Def Sci J, Vol 34, No 1, January 1984, pp 57-70

Laser Sources for Underwater Applications

D. P. JUYAL

Instruments Research & Development Establishment, Dehra Dun-248008

Received 16 January 1984

Abstract. Blue-green lasers are finding potential use in underwater applications-both civil as well as military. An attempt has been made to review the present state-of art of the blue-green lasers technology and future plans for achieving the desired goal.

1. Introduction

All systems, namely radar, communication and imaging, etc. utilize a particular band of the electromagnetic spectrum right from x-rays through UV, visible, infrared, upto microwaves and radiowaves. The optimum performance of these systems is very much dependent on the propagation characteristics of the radiation in the medium. The medium may absorb the radiation or produce significant scattering thus limiting the maximum range attainable. External disturbances such as temperature, pressure changes may cause turbulance in the medium and hence the received signal or the image quality is degraded due to various noise factors.

Lasers have, however, tendered much greater ranges owing to extremely high power, small beam divergence, narrow line width and tunability of the operating wavelength. A comparative data as shown in Table-I for various light sources and lasers from which one can see that there is no match of lasers for its brightness and directionality. Laser gated imaging systems with high pulse repetition rate have been developed for variety of airborne and ground applications.

Eversince, the first series of practical laser devices were developed in early sixties for various airborne and ground applications, researchers looked for the use of lasers in underwater applications as well[1], which mainly included underwater ranging, communication and imaging. The systems which are currently under development are as under :

Radar —Short laser pulses transmitted by an airborne laser may be used to range a particular submerged platform or ocean bed by processing

Table 1. Typical Values for Brightness

Source	Power	Beam Divergence	Area	Brightness
Hg arc	10 KW	4π sr	1 Cm^2	1000 W Cm^{-2}sr^{-1}
Sun	4×10^{26}W	4π sr	2.5X10^{23} Cm^1	130W Cm^{-2} sr^{-1}
He—Ne Laser	10mW	3X10^{-3}rad	0.1 Cm^2	10^6W Cm - sr$^{2-1}$
Ruby Laser	10MW	5X10^{-3}rad	1 Cm^2	4×10^{11}W Cm^{-2}sr^{-1}
Nd. glass laser	4 GW	4×10^{-5}rad	10 Cm^2	2×10^{17}W Cm^{-2}sr^{-1}

the return signals. It is also possible to scan and search wide ocean areas using a high repetition rate laser.

Communication—There are two types of communication system under development (a). Tactical — An airborne pulsed laser may be used to establish contact and maintain a communication link with a submerged platform. (b). Strategic — A few number of satellites located at proper positions and equipped with suitable laser sources will provide world wide communication link with submerged platforms, say nuclear submarines, stationed in different parts of the globe.

Imaging —A short pulse, high repetition rate laser is used in conjuction with gated receiver to eleminate the back-scattered light thus providing greater range and resolution for viewing and imaging.

2. Lasers and the Underwater Window

Ocean water has very high transmission for sound waves (20 KHz—1 MHz), on which are based the well perfected sonar systems for the above mentioned roles. Sea water is, however, very absorptive for the entire electromagnetic radiations, except blue-green region of the visible spectrum.

Let us analyse the propagation characteristics of laser radiation in ocean water. The attenuation of laser radiation through water is governed by the following exponential law

$$I_d = I_0 e^{-kd}$$

where d = depth in metre

k = attenuation coefficient in m^{-1}

I, = normal incident power or irradiance in wattslm^2.

