Advances in high repetition rate, ultra-short, gigawatt laser systems for time-resolved spectroscopy

Louis F. DiMauro

Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973

JAN 06 1992

1. INTRODUCTION

The evolution of lasers from their early conception to a general laboratory tool has been earmarked by periodic quantum jumps in the technology. Such advances include tunability, high peak power, and ultra-short temporal pulses. Since the mid-70's the advent of easily usable high peak-power pump lasers has made the generation of intense tunable radiation from 0.2 to 1 μm routine practice in many laboratory settings. The general philosophy has been the use of powerful pump lasers to efficiently produce radiation at wavelengths appropriate for the task. The use of this intense tunable radiation has opened the opportunity for studies involving the use of nonlinear probes, viz. resonantly enhanced multiphoton ionization (REMPI), pump-probe techniques and the generation of plasma continuum. Even the ability to produce tunable VUV radiation below 0.2 μm by third harmonic generation in various gases[1,2], although inefficient, becomes a viable spectroscopic technique with high peak power systems. Likewise, the use of intense pulses of radiation has led to the understanding of new fundamental phenomena[3,4] in the area of nonlinear optics. These are just a few examples where high peak power lasers have made an impact and it is beyond the scope of this review to cover all applications. However, the one thing that both the laser industry and the scientific community have been striving towards over the last decade is the development of a class of megawatt (MW) peak power lasers with kilohertz repetition rates. The ability to generate short pulses with low peak-power, 0.1-10 kilowatts (kW), at 50-100 megahertz (MHz) repetition rates has been available from mode-locked and colliding pulse (CPM) laser systems. Consequently, the availability of MHz source lasers has geared the approach towards the development of high peak power lasers as high repetition-rate pump amplifiers that would complement the existing technology. A schematic representation of a high-repetition rate, tunable, short pulse laser system is shown in Fig. 1. The low peak-power output of the mode-locked (ML) or cw-pumped CPM lasers are seeded into a tunable amplifier, i.e. dye or solid state. The tunable amplifier is in turn pumped by the output of a fixed-frequency amplifier pump operating in the kilohertz regime. This amplifier can be electrically and/or optically synchronized to the master oscillator, as indicated by the dashed line in Fig. 1. The objective of this article is to emphasize the current advances in the development of high-repetition rate amplifier pumps. Various approaches to this problem will be reviewed and contrasted along with our own developments here at Brookhaven National Laboratory (BNL). Although this review will highlight amplifier pump development, any recent data from achieved outputs via the tunable amplifier section will also be discussed albeit without detail. The first section will describe desirable parameters attributable to the pump amplifier while the rest of the article will deal with specific examples for various options. The pump amplifiers can be characterized into two distinct classes; those achieving operation in the hundred hertz regime and those performing at repetition rates ≥ 1 kHz.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

