A 200 W Average Power, Narrow Bandwidth, Tunable Waveguide Dye Laser

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Abstract—**A planar waveguide dye laser, driven by commercial xenon flashlamps with an average power output of 200 W at 50 pulse per second (pps) is described. Due to the planar structure, a narrow bandwidth operation down to 10 GHz has been obtained with a single grating arranged at grazing incidence. With this configuration, high overall efficiency up to 0.6 percent has been obtained, partially due to energy conversion of the broad-band emission spectrum of the flashlamps by circulating an appropriate dye solution between flashlamps and reflectors.**

I. Introduction

In the past few years, several groups have investigated the possibility of obtaining high average power from flashlamp-pumped dye lasers [1]-[8]. The motivation for using flashlamps as pumping light sources of the dye solution is inherent in an essentially simpler and lower cost system, with higher overall efficiency, as compared to laser-pumped dye lasers.

The attention of experimental investigations in this field has concentrated on three major aspects: 1) cavity perturbation due to variation of the refractive index of the solvent under the influence of heat induced by the pumping radiation and by shock waves; 2) reliability of the electrical circuits for flashlamp excitation and flashlamp lifetime [5], [6], [8]; 3) dye degradation due to photodissociation of the lasing dye, especially under UV excitation [9], [10]. Very little has been reported about tuning possibilities for high power emission, especially for those lasers which were operated at high energy/pulse.

Concentrating our attention on the possibility of obtaining high average power associated with narrow line emission, we started the construction of a high repetition rate planar waveguide dye laser [11], [12]. The planar structure for the dye cell takes advantage of the flashlamp-induced distortion and reflection from the walls to contain the laser light to the high gain region of the dye cell. In fact, the heat which is released by the absorbing molecules during the pumping process causes a refractive index gradient perpendicular to the cell walls, and the solvent itself becomes a planar selfoc structure. The laser in this configuration exerts a much higher gain as compared with conventional cylindrical cells, resulting in a strong superradiant output, even without any resonant cavity. It has also been demonstrated that the planar geometry is particularly suitable for narrow line tuning [13]. In the present laser, a grazing incidence arrangement has been adopted [14] for grating tuning of the cavity. By this simple method the superradiant output, which saturated the gain, could be induced almost completely in a spectral bandwidth of less than 10 GHz, with a wide flat tunability.

Another advantage of the waveguide configuration is the possibility of improving the efficiency by energy conversion of the pump photons emitted by the flashlamps, in order to obtain a better matching of the absorption profile of the lasing dye with the emission spectrum of the pump source [15]. By this method, a significant increase in power output has been obtained, even for those dyes, like Rhodamine 6G (R6G), which did not show any increase by energy conversion in conventional dye cells.

A six flashlamp system, driven by solid-state switching circuits has been built and tested. The design features and experimental results are presented, with a discussion of the technical choices adopted, and a critical analysis of the performance and capabilities of the device.

II. Design Features

A. *Laser Head*

The laser head consists of a slab cell, constructed by two sheets of glass with a useful area of 55 × 150 mm sealed together with appropriate spacers of 0.5 mm in thickness, as shown in the schematic drawing (Fig. 1). The dye solution flows transversely to the optical axis of the resonator. The laser light emerges as two beams which are collected and made parallel by two cylindrical lenses, placed with their foci in coincidence with the cell's exit windows. Fig. 2 shows a detailed cross section of the laser head construction. The dye enters in an expansion channel at the top of the dye cell, where the flow is made uniform by successive stainless steel nets. The bottom end is open and the dye is simply conveyed back into the reservoir. The dye cell is pumped by six ILC 7F6 flashlamps, accommodated in two rows, one on each side. The reflector profile is designed so that a sheet of cooling liquid of approximately 1 mm can surround the flashlamp cooling jackets. A thin glass plate is introduced

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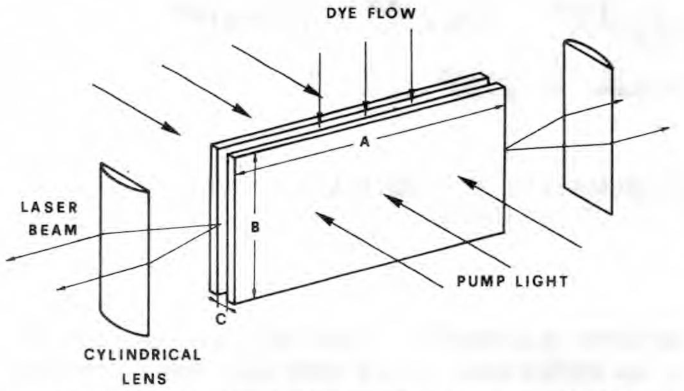