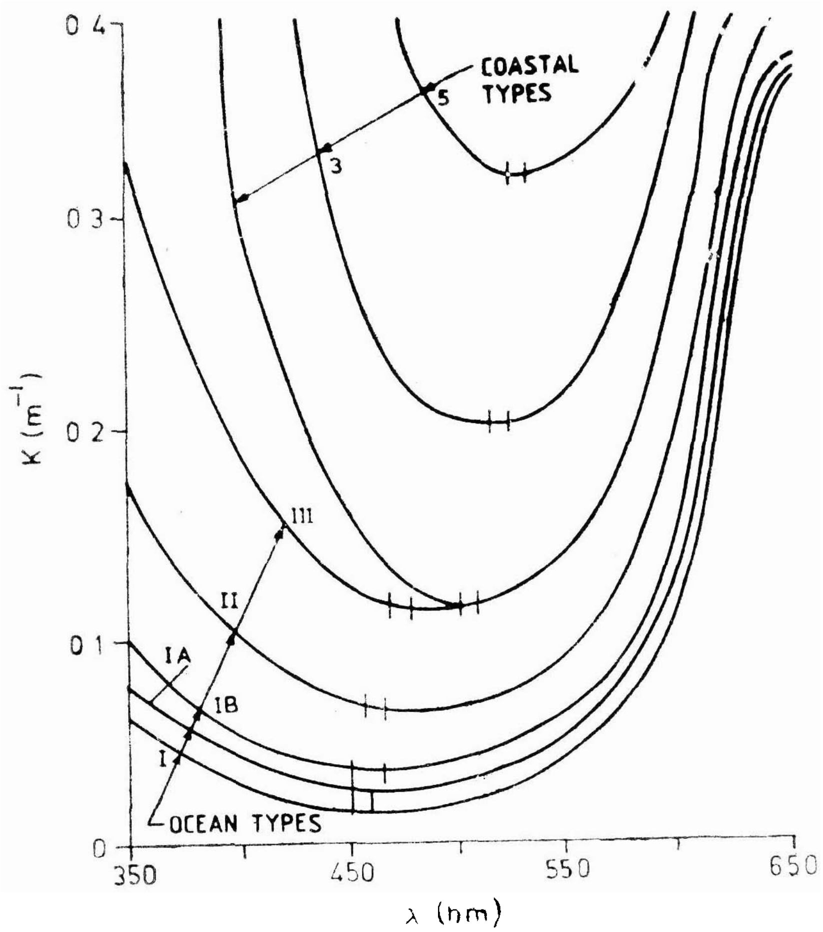

Figure 1. Attenuation, vs wavelength (λ) for various types of ocean water.

For a collimated light beam as provided by a low divergence laser, the main losses are due to selective absorption and scattering[2]. The scattering losses from single and multiple collisions with suspended particles in water amount to an increase in the laser beam divergence and hence spot size. Multiple scattering also tends to depolarize the beam and reduce the spatial coherence and hence one cannot fully take the advantage of high degree of spatial coherence and polarization available from lasers while operating in underwater environments.

The choice of a particular laser is greatly determined by the water absorption. Scattering does not depend significantly upon wavelength because of large size particles (1 to 100μ) present in water. The absorption study of pure water has shown a broad minimum in the blue-green region ie, 430 to 530 nm. Fig. 1 shows spectral attenuation behaviour for different types of ocean water[3&4]. It is clear from the curve that as one moves from deep ocean to coastal water the peak of the transmission window shifts to longer wavelengths. Thus the transmission window lies in the range from 430 to 470 nm for deep ocean water; the transmission window is 470 to 500 nm for cooler waters (e. g. North Atlantic) and it is in the region of 510 to 550 nm for coastal water. Various types of ocean waters with attenuation coefficient values, rate of power loss, optimum transmission window region and the possible laser sources to be used[5] is shown in Table 2. Values of attenuation coefficients K for four

Table 2. Underwater Windows For Various Ocean Waters

Water Type			Transmission Window			Lasers
Type	Location		K m^{-1}	Loss dB/m	nm	Type
Clearest Ocean	Open Ocean; tropical and Subtropical	Below Thermocline	0.02	0.087	430-470	Dyes, $He-N_2$ Trans Freq. Mixing
			0.03	0.130	440-480	Dyes, He-N, Trans Bismuth ?
Warm Ocean		Above Thermocline	0.04	0.170	470-490	Dyes, He-N, Trans Argon ion
Cool Ocean	Open Ocean, Temperate Subartic and Arctic		0.07	0.300	475-495	Dyes. $He-N_2$ Trans Cr-Vapor ?
Shelf	Continental Shelf	Surface to Bottom	0.10	0.430	490-510	Dyes Cu-Vapor
Coastal	Coastal, Relatively Shallow Water	Surface to Bottom	0.16	0.695	510-550	Dyes. F.D.Nd : YAG Argon, Neon
Very Turbid	Inshore Coastal Harbor and bay Water	Surface to Bottom	0.40	1.737	550-570	Dyes

