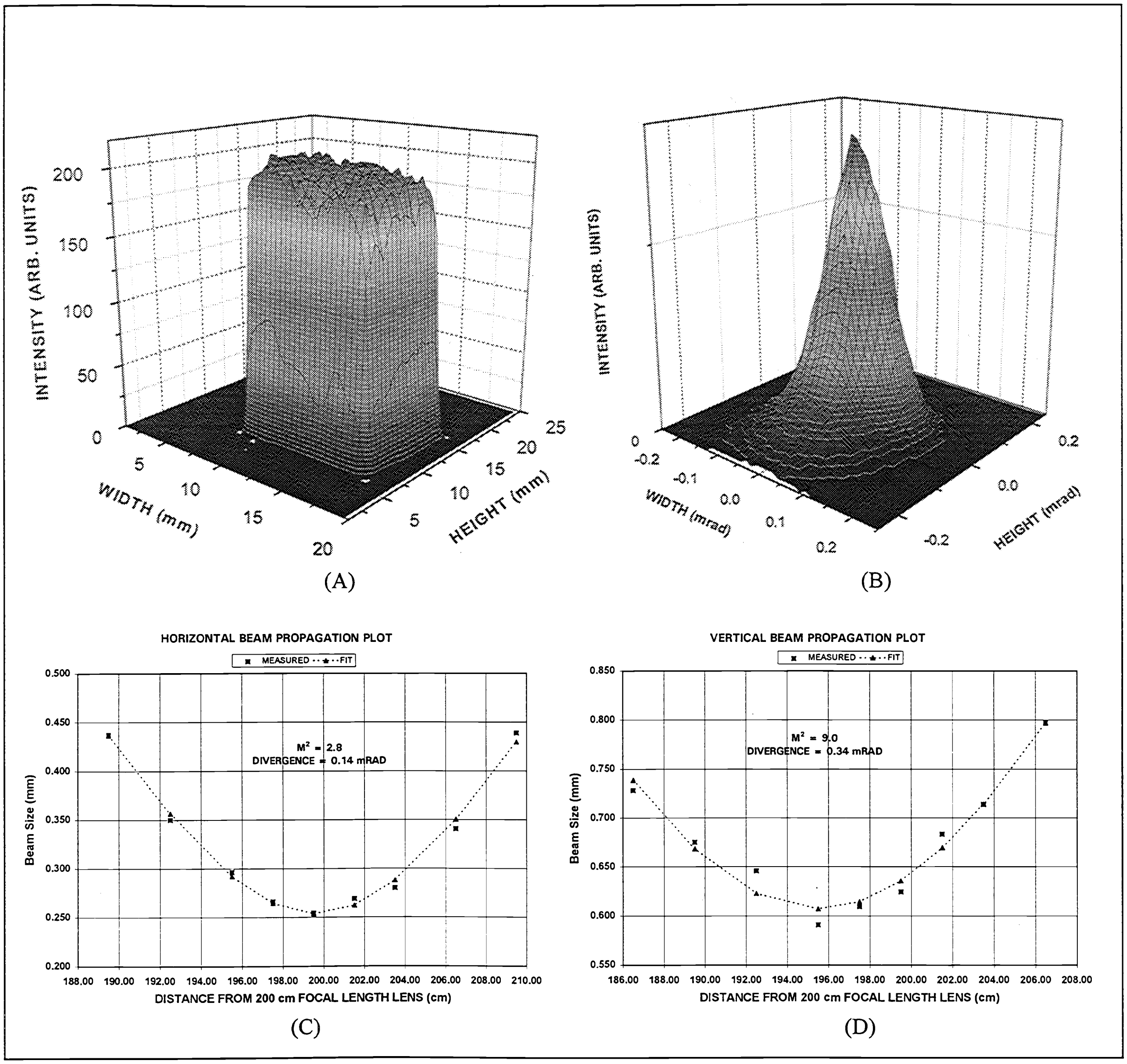


Figure 9. Unstable Resonator Optical beam properties measured at 60 watt power level. A) Typical Near-Field Spatial Intensity Distribution; B)) Typical Far-Field Spatial Intensity Distribution; C) Horizontal beam propagation through the Fourier plane; D) Vertical beam propagation through the Fourier plane