Fig. 1. Schematic drawing of the dye cell. Dimensions: A) 150 mm; B) 55 mm; C) 0.5 mm.

between the flashlamps and the dye cell, and the cooling liquid is distributed in such a way that a rapid flow can occur in a sheet of 1 mm in thickness, in contact with the cell walls. The cooling liquid of the external walls of the cell and the reflectors are flown through appropriate nozzles, and no sealing is necessary between reflectors and cell. In this arrangement, the removal of the reflectors for maintenance or flashlamp replacement is extremely simple. As in the case for the lasing solution, the liquid is discharged in an open chamber and conveyed back to the reservoir.

B. Cooling System

In order to avoid excessive thermal lensing, which can disfavorably compete with thermal waveguiding of the dye solution, it is essential to maintain a constant difference of temperature between the external cooling liquid and the dye solution. This criterion was simply accomplished by exchanging the heat of both dye solution and laser cooling in the same bath, which was provided by flowing tap water. The schematic diagram of heat exchangers and recirculating systems is presented as Fig. 3. The flashlamps were cooled independently by flowing deionized water in the cooling jackets.

In order to provide energy conversion, the cooling liquid in the reflectors could be replaced by a dye solution [15]. For this purpose, the flow system for the lasing dye and the reflector cooling solution were made identical. Two 40 l/min centrifugal pumps with a maximum pressure of 4 bar were considered more than appropriate to replace completely the external cooling sheet and the dye solution inside the cell between each shot at 50 Hz repetition rate. The flow loop was also provided with filters to eliminate bubbles and solid particles, and the speed could be regulated by means of bypass loops.

C. Electrical Excitation System

Each flashlamp was independently excited by switching a 20 μF capacitor (Bosch M.P. 5 kV) by means of high power thyristors. The electrical circuit is very similar to that used by Jethwa and Schäfer in their high power dye laser [6]. The modifications consisted in the use of commercially available components (switching thyristors: Ansaldo ATF 880 S 18, three in series for each flashlamp discharge circuit). The six flashlamps discharged a maximum total energy of 1000 J/shot, and were operated in the simmer mode by flowing a dc current of 40 mA in each flashlamp. The capacitors were resonantly charged by means of thyristors at a variable rate, up to 50 Hz, with a maximum voltage of 4 kV. The maximum energy/shot was limited by the maximum off-state voltage V_{DRM} and maximum rate of rise of the current of the flashlamp switching thyristors. In this condition, the flashlamps operated at less than 20 percent of the nominal explosion energy with an expected lifetime in excess of 10^6 shots. The maximum repetition rate is limited only by the maximum average power to be dissipated in the flashlamps.

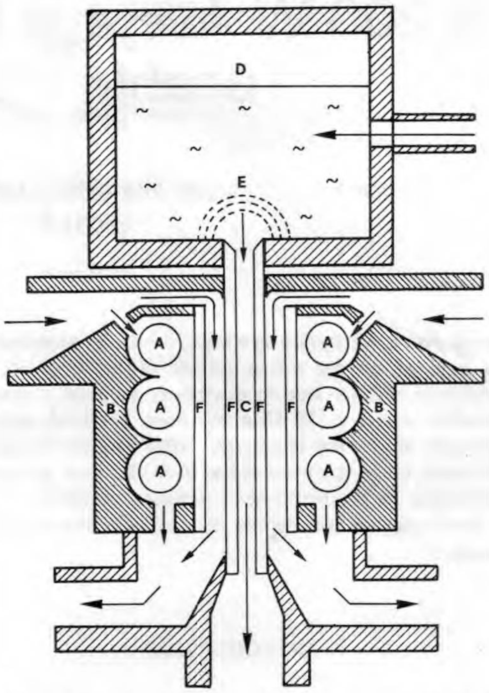


Fig. 2. Schematic cross section of the laser head. A) flashlamp; B) reflectors; C) dye cell; D) expansion channel; E) stainless steel nets; F) glass plates.