Table 3. Wavelength Versus Power loss for 100m Jerlov Type II Ocean Water

nm	$K(m^{-1})$	Loss Rate *dB/m*	Loss dB
465	0.062	0.26	26
510	0.070	0.30	30
530	0.081	0.35	35
540	0.090	0.39	39

Table 4. Laser Power Attenuation for Different Depths and Various Types of Ocean

Depth	(Freqency Doubled Nd : YAG Laser) Attenuation Coefficient (m^{-1})		
(m)	$K = .1$	$K = .08$	$K = .03$
50	14 KW	36 KW	446 KW
100	90 W	670 W	99 KW
150	0.6 W	12 W	22 KW
200	4 mW	0.22 W	5 KW
250	0.27 mW	4.1 mW	1 KW
300	1.8 nW	0.4 μW	0.24 KW
500	2.8×10^{-16}W	8.5×10^{-12}W	0.6 W
800	2.6×10^{-29}W	2.2×10^{-22}W	6.5×10^{-5}W
1000	7.4×10^{94}W	3.6×10^{-29}W	18×10^{-8}W

specific laser wavelengths and the power loss for 100 meter path on Jerlov type II ocean water[5] is represented a Table **3.** Similarly Table 4 shows laser power attenuation for frequency doubled neodymium-YAG laser (532 nm) with incident power of 2 MW for different depths and ocean types. It may be observed that maximum attainable range in coastal water with frequency doubled *Nd-YAG* laser is not more than 50 meters.

3. Laser Parameters Requirements

Owing to extremely large powers and high degree of directionality, lasers can penetrate through several hundred feet of ocean waters and still the laser pulses can be detected remotely using high sensitive photomultiplier tubes. Hence main thrust will be on development of appropriate laser sources, detectors and optical tracking systems to perform various military and civilian functions.

The laser parameter requirements for underwater applications can be listed as under.

Wavelength 1(λ, transmission window 430-550 nm)

Depending upon the type of ocean water, a specific laser source can be selected. Dye lasers, being tunable, has advantage in certain cases.

Pulse energy (10-1000 mJ)

The pulse energy is governed by the attenuation coefficient and the desired penetration depth. Optical radar requires greater pulse energy as compared to communication due to double path travel. There is a secondary dependence upon the optical receiver area and sensitivity of the detector.

Pulse width (3-30 ns)

The range resolution for laser radar is dependent upon the laser pulse width. Vary narrow laser pulses are required for under water range measurement as well as for viewing and imaging.

Beam divergence (5-40 m *radians*)

The laser beam divergence is determined by the desired spot size on the target and sensor platform distance. Beam spreading by multiple scattering within the water and surface effects usually cause the effective spot size to widen.

Pulse repetition rate (10-1000 Hz)

For optical radar, the **PRR** is dependent upon the desired area of search (search rate is square nautical miles per hour), the altitude and velocity of the moving platform and the spot size. For communication application, however, high repetition rate laser pulses are needed depending upon the data rate.

Average power (2-20 *W*)

Average power.greater than *20* watt will be required to search larger ocean areas.

Efficiency (0.1 — 1%)

More efficient lasers will be required to have reduced size and weight for airborne lasers.

Bandwidth (1-10 Å)

A narrow laser line width is essential for increased signal-to-noise ratio to suppress the background noise. Narrow band pass filters (10-50 Å) are normally used in the detection system to cut **down** the background noise.

Beam polarization

Signal-to-noise ratio can be improved by using polarized beam. However, the usefulness is limited by the degree of multiple scattering.

4. Present Technology status of Blue-green lasers

The early lasers used in underwater applications were frequency doubled neodymium laser (532 nm) and argon ion laser (488 and 514.5 nm). Since then many new types of lasers have been developed with improved performance. A list of various lasers of interest for underwater applications is shown in Table 5. Out of all the lasers, three major types (Table 6) are in advanced stage of technology and hence will be discussed as under.

