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The Final Report summarizes accomplishments over the 3-year period in several different areas of Laser Physics and Laser Techniques, including ultrafast optical measurements using tunable laser-induced gratings; development of a new subpicosecond photodetector technique; generation of tunable picosecond pulses in the IR using parametric mode locking; new developments in laser resonators and laser mode computations, experimental progress toward measuring an important and fundamental excess spontaneous emission or excess quantum noise mechanism in laser oscillators; and the development of new techniques for laser beam characterization and laser beam measurement.

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LASER PHYSICS AND LASER TECHNIQUES

Final Report to

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

under Contract No. F49620-89-K-0004

for the period

15 March 1989—14 March 1992

Principal Investigator

A. E. Siegman

Professor of Electrical Engineering

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TABLE OF CONTENTS

I. INTRODUCTION

This is the Final Report and summary of accomplishments for a three-year research program in laser physics and laser techniques in the research group of Professor A. E. Siegman, Edward L. Ginzton Laboratory, Stanford University, supported by Air Force Office of Scientific Research Contract No. F49620-89-K-0004 during the period 15 March 1989 to 14 March 1992.

This report covers accomplishments in several different areas of Laser Physics and Laser Techniques, including ultrafast optical measurements using tunable laser-induced gratings; development of a new subpicosecond photodetector technique; generation of tunable picosecond pulses in the IR using parametric mode locking; new developments in laser resonators and laser mode computations; experimental progress toward measuring an important and fundamental excess spontaneous emission or excess quantum noise mechanism in laser oscillators; and the development of new techniques for laser beam characterization and laser beam quality measurement.

Since the primary outputs from an academic research program such as this are scholarly publications and PhD students, we will summarize the results of this program in a number of sections dealing with each area of research in turn, giving in each case an annotated listing of the research publications and other outputs prepared under AFOSR support in each of these areas. Two completed PhD dissertations plus two other nearly completed dissertations along with approximately 18 journal articles published or in preparation are included in these summaries, along with a now commercially distributed laser beam and resonator software package.

II. ULTRAFAST OPTICAL MEASUREMENTS USING TUNABLE LASER-INDUCED GRATINGS

Over a period of several years under earlier AFOSR support prior to this program we developed a novel technique for making ultrafast optical measurements in the frequency domain, without requiring ultrashort pulses, by using a novel tunable-laser-induced grating approach. The basic technique was first developed and applied to picosecond measurements of organic dye lifetimes in the PhD dissertation of Dr. Rick Trebino, who has since continued to apply this technique in research work on many new systems at the Sandia Livermore Laboratories. This technique was then extended to the femtosecond range in the dissertation work of Charles Barker, who made important new measurements of the rise and fall times of the optical Kerr effect in transparent media. This project has now been successfully completed during the early portion of the present contract with publication of the major results of Dr. Barker's work on the femtosecond time response of the optical Kerr effect in CS_2, appearing in:

> Charles E. Barker, Rick Trebino, A.G. Kostenbauder, and A.E. Siegman, "Frequency-domain observation of the ultrafast inertial response of the optical Kerr effect in CS_2," *J. Chem. Phys.* 92, 4740–4748 (15 April 1990).

(Dr. Barker's PhD dissertation was completed and reported under earlier AFOSR support). Dr. Barker is now employed on laser and nonlinear optics research at Lawrence Livermore National Laboratory. An extensive and detailed theoretical discussion of the transient grating approach has now also been carried out under the current contract by A. G. Kostenbauder, in collaboration with R. H. Wentworth of Prof. R. L. Byer's group. This work is presently in the process of publication in the form of two articles:

> R. H. Wentworth and A. G. Kostenbauder, "Ultrafast optical Kerr effect and molecular reorientation in fluids with linear molecules: I. A model," *IEEE J. Quantum Electron.*, submitted for publication (March 1992).