III. PERFORMANCE DATA

A. Single Shot Energy Output

Optimization of the energy output has been attempted, for R6G as the lasing dye in an ethanol solution, as a function of some of the operating parameters. The optical cavity consisted of a plane totally reflecting mirror on one side, and an uncoated BK7 parallel plate as the exit coupler. Broadband output energy has been measured by means of a Gentec mod. ED 500 piroelectric Jm. All measurements were made at a concentration of 8.10^{-4} M/1, with the addition of 0.1 percent of C.O.T. as triplet quencher.

It is interesting to note that at high pump energy, the laser exerted a strong superradiant pulse, due to double-pass amplification. When the exit plate was removed, a higher energy could be measured. Energy output/pulse is plotted, versus input energy in Fig. 4. The effect of energy conversion was tested in the present system by adding to the cooling water of the reflector a 2.10^{-4} M/1 concentration of 9 Aminoacridine (SIGMA Chemical Co. Grade II). This dye strongly absorbs

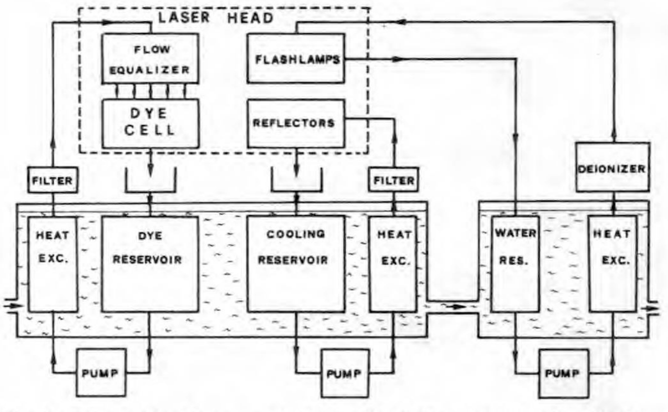


Fig. 3. Schematic diagram of the recirculating systems for the laser dye solution and for cooling of flashlamps and reflectors.

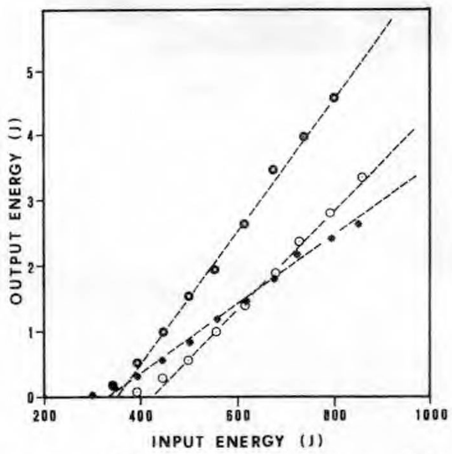


Fig. 4. Output energy/pulse versus input energy of the flashlamps. Laser dye solution 8.10^{-4} M/1 R6G. Heavy circles: 9-Aminoacridine (2.10^{-4} M/1) added to the reflector cooling water. Light circles: without conversion dye. Asterisks: same conditions with an output coupling mirror ($R = 10$ percent). Dashed lines are least square fits of each data group, showing threshold lowering and efficiency increasing by energy transfer.

the UV radiation below 430 nm, thus preventing photobleaching of R6G, and has an emission band between 440 and 510 nm, which matches reasonably well the absorption band of R6G. Its low cost and good water solubility played a major role in selecting this dye for use in a 30 l reservoir. Laser grade dyes, such as coumarine 102 or coumarine 6, have shown a better performance in a smaller device, and further work is programmed in this direction. In Fig. 4, the output energy/pulse when the 9-aminoacridine is added is also shown. It can be noted that energy conversion not only increases the overall efficiency (65 percent at maximum energy) by lowering the threshold, but also increases the differential efficiency. The increase in power output with energy conversion is more effective when the laser is operated at lower concentration in agreement with the behavior of conventional cylindrical dye cells [15].

The overall efficiency in the best conditions in our device was $\eta = 0.6$ percent. Further optimization is possible and is in progress. The effects of other parameters such as the reflector geometry, dye cell thickness, optical cavity configuration, and electrical circuitry for flashlamp excitation are still to be investigated.