In general, most experiments would benefit from an increase in repetition rate, assuming that the other characteristics of the laser are not dramatically compromised. Exceptions would of course be studies in which some dynamical decay or recovery time of the system under investigation is slow compared to the repetition rate of the laser. The most basic concept of signal averaging predicts that the signal-to-noise ratio (SNR) for an experiment is proportional to the square root of the number of counts. In principle, one could attain arbitrarily high precision by counting for long times but this is often not practical because of long term instabilities in the experimental system or finite sample quantities which introduce new sources of uncertainty to the signal. Consequently, high-repetition rate laser systems are advantageous in their ability to accumulate a statistically meaningful signal in a relatively short time period. The systems discussed in this article typically have a 100 fold increase in duty cycle compared to standard 10 Hz laser systems. A more subtle but important improvement in the signal-to-noise ratio of an experiment can be realized with high repetition rate lasers by application of signal-enhancement techniques based on bandwidth reduction[5]. Phase-sensitive or lock-in amplifier detection is one such technique that although widely used in various spectroscopy applications has not found wide spread use with low repetition rate pulsed laser systems. Although the ability to detect and process a signal against a white noise environment is significantly enhanced by such techniques the low-duty cycle associated with low repetition rate lasers makes application essentially impossible (inefficient). Such is not the case for laser systems approaching the kilohertz regime where the higher duty factor makes application of signal-enhancement techniques an effective detector. Finally, the need for high repetition rate systems can also be dictated by the specific details of an experiment. Thus, for certain experimental studies to achieve a minimal acceptable count rate there exists an important need for high peak power pulses for either driving a particular weak transition and/or efficiently up- or down-converting radiation in a spectral region of interest, but one finds that there is indeed a practical upper limit for usable peak power. That is, the signal does not continue to increase with increasing laser power. For instance, an experiment designed to perform transient Raman spectroscopy requires high peak power lasers to efficiently pump the inherently weak transition and overcome the low transient densities; however too much pump power leads to unwanted secondary processes, i.e. multiphoton ionization and dissociation, that tend to mask or diminish the desired signal. Thus, the ability to work at lower peak power dictates the need for higher repetition rates in order to successfully perform the experiment. The use of such laser systems also provides the ability to perform coincidence experiments, i.e. electron-ion, in molecular and atomic beams that were virtually impossible at lower repetition rates but now come into the realm of possibilities.

One of our interests at BNL is the coupling of high-repetition rate laser systems to accelerator-based facilities, i.e. National Synchrotron Light Source (NSLS). The NSLS is a facility that provides tunable VUV radiation from 10-1000 eV with high average power and megahertz repetition rates, but the energy per pulse is extremely low, 10^5 photons/pulse. Consequently, to pursue synchrotron-laser pulse-probe studies it is necessary that the laser system perform with a repetition rate closely matched with that of the synchrotron, high duty cycle. One approach to this problem is to use low peak-power cw or mode-locked lasers. However, if the specifics of an experiment require high peak-power from the laser then currently kilohertz based systems become the only viable alternative. We are also exploring the construction of a UV-FEL amplifier facility operating in the wavelength range from visible to VUV with millijoule output and kilohertz repetition rates[6]. High-powered, high-repetition rate lasers will be an integral part of this proposed facility. The lasers will not only drive the photocathode RF gun for the LINAC but will also provide the megawatt seed pulses for

injection in the FEL amplifier. A second interest in my group involves the use of neutral molecular beam detection techniques to study time-resolved vibrational relaxation and dissociation dynamics of medium sized molecules and clusters. Specifically, our beam machine will employ bolometric detection which directly detects the change in energy content of a neutral species. This technique has been used with great success in CW high resolution laser studies but has alluded application to time-resolved studies. The main reason for this shortcoming has been the low-duty cycle associated with conventional short pulse lasers. However, the high-repetition rate lasers discussed in this article makes application of this technique feasible and such a program is currently underway at BNL.

2. DESIRABLE AMPLIFIER PARAMETERS

The purpose of this section is to quantify the desirable output parameters of the "ideal" amplifier pump. Of course, this laser does not exist and the choices have to be based on the individual needs of the experiment. The *pulse repetition rate* is strongly coupled to the *energy per pulse* since the laser's average power is fixed. This is shown in Fig. 2 where the existing amplifier systems are clustered about the 1 and 10 Watt average power lines. The nanosecond green/uv amplifier pump sources are shown in Fig.2(a) while sub-nanosecond green sources are plotted in Fig.2(b). The available sub-nanosecond amplifiers are solely based on the second harmonic output of either Nd:YAG or Nd:YLF. The researcher must essentially choose between peak power or repetition rate in their application. However, it is our view that amplifiers operating in the 1-5 kHz regime represent the best compromise. Since this dynamic range offers peak power performance similar to commercial 10 Hz systems but with at least a 100-fold increase in repetition rate. The specifics of these sources are discussed in more detail in the next sections.

