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# Blue Green Lasers and Their Military Potential

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**Abstract.** An overview of the state of art regarding the Research & Development of lasers in the blue green region of the spectrum is presented. Possible application of these lasers in the area of underwater detection, ranging, and submarine communication, is discussed.

## 1. Introduction

Most of the major scientific discoveries in physics have been exploited by military people for either offence or defence and laser is no exception. Use of laser in ranging, tracking, and weapon guidance is well known. More recently, interest has been generated in laser communication with submersible objects giving rise to an intense activity in the development of specific new laser sources suited to this particular role[1-4].

Radiation in the blue green region of the spectrum has very good transmission in water[5]. Lasers operating in this region, therefore, have potential applications in the area of detection, communication and ranging of submersible objects in the coastal and deep sea waters. Possibility of global communication with submarines at high data rate is seriously being pursued[3]. In this paper it is intended to take an overview of the *state-of-art in* the development of Blue Green Lasers and to discuss their present and futuristic uses for military purposes.

## 2. Laser Sources in the Blue Green Region

The transmittance of water in the visible region of spectrum[5] is shown in Fig. 1. It is seen that there is good transmission in the region 0.42 to 0.52 $\mu m$ in clear water (Fig. 1, curves a, b) and that the peak transmission shifts to longer wavelength for turbid water (Fig. 1, curves c, d). The curves in Fig. 1. give only a general trend. For any

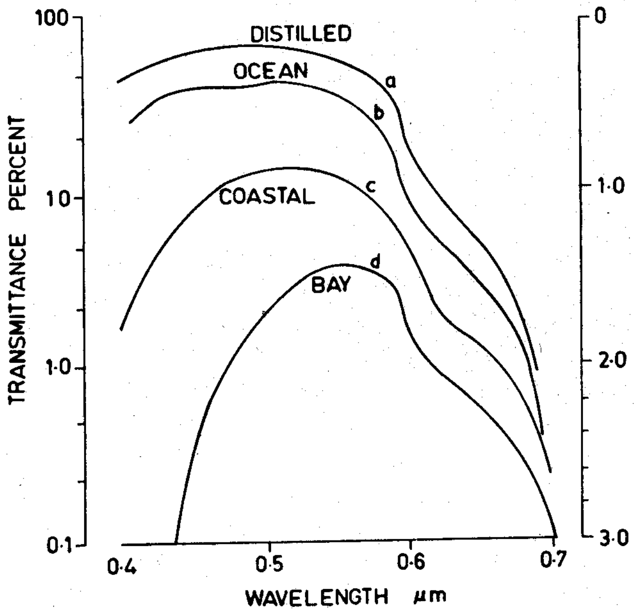


**Figure 1.** Transmittance of sea water.

specific region of sea, accurate charts have to be made by experimental observations which costs both time and money. This is particularly important for shallow coastal areas where depth of penetration is influenced by turbidity. The increase in turbidity enhances scattering and results in a decrease of light transmittance and a shift in the wavelength of maximum transmission. As a rough estimate one can consider that a ten metre layer of clean ocean water will transmit about 50% of incident radiation in the Blue Green region.

The spectrum of commercially available lasers in the range[6a] 0.2 to 2/$\mu m$ is shown in Fig. 2. It is easy to see that a variety of laser sources are available in the 0.4-0.6