4.1. *Frequency Donbled Nd-YAG Laser* (532 mm)

The solid state Nd-YAG laser technology is fairly well developed. Pulse energy in the range of 5-500 mJ and PRR upto 100 Hz have been attained. Pulse width around 3-20 n sec and overall efficiency 0.1 to 0.4% have been achieved. Average powers are, however, limited to 10 watt because of distortion in the nonlinear crystal. Operational life (MTBF) is also limited to 10^7 shots due to flash lamp life and degradation of the crystal. Second harmonic generation (SHG) conversion efficiency in excess of 50% has been reported. Table 7 gives technology status for frequency doubled Rd-YAG laser.

4.2. *Dye Lasers* (430-450 *mm* Tunable)

Organic dye lasers are available with tunable wavelengths in the complete blue-green region and therefore specific wavelength can be selected to match the transmission window of a particular ocean type i.e., coastal water to deep ocean. Dye lasers are both flash lamp as well as N_2 laser pumped. N_2 laser pumped (337.1 nm) is preferred as it has rendered pulse energy upto 10 mJ at 3371.1 nm with pulse duration 4-10 n sec and PRR 60 to 1200 Hz having overall efficiency of 0.1%. A Coumarin dye 102 when pumped with N_2 laser gives laser pulses at 465 nm (Ah tunable). Average powers of 0.5 W are achieved which is limited by low efficiency of N_2 laser.

Flash lamp pumped dyes (Rhodamine 6G) has produced greater pulse energies (upto 400 mJ) and large average powers upto 15 W and PRR 500 Hz. Laser pulses are, however, long having width 0.2 to 1.0 m sec and hence useful mainly in communication. Life time is again limited by the flash lamp life (10^7 shots). Overall efficiency is 0.1 to 0.4%.

4.3. *Copper Vaponr Laser* (λ *501.6* mm)

Copper vapour laser has operating wavelength of 501.6 nm (at temperature 1500°C). Pulse energy is about 1 to 2.5 mJ having pulse duration 5 to 20 n sec. and PRR 3 to 20 KHz. Average power is about 10 W and operational life around 100 hrs. has

Table 5. Technology Status for Pulsed Rlue-Green Laser

Laser	Mechanism	λ nm	P.W. ns	P.E. mj	PRR Hz	ASE.P W	EFF %	Problem Areas
Argon Ion	Elec. Discharg Mul. Collision	488 514	10^4	0.5	10 109	0.7	0.02	P.W. Too Long P.E. & EFF. low for Practical Field use
Xenon Ion	Elec. Discharg	526 535 540	300	0.1	60	0.005	0.01	Long P.W. Low P.E. & EFF, low laser level high above Ground State
Neon	Transverse Elec. Discharge	540	5	0.1	300	0.03	10^{-3}	Low Average Power Theoretical EFF 0.1%
Freq. D Nd. Yag	Non Linear Shg in Cda.	532 .	15	5-500	1500	10	0.1 0.4	Damage & Heating of Non Linear Crystal Life of 10^7 Shots
Dye Flash lamp pumped	Vortex flo Wing Gas Lamp	Blue Green	10^3	R6G 400	500	R6G 40	0.2	Low P.W. For Radar use life Limited by Dye and Lamp.
Dye N_2 Laser Pumped	Transverse N_2 Elec. Discharge	Tun Able 465	5	0.1	1200	0.1	10^{-3}	EFF. Low for N_2 Laser 0 05% Limits Power Output.
Copper	Low Imped Elec. Discharge	510.6	5	2.5	3 K	11	1.0	EFF. Limited by Quenching Lower Laser Level & Elec. Impe-Dance; 1500°C Temp. Req.
Copper Halide	Low Imped Elec. Discharg	510.6	8	1.0	7 K 20 K	18	1.0	Low Impedance P. Supply Thermal & Materials Tube Dev.
Freq. Mixing Cs Vapor	Nonlinear Freq. Mixing	457	Two 1.079 u Photon Plus One 3.1 u Photon Demonstrated in Laboratory					58% Conversion EFF. Demonstrated in UV. EFF. Limited by Solid State Laser.
High Pressure Gas He-N,	He-N, Transfer	428	10	14	Single Pulse		1.5	Demonstrated 1-1/2% EFF. New Pump Source required
Dye, Co_2-Xe Plasma Pump	Recombination of Xe Plasma	588	10 100	25	Single Shot		0.4	30 kw Peak Power Obtained from 5.65 Co_2 Laser, Xenon Recombination Time Limts EFF
Vapor Phase Dye	Popop Dye N_2 Laser Pumped	Tunable	10	0.24			5.7 N_2 Dye	Thermal Stability of Blue-Green Dyes