B. High Repetition Rate

Testing of high repetition rate performance is the essential motivation of our experimental setup. The investigation of thermal perturbation related to the average power can be divided into two characteristic effects which may influence the thermal waveguide, and consequently, the laser output: a short term effect, by which each pulse is affected by perturbations induced by the previous pulse, and a cumulative effect, due to long term heating of the cell and dye solution. Perturbations of the optical quality of the cavity, induced by refractive index fluctuations, may result in power degradation, beam divergence or frequency fluctuations, and line broadening when the laser is tuned.

Despite the fact that the waveguide structure is very sensitive to temperature gradients which may rise during intense pumping rates, the laser output has demonstrated good thermal stability. In effect, the recirculating systems seem to be overdimensioned. In fact, a reduction of the flow rate from 40 l/min to 12 l/min for the laser dye solution, and to 20 l/min for the reflector cooling liquid does not affect the output power at maximum repetition rate. A dye flow of 12 l/min means almost exactly one full change of laser medium between two shots at 50 Hz repetition rate; a further reduction of flow rate results in a shot-to-shot power degradation. The average power output versus repetition rate is plotted in Fig. 5. A slight decrease in the average power output at high repetition rate seems to be due to a modification of the electrical parameters of the flashlamp circuits. As indicated in Fig. 6, by heating up the flashlamp at high repetition rate, the current pulse, and consequently, the light emission pulse becomes longer with a significant decrease in peak power. The fractional decrease in the pumping light energy, which is radiated in the portion of the pulse which brings the laser above threshold, is consistent with the decrease of light energy/pulse.

It is to be noted that the decrease in the peak power does not mean a decrease in the efficiency of the flashlamps, which on the contrary, has a slight increase. This effect was observed by other authors [7], but in their case the short pulse condition, and consequently, the lower laser threshold, leads to an increasing laser efficiency at higher repetition rate.

C. Tuning Characteristics

The peculiar characteristics of a planar waveguide dye laser is to emit light in two beams which originate from a relatively narrow window. As the exit window can be considered a narrow slit and each of the two lobes are essentially single transverse modes, the condition is advantageous for tuning the laser emission by means of a grazing incidence diffraction grating. The mounting scheme can be understood from Fig. 7. A holographic grating (Jobin Yvon 2400 lines/mm) was placed at an angle $\theta = 80^\circ$, and the first order was retroreflected by a totally reflecting mirror. Tilting of the mirror caused frequency tuning. With R6G at the same concentration used for broad-band operation, we have found a resultant bandwidth of 10 GHz and an almost flat tunability range be-

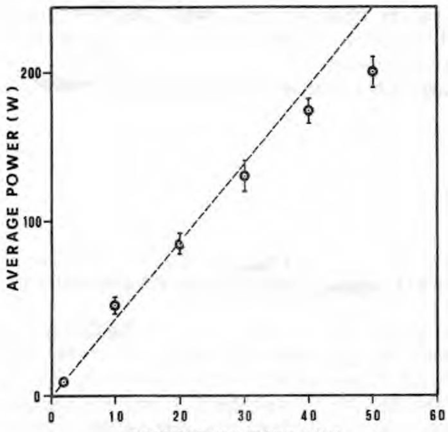


Fig. 5. Average power versus repetition rate. Dashed line is the expected value if the single-shot output energy were maintained.

tween 590-610 nm. Together with the narrow-band emission a wide-band background, due to double pass superradiant emission, was detected, but its integrated intensity was less than 1 percent.

Out of this wavelength range, the fluorescence to laser ratio increased up to 100 percent at the wavelengths shorter than 585 nm or longer than 620 nm. With narrow-band operation, the output energy loss with respect to the broad-band emission was less than 20 percent.