The temporal *pulse width* of the amplifier's output is crucial in determining the dye amplifier design. Since the gain lifetime of the dyes is of the order of a nanosecond[7], a clear distinction exists between the group of amplifiers plotted in Fig.2(a) and (b). The nanosecond amplifier pumps require a multipass cell arrangement[8], sometimes referred to as "butterfly" or "bow-tie", in order to maximize the use of the pump energy. However, the dye amplifier can be simplified to a single pass longitudinal pumping arrangement with sub-nanosecond amplifier pumps. Conversion efficiencies up to 15% can be realized for the shorter pump pulses as compared to 1% for nanosecond pump pulses. The amount of amplified spontaneous emission (ASE) present in the amplified tunable output is mainly determined by the amplifier pump duration. The use of sub-nanosecond pump pulses typically achieve 10 times less ASE than nanosecond pumps. However, if the tunable amplifier media is Ti:Sapphire with gain lifetimes of the order of a few microseconds then green nanosecond amplifier pump pulses are desirable in order to minimize the energy density. In particular, Q-switched CW pumped Nd:YLF amplifier pump pulses with 300 nsec width have been used in a Ti:Sapphire amplifier[9].

The *wavelength* of the amplifier pump should ideally coincide with the maximum in the absorption peak of the tunable media for good conversion efficiency. Likewise, the frequency or energy difference between the absorption and emission of the tunable amplifier should be minimized to reduce the heat load. Considering that the host of tunable short pulse generation techniques operate at wavelengths longer than 550nm, it is preferable to have an amplifier pump operating in the visible region. Furthermore, when considering Ti:Sapphire as the tunable media, one finds that the narrow absorption band limits the pump wavelength exclusively to the green ($\lambda_{max} \sim 500\text{nm}$).

Figure 2 does show the energy per pulse for various sources without reflecting the *beam quality*. Good beam quality means that the energy spatial distribution is described by a simple gaussian function, TEM₀₀ mode, and with no beam pointing instabilities. In order to optimize the conversion efficiency between the amplifier pump and amplified tunable pulse, it is essential to achieve good spatial overlap of the two beam volumes (mode-matching). This is most easily accomplished with diffraction limited gaussian pump beams. Furthermore, good beam quality is necessary if standard up- and/or down-nonlinear conversion techniques are to be employed to extend the wavelength coverage to the UV or near IR. This is illustrated in Fig. 1 by the dashed box labelled mixer where the amplified tunable output is mixed with the fundamental or harmonic frequency of the amplifier pump. Here the regenerative amplifier alternatives stand out because of their low timing jitter, appropriate wavelength, and excellent beam quality.

The *timing jitter* between the dye oscillator and the amplifier pump must be maintained within a fraction ($\leq 20\%$) of the dye's storage time. This requirement is easily achieved with amplifier schemes that are optically synchronized to the master oscillator, i.e. regenerative amplifiers. In the case of nanosecond amplifier pumps this criterion is somewhat relaxed but a typical jitter requirement should be ± 1 ns. The *energy stability* or shot-to-shot energy fluctuations presents an obvious choice; the more stable the better, since the final amplified tunable output (saturated) will be limited by the shot-to-shot noise of the amplifier pump. Finally, from a practical standpoint the *utility requirements* can also be a criterion for choice of amplifier pump, as well as the *cost of consumables* which can be substantial, viz. flash-lamps, rare gas consumption.