> A. G. Kostenbauder and R. H. Wentworth, "Ultrafast optical Kerr effect and molecular reorientation in fluids with linear molecules: II. Consequences of the model," *IEEE J. Quantum Electron.*, submitted for publication (March 1992)

Some additional work from our group on experimental nonlinear optical measurements during this same period was also published in:

> Daniel J. McGraw, A. E. Siegman, G. M. Wallraff, and R. D. Miller, "Resolution of the nuclear and electronic contributions to the optical nonlinearity in polysilanes," *Appl. Phys. Lett.* 54, 1713–1715 (1 May 1989).

This work was done during a postdoctoral stay at Stanford by Dr. Dan McGraw, who is currently at IEQ-CNR, Firenze, Italy.

III. SUBPICOSECOND PULSES AND PHOTODETECTORS

Another major project involving ultrafast optical concepts under the present contract was the PhD work of Dr. Adnah Kostenbauder on the development of a unique ultrafast diffusion-driven photodetector concept, and also a very useful new "ray-pulse matrix" approach for describing the propagation of ultrashort, tunable, or chirped pulses through dispersive optical systems. These projects were completed during the first year of the present contract and reported in Dr. Kostenbauder's PhD dissertation:

> Adnah Kostenbauder, *Picosecond Measurements of Dember Potentials Associated with Photocarrier Gratings*, PhD Dissertation, Department of Electrical Engineering, Stanford University, March 1990.

Dr. Kostenbauder's final results on the ultrafast diffusion-driven photodetector concept, in which he experimentally demonstrated a subpicosecond time response from the final version of this diffusion-driven photodetector, are expected to appear eventually in the publication:

> A.G. Kostenbauder, "Observation of subpicosecond photovoltaic response in thin silicon-on-sapphire films," *Appl. Phys. Lett.*. submitted for publication (presently in revision).

The experimental response time of this device was found to be at least as short as 700 fsec. (Several earlier publications from Dr. Kostenbauder's work carried out under earlier AFSOR support were reported in earlier contract reports.) A novel bipolar fiber optics communications concept using this photodetector was also experimentally demonstrated and published during the present contract period in:

> Paul Wysocki, A.G. Kostenbauder, B.Y. Kim, and A.E. Siegman, "Bipolar optical modulation and demodulation using a dual-mode fiber and a fast diffusion-driven photodetector," *IEEE J. Lightwave Technol.* **LT-7**, 1964–66 (December 1989).

A quite separate aspect of Dr. Kostenbauder's thesis was a very fundamental and useful new ray-pulse matrix approach to optical pulse propagation which was developed under this program. This analysis appeared in print in the journal article:

> A. G. Kostenbauder, "Ray-pulse matrices: A rational treatment for dispersive optical systems," *IEEE J. Quantum Electron.* **QE-26**, 1148–1157 (June 1990).

Since his graduation Dr. Kostenbauder has been pursuing a private scientific software development venture, and this particular project is viewed as completed.

IV. SUBPICOSECOND IR PULSE GENERATION VIA PARAMETRIC MODE LOCKING

Advances in mode-locked laser technology, in nonlinear crystal growth, and in diode-pumped solid-state laser technology during the period of this contract have combined to open up new possibilities for the generation of ultrashort (i.e., picosecond and femtosecond) pulses in previously inaccessible regions of the infrared spectrum. As one very promising approach to the development of tunable IR ultrashort pulses, during the current contract period we demonstrated the possibility of using synchronously pumped and mode-locked parametric oscillators to generate continuous trains of ultrashort IR pulses in the wavelength region beyond 1 micron. The approach we have developed has involved singly resonant optical parametric oscillators (OPOs) which are synchronously pumped and mode-locked by a CW mode-locked YAG laser. We have constructed and operated two such systems, making use in the first case of a $LiNbO_3$ crystal pumped at the doubled-YAG wavelength of 532 nm and oscillating at signal and idler wavelengths of ≈880 nm and ≈1350 nm, and in the second case of a KTP crystal pumped at the fundamental 1064 nm YAG wavelength with signal at ≈1.5 microns and and idler at ≈3.5 microns. Both systems yielded output pulse widths of approximately 1 to 1.5 psec. at the signal and idler wavelengths. We were able to operate both of these systems reliably at operating levels well above threshold with the YAG pump laser operating in a mode-locked plus repetitively Q-switched mode at a 1 kHz repetition rate. The KTP system could also be reliably operated in a true CW fashion, without repetitive Q-switching, thus providing the first successful demonstrations of CW synch-pumped mode-locked operation of an optical parametric oscillator using the widely available CW lamp-pumped Nd:YAG laser. We believe this may be a very useful development as a pulse source for ultrafast spectroscopy at infrared wavelengths.