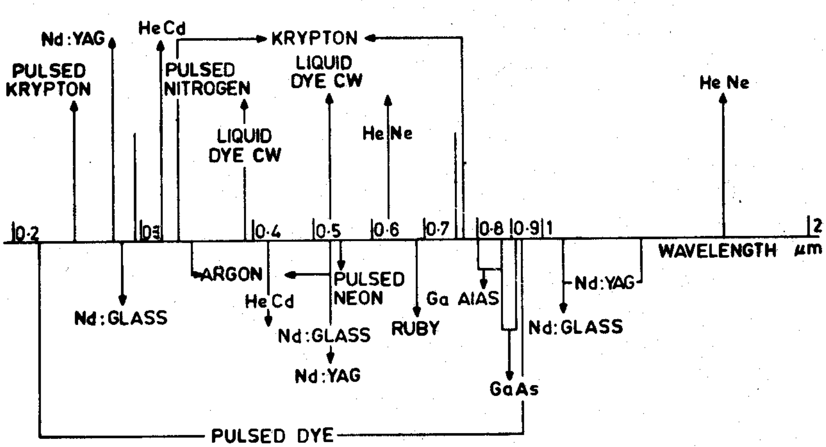


**Figure 2.** Spectrum of commercially available lasers in the range 0.2 — 2$\mu m$.

$\mu m$ region some of which are direct sources like the *Ar* ion or the *Kr* ion, while others give the radiation indirectly i.e. second harmonic of 1.06 $\mu m$ *Nd YAG* and liquid dye lasers pumped either by flash lamp or by uV sources like $N_2$ laser or the rare gas halide excimer lasers. In addition there are metal vapour lasers utilising the excitation of copper vapour or the cadmium vapour. All these are well documented lasers but suffer from the deficiency of low electrical to optical efficiency and relatively poor operating life. Poor life results from either the degradation of laser medium or the operating life of flash lamps or both. To meet the specific need of certain applications like satellite to submarine communication, R & D effort is now on to develop Blue Green Lasers with high power, high efficiency, and long life required for space-borne devices.

### (i) *Rare Gas Ion Lasers*

Argon ion and krypton ion lasers are the common commercial types which use high current electric discharge and give upto a few watts of CW power. Argon ion laser gives upto ten wavelengths in the Blue Green region[7] (455-529 *nm*) and is normally rated by the max power level typically produced by six simultaneously lasing wavelengths from 514.5 nm to 457nm. Commercial power levels vary from less than 100 mW to over 15 watts. With intracavity wavelength selection, these can be made to lase on any single line. Most prominent wavelengths are 514.5 nm (green) and 488.0 nm (blue). At either line one can get 30 to 50% of the rated multi-line power. Using *BeO* plasma tubes, operating life upto 10,000 hrs is possible.

Krypton laser has prominent lines in the red region but it lases over a very wide range of the visible spectrum (462 nm to 676 nm). In the blue green region however, its output is comparatively smaller in relation to the Ion Argon laser of similar size.

### (ii) *Metal Vapour Lasers*

Lasers of this type give radiation in the Blue Green at 441.6 *nm* (*He Cd*) and 570, 578 nm (*Cu*). The commercial versions of *He-Cd* have output upto 40 mW but laboratory prototypes upto 100 mW have been demonstrated[8a]. Operating life upto 5000 hrs can be expected. The copper vapour lasers are available upto 10 W average giving 2 mJ, 5 KHz, 30 ns pulses with operating life upto 200 to 300 hrs (1000 hrs is possible at reduced average power upto 1W). These high power versions require water cooling and are relatively costly compared to the *He-Cd* by an order of magnitude[8b,9a].

### (iii) *Solid State Lasers*

Second harmonic generation from *Nd* doped *YAG* or glass gives radiation at 532 nm which lies at the edge of the transmission curve (Fig. 1). Very large powers are available from these sources by using oscillator amplifier combination. $Q$ switched peak powers in the range of Gigawatt and pulse energy in the normal mode upto 100J is possible. $Nd+YAG$ lasers can be operated in both CW pulsed modes-even compact miniature versions are avilable giving a few $m$-joules of pulse energy in $Q$-switched mode and weighing only about 100 gm. The life of these lasers depends on the operating life of replaceable flash lamps. Electrical to optical efficiency is 2-3 per cent. Output can be varied from truly CW to pulses of 0.1 ns duration. With mode locking a pulse rate of 1 GHz can be achieved. In the Blue Green region the *SHG Nd YAG* can given upto 5W average at 532 nm with a 10W $TEM_{00}$ *Nd YAG* laser[10].

### (iv) *Liquid Dye Lasers*

Dye lasers are available in the spectral band covering near UV to near IR and are characterised by the capability of tuning over a wide range. Both CW and pulsed powers are available. The dyes can be pumped by *Ar* or *Kr* laser (for CW) and $N_2$ laser (330 nm), *Nd YAG SHG* (532 nm) or *Xe* flash-lamps for pulsed operation. Depending upon the absorption spectrum for the given dye, suitable pumping source can be chosen. Most of the dyes can however be pumped in the UV band to obtain the characteristic fluorescence spectrum of the dye. Recently high power excimer lasers, giving output in the UV band, have been used for pumping the dyes. Very large peak powers (upto MW) are possible in the pulsed operation though average power is larger in the CW mode. Pulse widths from microsec (in normal mode) to picosec (in mode locked operation) are possible.

A number of dyes are available which can give radiation in the blue green region. A recent listing[11] by a commercial firm shows more than a dozen dyes which lase in the blue green. Majority of these can be pumped by either of the four ways: ie. (a) *Ar*, *Kr* laser, (b) $N_2$ laser, (c) flash pump, and (d) *Nd YAG SHG*. With flash pump, pulse energies upto 2 to 4J at 10 Hz with an input of 400J can be obtained in the wavelength region[8c] 460-510 nm. Excimer lasers, *Kr F* at 248 nm and *Xe Cl* at 308 nm, when used for pumping dyes can give blue green output upto 20-40 mJ per pulse and upto 4W average[8d] at 100Hz.