3. REGENERATIVE AMPLIFIER PUMP SOURCES

In recent years there has been work directed toward the development of a unique class of solid state optical amplifiers capable of producing high gain and repetition rates in the kilohertz regime. This class of lasers has become known as regenerative amplifiers. The pioneering work of Lowdermilk and Murray[10] laid the foundations for amplifying picosecond IR pulses to nearly a millijoule with a 10 Hz regenerative amplifier. In their scheme, a single pulse from a mode-locked Nd:YAG laser was seeded into a pulsed flashlamp pumped Nd:YAG regenerative amplifier, where it made several passes through the gain medium before being cavity dumped. The single pass gain within the amplifier cavity was kept low allowing the seed pulse to make ≈ 100 passes before reaching the saturation limit. It is the multipass operation of this system which makes it distinctive from conventional traveling wave amplifiers. In this section, we will examine two different pumping schemes (*cw or pulsed*), as well as different gain media. Since the emphasis of this article is on high repetition rate sources, we will not discuss low repetition-rate ($\leq 100\text{Hz}$) chain amplifiers which can pump short pulses with very high energy per pulse.

3.1. CW-pumped regenerative amplifiers

A new arrival in the multi-kilohertz amplifier pump arena is the cw-pumped solid-state regenerative amplifier[11] (RGA). The early work on cw RGA were limited in their repetition rate to 1 kHz and energies of 1 mJ. However, substantial work on improving the resonator design and electro-optics have resulted in multi-kilohertz performance with higher output energies[12]. Our work at BNL has produced a cw-pumped YLF RGA capable of producing 4 watts average power at repetition rates of 5 kHz. Our system, shown in Fig.3, utilizes a convex-concave stable resonator design which produces excellent beam quality (TEM₀₀) with 4 mJ pulse output in 50 psec at a 1

kHz repetition rate while minimizing the energy density on critical optical components. This allows us to produce 2.5 watts of 40 psec green light in order to pump our dye amplifier. Wang et al.[13] using an improved electro-optic driving scheme and proper acoustic damping in a BNL resonator have reported an output power of 6.6 watt with up to 10 kHz operation.

The RGA operation can be visualized as four simple steps, (1) trapping a single pulse from the mode-locked seed train in the amplifier resonator, (2) simultaneously Q-switching the amplifier resonator, (3) letting the trapped pulse build up gain by undergoing N round trips, where $N \geq 2$, and (4) at saturation, cavity dumping the amplified pulse. For our RGA operating in the low gain single pass limit the number of roundtrips is typically 75 to 100. This is shown in Fig. 4(a) where the single trapped pulse builds up gain with each successive roundtrip through the amplifier. At the Q-switched build-up time the cavity dumping step is applied extracting all the energy from the amplifier which results in a single pulse output as shown in Fig. 4(b). This large number of roundtrips in our resonator contributes to better stability, 1% shot-to-shot energy fluctuations, and excellent beam quality. The advantages of cw-pumped RGA include the absence of any pulsed power supplies which are inherently cumbersome, gaussian beam quality, large dynamic range of operation (especially true for YLF), multi-kilohertz performance, short pump pulses, low energy fluctuations and timing jitter (optically synchronized). Damage threshold becomes a limitation with any RGA resonator and extraction of average powers in excess of 10 watts seems unlikely.

A recent development at the University of Chicago[14] has resulted in the operation of a 100 kHz cw RGA using acousto-optic switching. This system yields a gaussian beam with $8\mu\text{J}$ of green energy at 100 kHz and 5% conversion efficiency upon pumping a dye amplifier. Both YAG and YLF systems are now commercially available with multi-kilohertz outputs. The use of the second harmonic of a cw RGA system for an amplifier pump at 1 kHz has been reported to give conversion efficiencies between 1-5% for 7 psec[15] and 150 fsec[16] tunable pulses. Using 527nm radiation from our BNL regenerative amplifier, we have achieved 15% conversion efficiencies for 250 fsec TEM_{00} pulses using a three-stage longitudinally pumped dye amplifier scheme[17]. Three dye cells with 1, 2, and 10 mm thickness produced gains of 200, 35, and 50, respectively. The pump geometry consisted of counter-propagating pump/seed beams to ensure good spatial overlap in the dye cells. The green 527 nm light was distributed among the dye cells using 14%, 26%, and 60% pump energies, respectively. Using 1 mJ green energy at 1 kHz repetition rate we have observed over 140 μJ output at 590 nm and 250 fsec with less than 1% ASE. We believe that a combination of *excellent mode quality* from our RGA and dye oscillator and *good spatial overlap* in our dye lasers results in our high conversion efficiencies, which are the highest reported to date for any kilohertz picosecond dye system.