The successful operation of this type of synchronously pumped OPO is made significantly easier by any form of pulse shortening or pulse compression in the output from the mode-locked Nd:YAG pump laser. During the contract period, therefore, we also carried out a number of studies of methods for shortening the mode-locked pulses from conventional Nd:YAG lasers, particularly by the use of either intracavity self-phase modulation (SPM) or optical Kerr lens mode-locking (KLM) inside a conventional lamp-pumped and mode-locked ND:YAG laser. These studies were carried out both for their potential application to our mode-locked OPO experiments, and as a potentially simple and inexpensive way of retrofitting a large number of existing YAG lasers to obtain substantially shorter mode-locked pulses. Very useful results were obtained in this work, with the primary experimental and theoretical conclusions being that:

- Introducing the proper amount of self-phase modulation (SPM), such as can be produced by introducing an SF57 glass wedge as a simple intracavity nonlinear element, can cut the pulse width of a conventional mode-locked Nd:YAG laser approximately in half;
- Both experiment and theory show, however, that the pulse shortening effects of SPM can not be easily increased beyond this point because of instability effects that occur at stronger values of SPM, unless some suitable form of group-velocity dispersion adjustment suitable for wider laser pulses can be developed; and finally
- Kerr lens mode locking (KLM), which has been demonstrated to be a very useful method for diode-pumped solid-state lasers, is probably not a suitable mode-compression method for lamp-pumped Nd:YAG lasers because of inherent spatial instabilities in the thermal focusing and thermal displacement of the modal axis inside a lamp-pumped Nd:YAG rod — an effect which appear to be very difficult to eliminate in practical lasers.

All of the experimental results summarized in the present section had been completed or were very near completion as of the ending date of the contract period reported here; but no journal articles had yet been prepared as of the end of this contract. This work will, however, form the basis of the PhD dissertation for Mr. Joon Chung. The research work for this dissertation is now essentially completed (along with Mr. Chung's oral dissertation defense) and the dissertation itself is being written, together with several anticipated journal articles which are now being prepared. It is expected that the completion of these publications will be reported at an early date under subsequent AFOSR contract support.

V. NEW DEVELOPMENTS IN LASER RESONATOR THEORY AND LASER MODE COMPUTATION

Our group has made many significant contributions in previous years to optical resonator concepts and to fundamental methods for the analysis of optical beam propagation and the calculation of laser resonator modes. As an indication of this, an invited review of current and expected future developments in this field was presented and published early in the contract period in:

> A. E. Siegman, "New developments in laser resonators," in *Optical Resonators*, Dale A. Holmes, Editor, *Proc. SPIE* **1224**, 2--14 (January 1990).

and a survey of advances in laser resonators and resonator theory over the past two decades was also presented as an invited memorial lecture at the 1990 CLEO/QELS meeting:

> A. E. Siegman, "Laser Resonators: Retrospective and Prospective," R.V. Pole Memorial Lecture, presented at CLEO/QELS '90, Anaheim, CA (21 May 1990).