Table 6. Present Blue-Green Lasers

Laser Type	Energ/Puls J.	PRF Hz	Wave L. nm	Pulse **W.** ns	EFF. %	Life	Remarks
Dye Laser	1						
Linear Lamp	**0.01–0.1**	**≤ 500**	**460–500**	500/50	**0.2**	~10^5 Shots	Pulsewidth can be Shortended by cavity Dumping **(3)**
Coaxial Lamp	**0.1**–1	≤ **10**	**460–500**	,,	**0.5**	~10^4 Shots	Lifetime Limited by Lamps and Dyes
Vortex Stab. Lamp	**0.01–1**	**≤ 103**	**460–500**	,,	**0.2**	**≥ 107** Shots	**EFF.** Increase Unlikely
Copper Laser Metallic	**0.002–0.01**	**103–104**	**510.6**	~10	**0.7**	~100 Hrs	Copper Lasers have Limited Pulse Energy **Increase** to Joule Level Unlikely
Halide	0.001	**104**	**510.6**	**10**	0.3(2)	> **100** Hrs	
Doubled ND^{+3}: YAG	**0.01**–1	**10–100**	532	**20**	**0.2**	**10^7 Shots**	Lifetime limted by Lamp Degradiation and Doubling Crystals; Surface Cooling of Laser Rod Makes High Average Power at **532** nm Unlikely to Achieve.

Table 7 Frequency Doubled Nd : YAG Laser 532 nm Technology Status

1978	1980
YTM MODE	P_{pK} – 1 MW (532 nm).
P_{pK} – 6 MW (1.06μm)	PRR – 40 Hz.
P_{pK} – 2.5 MW (532 nm)	
P_E – 40mJ	Using 2 lasers and by multiplexing – 80 Hz.
Pulse-width – 6 nSec.	
PRR – 50 Hz.	Further scaling – 160 Hz.
EFF. – .5%	Efficiency – .5%

been achieved. Copper vapour laser still needs lots of engineering efforts to make it practical device for field use.

5. Future Blue-green Laser (BGL) Sources

The three main types of lasers viz. frequency doubled Nd-YAG, dye lasers. and copper vapour laser are the potential candidates for underwater applications as these meet some of the primary requirements. However, all the three lasers still have short-comings in one or more ways. Efficiency and operational life are poor and it appears there is no chances of further improvement upon these parameters. Frequency doubled Nd-YAG lasers have been installed on airborne platform in the past and a dye laser of more than 100 W average power with pulse compression is presently under development for field use. Copper vapour laser although most promising has not yet attained the desired pulse energy levels and operational life.

Heat dissipation is the main problem in Nd-YAG and dye lasers. The most demanding application of Blue-green lasers seems to be for space-based lasers that would transmit strategic communication signals to submerged platforms, such as nuclear submarines. Lasers for this application should have output energy of more than 10 Joules and PRR of at least 100 Hz, because the lasers will be placed in the satellites. They must be highly efficient and should have sufficiently longer life (> 10,000 hrs).

To attain the desired lasers performance, the laser medium of choice now seems to be a gas directly excited by an electrical discharge. Rapid gas flow can be used effectively to remove excess heat from the laser medium via an external heat exchanger and a gas recycling system to replenish the gas supply. Further, to obtain maximum energy storage and conversion efficiency, molecular lasers rather than atomic are preferred. At present, work is being concentrated on two types of molecular lasers which are likely to meet most of the above mentioned requirements. One is Xe Cl (λ 308 nm) which requires frequency shifting to Blue Green region and the other is Hg Br (λ 502, 504 nm). Some of the salient features of these two lasers and their technology status have been discussed below.