3.2. Pulsed pumped regenerative amplifiers

The first solid state regenerative amplifier was a pulsed flash-lamp pumped Nd:YAG amplifier[10]. The principle of operation is similar to that described in the section on cw RGA but the details of operation are quite different. First, there is the need to have pulsed power supplies which become an obvious limit on repetition rate performance. Commercial YAG systems are available that will operate at discrete repetition rates up to 1 kHz but multi-kilohertz rates have not been achieved. A second difference is that they operate in the high gain single pass limit, thus the number of roundtrips in the amplifier is about 5. A consequence of this limited time in the resonator results in poorer mode quality (near-gaussian) and greater shot-to-shot energy fluctuations (7-10%). However, the

advantages of pulsed RGA are still provided by optical coupling to the oscillator and short pump pulse generation. The pulsed RGA provide output energies similar to their cw counterpart since both resonators are damage threshold limited. However, the commercial systems offer the possibility of further amplification via single pass high gain amplifiers after the RGA. Of course, such a scheme can be applied to cw-based RGA. This scheme can produce 15 mJ/pulse of green amplifier pump at 540 Hz operation. The conversion efficiencies reported[18] for short pulse dye amplification are similar to those given by cw RGA's.

4. ALTERNATIVE PUMP SOURCES

There is a number of alternate pump laser sources available to the researchers with widely varying characteristics, as discussed above. The choice of amplifier system depends upon the desirable characteristics necessary for each individual experiment. For example, if high peak power is desirable than a compromise on high kilohertz performance must be made. However, it should be noted that certain systems are inherently more flexible than others. The following section will describe some different schemes for amplifying tunable light.

4.1. Excimers

This group of pulsed, high pressure gas lasers emits radiation in discrete lines in the uv region. Commercially available excimer lasers use electronically excited diatomic rare gas halide molecules (XeF^* , XeCl^*) as the lasing medium. Even though their power supplies are pulsed circuitry and they still use thyratrons for electronically switching high voltages to initiate a discharge, they have the advantage of well established commercial technology, high energy per pulse, and the flexibility to pump a wide range of dyes. The XeCl and XeF transitions at 308nm and 351nm, respectively, are the best suited excimers for pumping dye amplifiers. However, for amplifying short pulses two major difficulties exist. First, amplification of short red pulses ($\lambda \geq 550\text{nm}$) with UV pump pulses results in a large frequency mismatch and consequently present problems associated with a large heat load. Second, the long nanosecond pulses are temporally mismatched with short seed pulses ($\tau \leq 5\text{ps}$), even when accounting for the dye's lifetime. This will lead to low conversion efficiencies and high ASE. Lasers with 308nm output with about 50 mJ of energy per pulse at 500 Hz in 20 nsec are commercially available. The problem associated with the nonuniform pumping of dye media because of the rectangular spatial distribution of excimer beams can be overcome by transverse pumping of prism or Bethune[19] cells. Rolland and Corkum[20] have demonstrated an excimer pumped dye amplifier with an output of 550 uJ in 70 fsec pulses and a maximum repetition rate of 125 Hz. The conversion efficiency for their four stage amplifier is 1% and the amount of ASE was about 10%. This same scheme could easily be used with commercial 500 Hz excimer lasers but this appears to be the upper limit in high repetition rate performance.