One of the more significant advances in resonator analysis during recent years has resulted from a combination of major advances in the capabilities of desktop personal computers, together with needs for specialized new laser resonator designs and the development of new algorithms for resonator mode analysis and calculation. This combination has led to a large resurgence of interest in laser resonator theory and to new techniques for solving laser resonator and beam propagation problems in real time on desktop computers. In response to this, during the current program we completed the development of an integrated package of software programs with which optics engineers and laser researchers can carry out detailed optical beam and resonator calculations in real time on the Macintosh family of desktop personal computers. This software package, which has been named PARAXIA because of its basic dependence on the paraxial wave approximation, includes:

- An ABCD program for carrying out complex-valued ABCD matrix calculations, including two-transverse-dimension or astigmatic systems. This program is particularly useful in both stable and unstable optical resonator evaluation and in optical system design.
- A program FRESNEL which carries out accurate optical beam propagation and diffraction calculations in rectangular or radial coordinates using fast transform algorithms. This program also includes scripting, iteration, and external function capabilities for doing iterative Fox-and-Li resonator mode calculations.
- A program VSOURCE which implements the fast and efficient virtual source algorithm for calculating the modes of rectangular and circular unstable laser resonators, including both lowest and higher-order modes.
- A VRM program for designing and evaluating the mode properties of gaussian variable-reflectivity-mirror resonators.

The VSOURCE program in particular implements the "virtual source" algorithm for unstable resonators which was originally conceived by Horwitz and authors, and later converted into a more physically transparent form by our group in earlier AFOSR-supported work.

Because of its usefulness to other laser designers and researchers and the number of requests for copies we received, this PARAXIA package was initially made available to other university, industrial and government laser laboratories through the Stanford Software Distribution Center; and at least several dozen copies were distributed to other laser researchers in this fashion, including site licenses to several large laser firms. We have since received very favorable comments concerning the usefulness of this software from a number of university and industrial users. A PhD dissertation reporting on the development of these programs and some of their applications to our other research programs was also completed during the program:

> Jean-luc Doumont, *Laser Beam and Resonator Calculations on Desktop Computers*, Ph.D. Dissertation, Department of Applied Physics, Stanford University, (August 1991).

This software was also described in a conference proceedings:

> Jean-luc Doumont and A. E. Siegman, "Laser beam and resonator calculations on the Macintosh," First Annual Conference on Scientific and Engineering Applications of the Macintosh (SEAM '92), San Francisco CA, January 1992.

The completed PARAXIA package has now been licensed to Genesee Optics Software, Inc., of Rochester, NY, a widely known vendor of lens design and optics software packages for the Macintosh, for commercial distribution, with the expectation that it will receive still wider distribution and use in the future through this channel. (All royalties received from this distribution are returned to the university research programs at Stanford University, and none of the students or faculty members involved with these programs receive any personal compensation from this distribution.)

The PARAXIA programs were initially written primarily for our internal use on various projects within our own research group, and we have made extensive use of these programs ourselves in our own resonator design and laser beam quality research, as described in later sections of this report. For example, the FRESNEL and VSOURCE programs were used to develop a useful new stable-unstable resonator design for a very wide tuning range infrared free electron laser being developed at the Lawrence Berkeley Laboratory, as reported in:

> A.E. Siegman, "Stable-unstable resonator design for a wide-tuning-range free electron laser," *IEEE JQE.* **28**, 1243-1247 (May 1992).

These programs were also used to carry out two studies of unstable resonator modes for high-power industrial materials-processing lasers by a postdoctoral visitor from the Japanese firm Mitsubishi firm who completed a one-year stay in our group. These results will be reported in two publications that are nearly ready for submission:

> K. Yasui, P. Mussche, J-L. Doumont, and A.E. Siegman, "Off-axis one-sided positive and negative branch unstable oscillators," *Applied Optics*, to be submitted (1992).
>
> K. Yasui, P. Mussche, J-L. Doumont, and A.E. Siegman, "Comparison of misalignment sensitivities for positive and negative branch strip confocal unstable resonators," *Applied Optics*, to be submitted (1992).

Both of these papers are essentially completed, although publication has been delayed slightly by the return of Dr. Yasui to Japan. They are representative of the way in which these programs can be used as working tools for resonator designs of interest to industrial and defense laboratories. As another effort in resonator theory, we also carried out a slightly extended analysis and evaluation of the so-called self-filtering unstable resonator (SFUR) design concept, leading to a brief journal article:

> A. E. Siegman, "*Performance limitations of the self-filtering* unstable resonator", *Opt. Commun.* 88, 295--297 (1 April 1992).