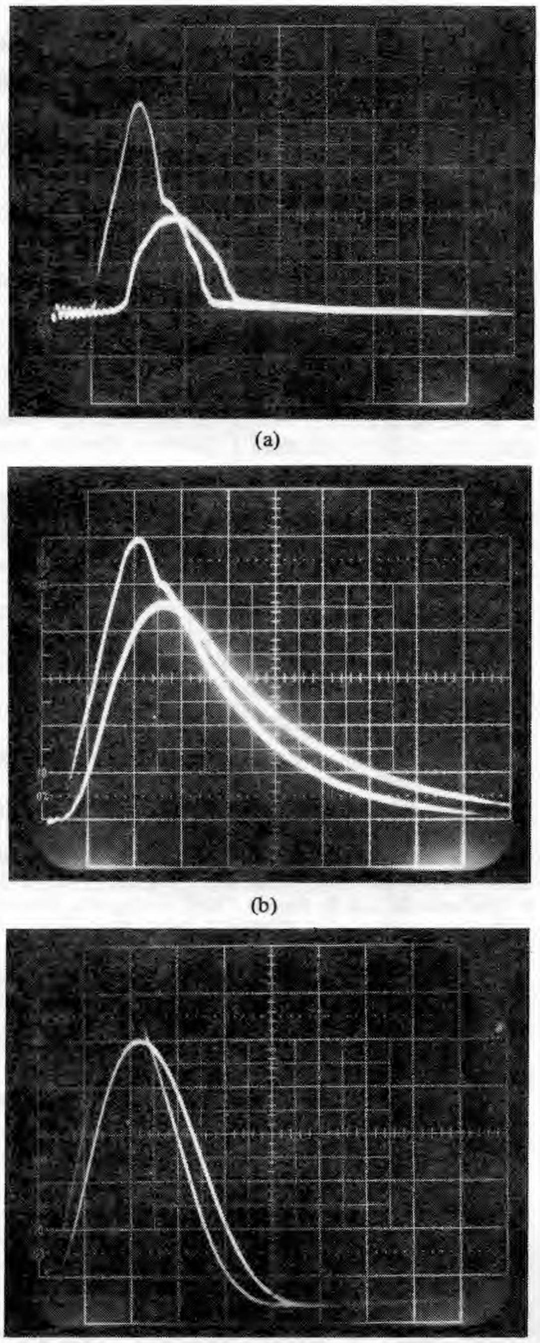
As the laser was operated at a high repetition rate, the frequency fluctuations become of the order of the linewidth. This occurs mostly because of the extreme sensitivity of the grazing incidence tuning technique to beam stearing, combined with the poor thermal quality of ethanol. We believe that better results can be achieved by using a water-ethanol mixture as a dye solvent.

IV. CONCLUSIONS

In conclusion, high repetition rate and good tunability of a planar waveguide dye laser have been demonstrated. An average power up to 200 W, by using an ethanol solution of R6G at 50 Hz repetition rate has been obtained. A good efficiency (0.6 percent) has been obtained even with relatively long pulses, allowing the use of solid-state switching techniques with inherent lower cost and higher reliability respect to high power thyratrons. The output beam shows good stability and good reproducibility of energy emission/pulse.

Frequency tuning has been conventionally accomplished with a grazing incidence technique by using a holographic grating. A linewidth of less than 10 GHz has been obtained. The power loss in the tunable arrangement with respect to broad-band emission was of 20 percent.

The system was not fully optimized, and we believe that by using better energy conversion dyes and by optimizing some parameters such as reflector geometry, cell thickness, and electrical circuitry, a substantial increase in efficiency can still be gained. This would increase flashlamp lifetime and decrease operating and manufacturing costs, which are the major drawbacks of high power dye laser.


(a)

(b)

(c)

Fig. 6. (a) Laser output, (b) flashlamp output, (c) discharge current in the flashlamps. Horizontal scale: 10 μs/div. In all the pictures, the higher trace is with laser at 1 Hz repetition rate, the lower at 50 Hz.

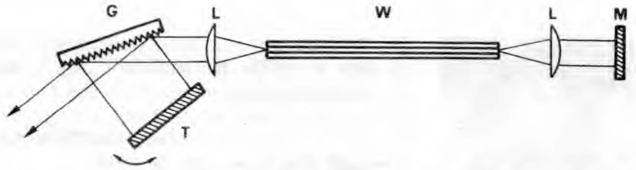


Fig. 7. Tunable arrangement: W) waveguide; L) cylindrical lens; M) totally reflecting mirror; G) grating: T) tuning mirror.

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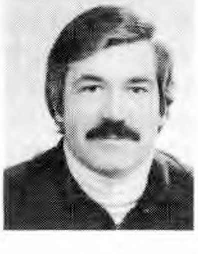

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