4.2. "All-in-one" solid-state laser

The mode-locked, Q-switched, and cavity dumped lasers or "all in ones" as they are sometimes called span the moderately high repetition rate range with about 1 mJ of energy per pulse. These solid-state (YAG or YLF) lasers have all three mechanisms combined in one resonator. Briefly, these lasers are operated in a prelasing mode such that there is a low level of cw mode-locked operation between Q-switched bursts. Once mode-locked operation is achieved, the resonator is Q-switched and ample time is allowed for the photon density to reach a maximum, at which time cavity dumping

is initiated. For pulsewidths in the range of 75 to 120 psec repetition rates of up to 1 kHz have been reported[21]. Extensive research has been conducted on both YAG[22] and YLF[23] lasers in order to achieve high repetition rate. Currently, 1 kHz seems to be the performance limit because there is about a 1 msec recovery time after each cavity dumping step for these resonators to return to their mode-locked steady-state. Advantages of "all in ones" include stand-alone resonator operation which can perform with any choice of oscillator/dye laser system, optical independence from any master oscillator which is a desirable feature in adjusting the arrival times of pump and seed pulses at the dye amplifier. Disadvantages include a limited repetition rate and critical alignment of several active optical components in the cavity which are necessary for achieving good mode and short pulse operation. Newell et al.[21] have reported 1 kHz amplification of 150-300 fsec pulses in the range of 560-680 nm with a maximum energy of 50 μ J. The conversion efficiency for their system was 7%.

4.3. Copper vapor lasers

Copper vapor lasers (CVL) are pulsed lasers with output distributed between two wavelengths, 511 and 578 nm. A major advantage of a copper vapor laser is its repetition rate. Presently these lasers are available with repetition rates ranging between 2 and 32 kHz. CVL is inherently pulsed because of the metastable lower laser levels and therefore the optimum repetition rate is dependent on the lifetime of these levels. Typical commercial copper vapor laser outputs are 6 mJ at an optimized rate of 6.5 kHz in pulses which are 20 to 40 nsec wide. High ASE problems associated in pumping with CVL can be minimized by utilizing the well known bow-tie arrangement[8] shown in Fig. 3(a). Pulse energies of over 1 uJ were obtained in 100 fsec pulses at 5 kHz which corresponds to a conversion efficiency less than 1%. Since the two emission lines are visible nanosecond pulses any sum or difference frequency mixing techniques is not possible with CVL.

5. CONCLUSION

The recent advances in research on high powered, high repetition-rate laser systems, as discussed in this article, provide the impetus for a new generation of laser systems that will evolve into a general laboratory tool in the 1990's. Likewise, the potential for novel applications driven by the advantages provided by higher repetition rates will lead to new innovations and discoveries in science and technology.

6. ACKNOWLEDGEMENTS

I would like to thank the members of my group Joseph Dolce, Muhammad Saeed, and Baorui Yang for their contributions to the developments in my laboratory. The research carried out at Brookhaven National Laboratory under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy and supported, in part, by its Division of Chemical Sciences, Office of Basic Energy Sciences.

References

- [1] R.H. Page, R.J. Larkin, A.H. Kung, Y.R. Shen, and Y.T. Lee, *Rev. Sci. Instrum.* 58, 1616 (1987).