This communication points out that the SFUR concept, which has been widely discussed by other groups, while it does offer very good mode properties for laser systems with low Fresnel numbers, is still not a useful solution for the more difficult (and generally more realistic) case of large-Fresnel-number laser resonators. The reason is that as the Fresnel number increases much above a few times unity, the output coupling of the SFUR design inherently must become very large, or the effective reflectivity of the output mirror becomes very small, and so this type of resonator cannot be used with any normal gain medium.

VI. EXCESS SPONTANEOUS EMISSION AND EXCESS QUANTUM NOISE IN LASER OSCILLATORS

Another of the major activities under this program has been a continuing effort to verify experimentally a fundamental (and potentially quite large) excess quantum noise effect that we have predicted should occur in laser oscillators using unstable resonators. By way of background, in 1979 K. Petermann in Germany published a theoretical analysis predicting the existence of an "excess spontaneous emission factor" or excess quantum noise emission effect in gain-guided semiconductor diode lasers. In 1989 under earlier AFOSR support we then developed and published several theoretical analyses showing that this kind of excess emission would also occur and would lead to a sizable enhancement of the fundamental quantum noise fluctuations in any kind of laser oscillator using an unstable optical resonator. Our analysis, aided by theoretical calculations using the PARAXIA software described in Section III, showed that the excess noise factors in a typical unstable resonator laser design could range from several hundred to several thousand times, according to our calculations. These quantum fluctuations in turn will represent the ultimate lower limit on the amplitude and frequency stability of any laser device using such a resonator. Environmental or technical noise is usually predominant over quantum noise effects in practical laser devices. Current developments in laser technology, however, are leading to new laser devices having extremely small noise fluctuations and spectral widths, approaching the quantum limit; and such ultrastable laser devices are now becoming of practical importance in ultrahigh-performance coherent optical communications systems, in laser radars, and potentially also in gravity wave experiments. It becomes important, therefore, to verify experimentally the existence of this excess noise emission and the correctness of our theoretical predictions, not only for their fundamental interest as an unusual consequence of quantum electronics, but also in order to set the ultimate quantum limits on the performance of ultrastable laser devices.

We have therefore been carrying out as part of our current work a project to make a careful and definitive measurement of this excess noise factor in an unstable-resonator laser. Our current experimental setup consists of a miniaturized monolithic diode-pumped Nd:YAG laser which is pumped by a stabilized single-mode 100 mW for pump stability. The 3 mm long monolithic rod, which is used for mechanical and acoustic stability, has its planar and divergent mirrors directly on the rod ends and is nitrogen-cooled in a small nitrogen refrigerator to narrow the laser linewidth and thus obtain the increased gain needed for the unstable cavity. Much of the theoretical background and experimental design of this project is summarized in a published conference proceedings report:

> P. L Mussche and A. E. Siegman, "Enhanced Schawlow-Townes linewidth in lasers with nonorthogonal transverse eigenmodes," in Laser Noise, Rajarshi Roy, ed., Proc. SPIE 1376 (November 1990). [Presented at SPIE Symposium on Laser Noise, OPTCON 90, November 1990.]

We have also designed and carefully tested a Pound-Drever cavity stabilization system and noise measurement system which is used to measure the quantum frequency fluctuations of our experimental laser. In this system a slow feedback loop is used to lock the reference cavity to the laser frequency, so that the Pound-Drever system tracks slow drifts in the laser frequency. At the same time, faster fluctuations which are above the cutoff frequency of the feedback system are measured in the Pound-Drever output signal and used to determine the quantum noise spectrum of the laser output. This system has been carefully tested and calibrated, and works very well. For example, both the shot noise level in the measurement system and the calibration level for quantum noise measurements has been established by making preliminary measurements on a similar but stable-cavity diode-pumped YAG laser with a much lower Schawlow-Townes noise level, giving results in excellent agreement with theory. This work will be reported in a nearly completed publication:

> Yuh-Jen Cheng, Paul Mussche, and A. E. Siegman, "Measurement of laser quantum frequency fluctuations using a Pound-Drever stabilization system," *IEEE J. Quantum Electron.*, in preparation (1992).