5.1. Xe *Cl UV-Excimer* Laser

Xe *Cl* excimer laser[6-9], produces UV radiation at 308 nm. The excitation may be either *UV* preionized, X-ray-ionized or e-beam sustained. Pulse energy upto 5 Joules has been obtained with PRR of 1000 Hz. Efficiency around 1% has been achieved which is likely to go upto 2-3% in the near future.

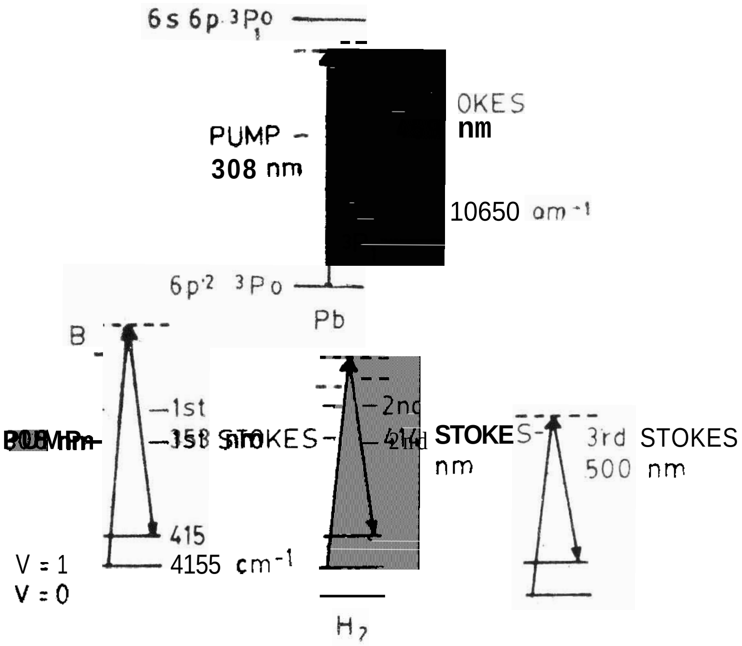

Figure 2. *XeCl* **Raman laser** in H_2 **gas.**

Down conversion of the Xe *Cl* 308 nm output by stimulated Raman scattering process in ***Pb*** vapour (temperature 1200°C) has produced wavelength in the Blue-green region at 459 nm with 50% conversion efficiency (Fig 2). With H_2 as Raman medium three consecutive steps are required to arrive in the blue-green region at 480 nm Fig. 3