- [2] C.T. Rettner, E.E. Marinero, R.N. Zare, and A.H. Kung, *J. Phys. Chem.* 88, 4459 (1984).
- [3] "Short Wavelength Coherent Radiation: Generation and Applications", eds. D.T. Attwood and J. Bokor, A.I.P. Conference Proceedings No. 147, articles therein, (1986).
- [4] "Atomic and Molecular Processes with Short Intense Laser Pulses", ed. A. Bandrauk, Plenum Press, NY and London (1988).
- [5] J.H. Moore, C.C. Davis, and M.A. Coplan, "Building Scientific Apparatus: A Practical Guide to Design and Construction" Addison-Wesley Pub. Co., London, Chapter 6.8(1983).
- [6] I. Ben-Zvi, L.F. DiMauro, S. Krinsky, M.G. White, and L.H. Yu, *Nuclear Inst. and Methods*, in press (1990).
- [7] K.H. Drexhage, in "Dye Lasers" ed. F.P. Schäfer, Chapt. 5, Springer-Verlag, New York (1990).
- [8] W.H. Knox, M.C. Downer, R.L. Fork, and C.V. Shank, *Opt. Lett.* 9, 554 (1984).
- [9] G. Vaillancourt, T.B. Norris, J.S. Coe, P. Bado, and G. Mourou, *Opt. Lett.* 15, 317 (1990).
- [10] J. E. Murray and W. H. Lowdermilk, *J. Appl. Phys.* 51, 3548 (1980).
- [11] P. Bado, M. Bouvier, and J. Scott Coe, *Opt. Lett.* 12, 319 (1987).
- [12] M. Saeed, Dalwoo Kim, and L.F. DiMauro, *Appl. Opt.* 29, 1752 (1990).
- [13] X.D. Wang, P. Basseras, R.J. Miller, J. Sweetser, and I.A. Walmsley, *Opt. Lett.*, in press (1990).
- [14] A.J. Ruggiero, N. F. Scherer, G. M. Mitchell, G. R. Fleming, and J. N. Hogan, *J. Opt. Soc. Am. B* 8, 2061 (1991).
- [15] T. Juhasz, J. Kuhl, and W.E. Bron, *Opt. Lett.* 13, 577 (1988).
- [16] I.N. Duling III, T. Norris, T. Sizer II, P. Bado, and G.A. Mourou, *J. Opt. Soc. Am. B* 2, 616 (1985).
- [17] J. Dolce, B. Yang, M. Saeed, G. Scoles, and L. F. DiMauro, to be published.
- [18] A.J. Taylor, J.P. Roberts, T.R. Gosnell, and C.S. Lester, *Opt. Lett.* 14, 444 (1989).
- [19] D. S. Bethune, *Appl. Opt.* 20, 1897 (1981).
- [20] C. Rolland and P. B. Corkum, *Opt. Comm.* 59, 64 (1986).
- [21] V. J. Newell, F. W. Deeg, S. R. Greenfield, and M. D. Fayer, *J. Opt. Soc. Am. B* 6, 257 (1989).
- [22] I. N. Dulling and T. Sizer, *Proc. Opt. Soc. Amer.* annual meeting Seattle, WA, Oct.23, 1986 paper I - PD6
- [23] L. Min, Q. Bao and R. Miller, *Opt. Comm.* 68, 427 (1988).

Fig. 1. Schematic representation of a high repetition-rate, tunable, short pulse laser system. The dashed line between the oscillator and amplifier pump exists for optically coupled systems, i.e. regenerative amplifiers. The dashed boxes indicated optional extensions of some of these systems.

Fig. 2. Log-log plot of energy per pulse versus repetition rates for (a) nanosecond and (b) sub-nanosecond amplifier pumps. The small dashed line is for 1 watt average power and the large dashed line is for 10 watt. The abbreviations in the plot are; QS-Q-switched, pp-pulsed pumped, CD-cavity dumped, ao-acousto-optic, and RGA-regenerative amplifier.

Fig. 3. A block diagram of the BNL regenerative amplifier system. M1 and M2 are concave and convex resonator mirrors, PC Pockels cell, L cylindrical lens, A mode selector, P1 and P2 Brewster angle polarizers, WP1 and WP2 half- and quarter-wave plates, BS1 and BS2 5% beam splitters. The e^{-2} diameters in mm are indicated at various positions (the positions in cm are in parenthesis) in the amplifier.

Fig. 4. Fast photodiode output during regenerative amplifier operation including cavity dumping. Trace *a* is output from a photodiode viewing 1% resonator leakage through mirror M1 and trace *b* is photodiode output of amplifier output. Note that at the time of cavity dumping all the energy is extracted from the cavity (trace *a*) and emerges as a single pulse (trace *b*).

**DATE
FILMED**

2 / 18 / 92