With this experimental system we have also been able during the final year of the program reported on here to make extensive measurements of the expected excess quantum noise and the resulting enhanced Schawlow-Townes frequency fluctuations in our unstable-resonator laser as well, giving results which provide at least tentative confirmation of the expected excess noise level in our unstable laser. That is, the excess noise values we have measured on this configuration are as large as more than 1000 times the conventional quantum noise results, and appear to be in reasonable agreement with the excess-noise theory for our unstable-resonator device. The only remaining difficulty is that the theoretical predictions of the excess Schawlow-Townes noise depend quite strongly on the cavity loss factor (or the mirror reflectivity plus diffraction losses) for the unstable cavity, and this factor is somewhat difficult to establish for our unstable cavity. In an effort to confirm the expected value of the cavity loss factors for our stable and unstable-resonator cavities, we measured the spiking frequencies or relaxation oscillation frequencies for each of these cavities as a function of pumping level above threshold (this is a standard way of measuring the cavity loss factor for a laser cavity). The results for the stable-cavity laser were in excellent agreement with the specified mirror reflectivity and also with the stable-cavity quantum noise measurements. The unstable-cavity spiking frequency measurements, however, appeared to indicate a cavity loss factor for the unstable cavity which was more than six times larger than predicted from the specified mirror reflectivity of the cavity, thus seriously undercutting the reliability of the measured excess quantum noise in this laser. This result appeared very difficult to understand, however, in that the stable and unstable-cavity lasers both employed essentially identical rods and mirror coatings; and moreover if the unstable cavity losses were truly six times larger than expected, the required threshold pump power should be approximately six times higher than what we observe, and indeed we should probably be unable to even reach threshold with our current pump source.

This unresolved and quite frustrating discrepancy has to date blocked the publication of our excess quantum noise results, since we are unwilling to publish any claimed verification for a fundamental new quantum noise process until this difficulty can be resolved. Very recently, however, after the close of the current program but before the writing of this report, we have realized that the same transverse mode nonorthogonality and the resulting coupling between transverse modes that leads to the excess quantum noise also invalidates some of the fundamental assumptions of the relaxation-oscillation theory; and as a result we may well be able to fully explain the spiking frequency discrepancy, not as a discrepancy, but in fact as further confirmation of the theory. We are at present actively pursuing this possibility, with good hopes of resolving the spiking measurement problems. In any event, much of the work on the earlier development of this measurement will form the PhD dissertation of Paul Mussche, which is at present essentially complete; and additional excellent work building on his results should also lead within a year or two to a second PhD dissertation for Mr. Yuh-Jen Cheng. These results should then provide a firm foundation for future design and evaluation of ultrastable or ultraquiet laser oscillator and laser system designs, as well as confirming the unusual quantum aspects of the predicted excess spontaneous emission.

VII. DEVELOPMENTS IN LASER BEAM QUALITY DEFINITION AND MEASUREMENT

Finally, an important new area of research in laser technology that has developed in our group during the later stages of the current program has been the general topic of laser beam quality definition and measurement. Although this topic is a major new effort in our group, it grows directly out of our earlier research interests in optical beams and resonators; and we believe it may have a substantial impact on the development and improvement of many types of lasers. By way of background, since the earliest days of the laser there has been great interest in the transverse mode properties of lasers, and much effort has been devoted to obtaining laser output beams that were"single transverse mode" or "diffraction limited" in character. This aspect of a laser beam has a critical impact on the usefulness of the laser beam in practical applications, since it impacts directly on the propagation and the far field beam spread of laser beams used in laser radars, or on the focusing properties of a laser beam for laser materials processing. Despite the importance of laser beam quality, however, there has been very little work in the past either on rigorous and meaningful definitions of laser beam quality, or on practical tools for accurate measurement of these laser beam properties. Although the term "beam quality" has often been used (or abused) in referring to laser output beams, the fact has been that convenient techniques or instruments for measuring laser beam quality have been largely unavailable or unsatisfactory up to the present time. Indeed even satisfactory and standardized or widely accepted definitions for the term "beam quality" have not been available.