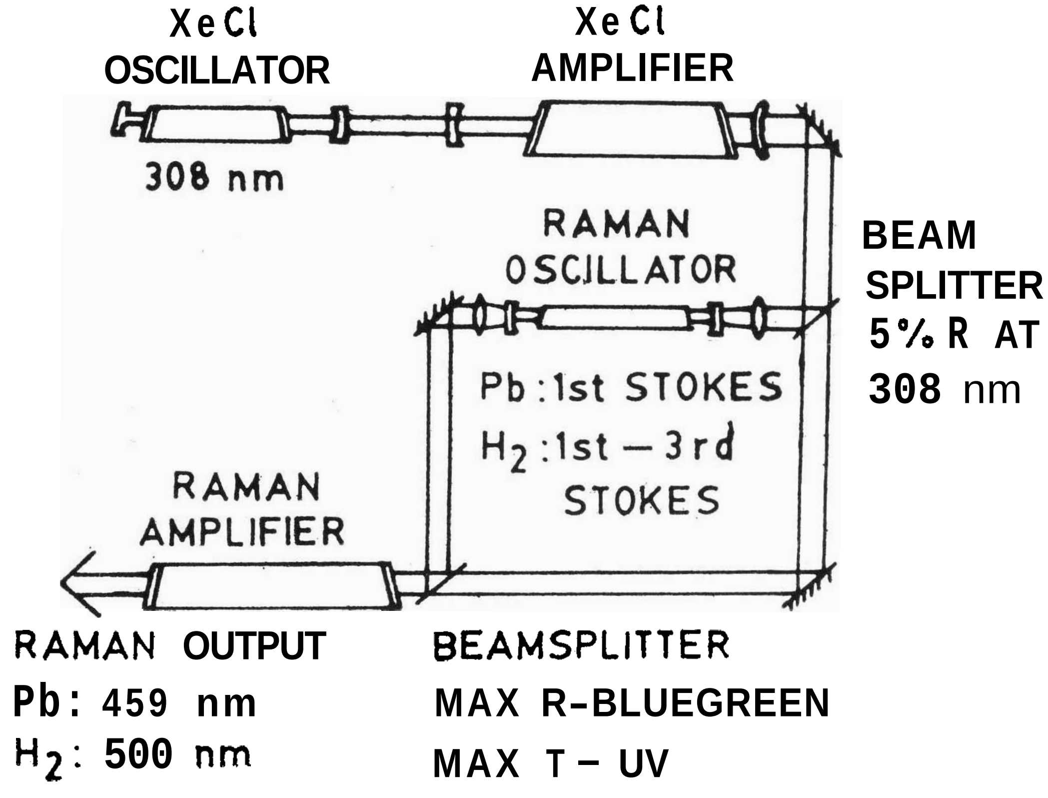

Figure 3. *XeCl* Raman laser. MOPA **system**

shows a master oscillator power amplifire (MOPA) system for *Xe Cl* Raman laser in order to boost up the Raman wavelength.

5.2. *Hg Br Dissociation Laser*

The other laser actively being considered for blue-green region is the murcuric bromide (*Hg* Br_2/*Hg Br*) laser$^{10-12}$ excited by an electric discharge. This laser has the advantage of directly operating in the blue-green region between 502 and 504 nm involving no frequency down conversion like Xe *Cl* laser. The schematic energy level diagram for this laser is shown in Fig. 4. It is important to note that the parent molecule i.e., *Hg* Br_2 recombines after dissociation. E-beam sustained discharge produced around 10 Joules pulse energy with an efficiency greater than one percent. Long operational life is yet to be achieved.

For communication, it is important to use a narrow laser line width matched to the band pass of an interference filter. That way, solar background noise can be effectively cut down. Both the *Hg* Br and the down converted Xe *Cl* lasers have been operated in this way. Table 8 presents the typical characteristics of *Xe Cl* and *Hg Br* lasers.