During the period covered by this report one important advance toward making available a widely useful beam quality measurement instrument took place with the development of the so-called "ModeMaster" beam quality measuring instrument by Coherent, Inc., a commercial laser company. In closely related work under the program reported here, our group first developed a very meaningful and widely useful, but also precise and universal definition for laser beam quality. This work produced a rigorous definition for the so-called "M^2 factor" of a laser beam, based on the spatial and angular second moments or standard deviations of a laser beam and their space-beamwidth product. Our analysis, which was based on the so-called "moments method" for laser beam propagation, in fact gave a complete description of the propagation properties of any arbitrary real, distorted, multimode, or astigmatic laser beam in terms of only six easily measurable parameters: the real-beam waist size, the real-beam waist location, and the real-beam quality factor M^2 in each transverse coordinate. The motivation behind this work was to provide quantitative, measurable, and widely useful measures both of "beam quality" and of beam propagation parameters in the form of a few numbers which can be determined for a given optical beam and be valid at any point along the beam, rather than merely stating some quantitative measure of performance such as far-field brightness in watts per steradian or focused spot size in microns for a specific laser device under specific operating conditions. In subsequent work we have also worked out many of the theoretical applications of this definition to laser oscillator mode studies, the design of laser beam trains and focusing systems, and other applications of the M^2 factor. We plan eventually to write an extensive and hopefully definitive report on the definition and measurement of laser beam quality, although the draft of this document has remained only an internal report to date. A basic summary of this work and of the moments-based definition of beam quality factor M^2 is however summarized in the SPIE Proceedings publication on "New developments in laser resonators" cited at the beginning of Section V.

A number of other related publications concerned with laser beam quality have however been completed during the current program. First of all, for experimental simplicity the Coherent instrument mentioned above measures laser beam width in terms of a knife-edge clip width, rather than a direct evaluation of the second moment of the laser beam profile. The approximations involved in this design compromise were evaluated in a joint publication from our two laboratories:

> A. E. Siegman, M. W. Sasnett, and T. F. Johnston, Jr., "Choice of clip levels for beam width measurements using knife-edge techniques," *IEEE J. Quantum Electron.* QE-27, 1098–1104 (April 1991).

Also, the basic analysis of the propagation of a general laser beam has in the past focused on the axial variation of the various transverse moments of the intensity profile of an arbitrary real beam. As one extension of this analysis, during the current period we were able to extend this analysis to give a very general definition of the effective spherical radius of curvature for an arbitrary laser beam, even one with an arbitrarily distorted or wrinkled phase front. This result was published as:

> A. E. Siegman, "Defining the effective radius of curvature for a nonideal optical beam," *IEEE J. Quantum Electron.* QE-27, 1146–1148 (May 1991).

This new result has proven to be extremely useful in evaluating the effects on beam quality of, for example, phasefront distortion by spherical aberration or other phase aberration effects. Our group has also collaborated in using one of the Coherent instruments to demonstrate how beam quality measurements can be used to understand the modal performance of a typical laser, as reported in:

> T. F. Johnston, Jr., M. W. Sasnett, Jean-luc Doumont, and A. E. Siegman, "Laser beam quality versus aperture size in a cw argon-ion laser," *Optics Letters* 17, 198-200 (Feb. 1992).

The Coherent beam quality measuring instrument as mentioned above above employs a mechanical scanning knife-edge measurement technique, which limits the operation of this instrument to the measurement of cw or very high repetition rate laser beams, although this can be done over a very wide range of wavelengths. It would be very desirable to have in addition an instrument of the same type suitable for single-shot or pulsed lasers, including in particular semiconductor diode lasers. To this end, under the current project our group developed a prototype beam quality measuring system using three CCD cameras linked to a video frame grabber and desktop computer for beam profile acquisition and processing. The experimental set-up consisted of the three CCD cameras with associated optics which could measure the transverse beam profile of an input laser beam at an internal waist and at two other locations some distance away from the internal waist. A frame-grabber board in a Macintosh computer captured each of the three intensity patterns, and fast assembly language programs on the computer evaluated the principle axes of the beam and the first and second moments of the beam patterns relative to these axes in real time. By fitting quadratic curves to the measured second moment values as a function of propagation distance, the M^2 factor along with all other basic beam propagation parameters in each transverse direction could be obtained directly. This work is described in:

> J. A. Ruff and A. E. Siegman, "Single pulse laser beam quality measurements using a CCD camera system," *Appl. Optics*, **31**, 4907—4909 (20 August 1992).

An extended version of this approach is expected to be very useful for several types of pulsed lasers, such as Q-switched solid-state lasers and pulsed excimer lasers.

As one particularly interesting example of the utility of beam quality measurements, we have during the final portion of the program reported here begun a series of measurements of the laser beam quality and beam propagation factors in both transverse directions simultaneously for a variety of semiconductor diode lasers, including both narrow-stripe single-mode and wide-stripe multimode diode lasers. These measurements are being made using both the Coherent beam quality measuring instrument and our own CCD-camera-based beam quality meter. Preliminary indications are that measurements of this type can bring out very interesting new information concerning the modal properties and oscillation behavior of diode lasers, including correlations between the "kink" phenomena that are often observed in such diode lasers and discontinuities in the beam quality parameters. In preliminary tests of this concept we have also discovered that the beam quality and other beam properties of wide-stripe diode lasers can be measured even in the sub-threshold ASE region, and the variation in all of the diode mode parameters followed continuously through the threshold region. To date we have not completed any publications on this work, but some of our results were reported in a conference talk:

> A. E. Siegman, ``Beam Quality Measurements on Diode Lasers," presented at Diode Laser Technology Program Conference, Ft. Walton Beach FL, April 1992.

We believe that real-time beam quality measurements can be a very useful new tool for studying the modal properties and beam properties of semiconductor diodes, and additional work in this area is presently being carried out under continuing AFOSR support.

VIII. MISCELLANEOUS PUBLICATIONS

Aside from the research results summarized in the preceding sections, some miscellaneous professional publications which were written and published during the current period included:

A. E. Siegman, "Technical Writing and Word Processing using TeX," *Optics and Photonics News*, pp. 12—16 (April 1991).

A.E. Siegman, "Computer Display Tools for Lasers and Optics," *Education in Optics*, Grigori B. Altshuler and Brian J. Thompson, eds., *SPIE Proc.* **1603**, pp. 338–347, (September 1991).

A.E. Siegman, "Respecting the Real-World Problems of Industry," Honored Speaker Address on receipt of the Arthur L. Schawlow Award at the Tenth International Congress on Applications of Lasers and Electro-Optics, San Jose, CA, November 1991; published in *J. Laser Applications* **4**, 5-8 (Winter 1992).

IX. HONORS AND AWARDS

In recognition of the renewed interest in laser resonator concepts, Professor Siegman was invited to give the lead-off talk on "New Developments in Laser Resonators" at an SPIE Conference on Laser Resonators, part of the OE-LASE '90 meeting held in Los Angeles in January 1990. The main points of this talk were published in "New developments in laser resonators," *Optical Resonators*, Dale A. Holmes, editor, *Proc. SPIE* **1224**, 2—14 (January 1990).

Professor Siegman was also invited to give the R.V. Pole Memorial Lecture on "Laser Resonators: Retrospective and Prospective" during the Plenary Session of the 1990 Joint CLEO/IQEC Meeting held in Anaheim, CA in May 1990.

During the period of this program Professor Siegman presented a George Eastman Invited Lecture on "Defining and Measuring Laser Beam Quality," to the Optical Society of America, Washington DC, April 18, 1990; and also gave an invited lecture on "Computer

Display Tools for Lasers and Optics Education," at the Education in Optics '91 Symposium in Leningrad, Russia, in September 1991.

Finally, in November 1991 Professor Siegman received the 1991 Schawlow Award of the Laser Institute of America and was the Honored Speaker at the LIA's Annual ICALEO Meeting in San Jose.