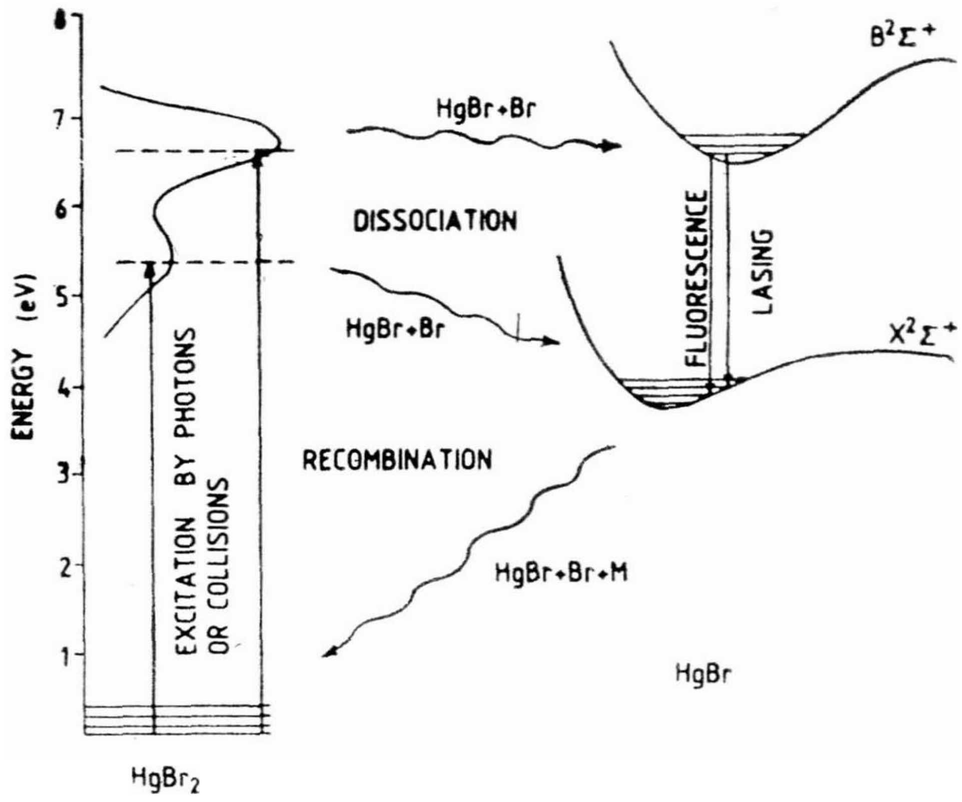

Figure 4. Schematic energy level diagram for *Hg* Br_2/*Hg Br* dissociation laser

Table 8 Two Types of Blue-Green Lasers for Future Underwater Applications
***XeCl* Raman** Lasers (*XeCl* Laser a **308** nm)

Raman medium	**XeCl** laser **output** (J)	Laser **Eff.** (%)	**Raman** output (J)	Overall Eff. (%)	PRR	Operational life
Pb **(459** nm)	1.0	1.0	**0.4**	**0.4**	**1000 Hz**	**10^7 shots**
	4.5	2.0	–			
H_2 (500 nm)	0.05	—	0.01	0.2		

Tunable operation **458** — **460 nm**

Line width — **0.015** nm

Hg BrHg **Br_2** Dissociation Lasers
(Δλ – 502 – 504 nm)

Discharge **Type**	Laser output (J)	Overall Eff. (%)	Vol. Eff. (J/1) amagat.	**PRR**	Operational life
UV–**preionized**	**0.09**	1.1	1.0	**100Hz**	Long operation
	0.36	**0·3**	**0.5**	**in** small device	time yet to be achieved.
X—ray preionized	1.75	1.4	0.7		
E—beam sustained	**9.8**	1.8	1.0		

Tunable Operations **495** – **505** nm

Line width **0.05** nm

2 – 3 yrs time

Average Power 100 – 1000 W

Eff. – >%

Operational life – Several hundred hrs.

PRR – 1000 Hz.

Immediate Applications – Military and Civil both.

6. Conclusion

Over the past few years enough head way has been made in the blue-green laser technology. It is hoped that in coming few years **well** perfected devices will emerge with average powers of 100 to 1000 watts and efficiency better than one percent. This first generation device may have operational life **upto** several hundred hours. Some military and civilian applications can be foreseen. To reach operational life more than 10,000 hrs, will require much more concerted efforts towards engineering and technological aspects of such devices.

References

Duntley, S. Q. 'Underwater lighting by submerged lasers and incondescent sources'. Final report S 10 Ref 71–1, ONR contract N00015-69-A-0200-6013, June 1971, p. 5.

2. Duntley, S. Q. JOS.4 53, (1963), 214–33.
3. Jerlov, N. G., 'Optical Oceanography' (Elsevier Amsterdem), 1969.
4. Jerlov, N. G., 'Optical studies of ocean waters'. Report of Swedish Deep-Sen Expedition, 1947–1948, Vol. 3 Fascl (Gateborg, 1951).
5. Farguson, G. D., Ocean Optics *SPIE Proc.*, 64 (1975), 150.
6. Champagne, L. F., *Appl.* Phys. Letters, 33 (1978) 523.
7. Rothe, D. E., West, J. B. & Bhaumik, M. L., *IEEE J QE* 15-No. 5, (1979), 313.
8. Miller, J. L., Dickie, J., Davin, J. & Kan, T., *Appl.* Phys. Letters, 35 (1979), 912.
9. Taylor, R. S., Alcock, A. J, & Leopold, K. E., Optics Letters, 5 (1980). 216.
10. Schimitschek, E. J., Celto, J. E. & Trias, J. A., Appl. Phys. Letters, 31 (1977). 608.
11. Schimitschek, E. J., Celto, J. E. & Trias, J. A., Optics *Letters*, 2 (1978). 64.
12. Burnham, R.. Appl. Phys. Letters, 33 (1978), 156.