### (v) *Blue Green Lasers Based on Excimer Complex*

In certain high pressure gases there are molecular complex in which the excited state is bound and the ground state is either totally unbound or only weakly bound. When one of the molecules in this complex goes to the ground state, it dissociates on picosec scale. Some of the most efficient near UV lasers are based on this principle using rare gas halides or metal halides as gaseous medium[12].

For the specific purpose of satellite to submarine communication where the requirements for the laser are very demanding two special types of excimer lasers are being developed[4]. One is the Raman shifted *Xe Cl* laser and the other is the $Hg_2$

*Br/HgBr* dissociation laser. Theselasers are designed to give multi joule output (1-10J pulse) at a rep rate exceeding 100 *Hz* with high efficiency (> 1% overall) and long operating life (MTBF > 10,000 hrs).

*Xe Cl* laser has been operated to give 5-10 J per pulse at 308 nm with 2-4% efficiency utilising X-ray preionisation or electron beam pumping. A very narrow line width of 0.015 nm is possible with injection locking and more than a million shots can be obtained before the power drops to one half. To obtain output in the blue green, the UV output at 308 nm is down converted to 459 nm in single step Raman shift in lead vapour and to 500 nm in 3 step process in molecular hydrogen. Stimulated Raman conversion to 459 nm has been demonstrated with overall efficiency of 40 to 50%. The lead vapour Raman active cell however has to be operated at 1200°C to 1300°C. Long time operation of this cell is still a problem. The hydrogen Raman medium however can be operated at room temperature and net efficiency of 30% for the third stokes radiation has been observed. Raman down conversion of the UV to blue green is an area of current interest and experimentation is in progress to improve the performance.

The *HgBr* dissociation laser giving output at 502 nm and 504 nm is the most promising of the high power blue green lasers. Its operation (Fig. 3) is similar to the

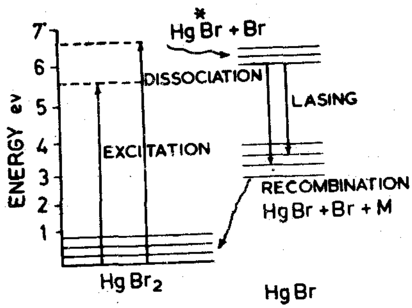


**Figure 3.** Energy levels for the *Hg Br₂/HgBr* dissociation laser.

rare gas halide excimer in which the excited state is strongly bound while the ground state is only weakly bound. However the difference lies in that the ground state *HgBr* does not dissociate but rather combines with bromine atoms to form $HgBr_2$ with a high probability. Pumping is through the dissociation of the stable molecule $HgBr_2$ by electron impact in the electric discharge. Using UV preionisation laser output upto 1J/liter with 1% overall efficiency in a 100 cm³ volume has been obtained. Line width of 0.05 nm with injection locking is possible. The laser medium is corrosive but an operating life of million shots to half power is available. Further development is aimed to upscale the pulse energy, efficiency and operating life.

## 3. Applications

### (i) *Detection and Ranging of Immersed Objects*

As an alternative to the ultrasonic radiation, the blue green radiation could also be used for the detection and ranging of underwater objects. The possible advantages can be compactness of transmitting and receiving systems and also narrower beams for better spatial resolution.

An estimate of the range capability can be made from the attenuation of the beam with distance which is given by

$$P_1 \, e^{-ax} = P_2 \tag{1}$$

where $a$ is the attenuation coefficient, $x$ is the distance transversed by the beam and $P_1$,$P_2$ are the incident and received powers respectively. An estimate of $a$ is given by the transmission curve (Fig. 1). Considering that 10 m traversal reduces the beam to 50%, we set $a = 0.07$ per meter.

If the beam is sensed with a detector with sensitivity $10^{-6}$ watts the maximum length of traversal for a beam of 1 $MW$ power would be 400 meters. In actual situation, there is a spreading of the beam as it travels and also the size of the detector is smaller than the size of the beam at receiver. Further, for a target to be ranged or detected, its reflecting characteristics have also to be taken into account. All these factors would further limit the range considerably. If $r$ is the target reflectivity at the wavelength of interest, $R$ is the distance of target and $d$ is the diameter of the receiver aperture then :

$$P_2 = P_1 \, e^{-2aR} \, \frac{r \, d^2}{16R^2} \tag{2}$$

It is assumed that both transmitter and receiver are under water and the beam size on the target is smaller than the reflecting area and that the reflected energy spreads in the inverse square manner. However, if the reflected energy spreads in a cone of $\theta$ radians then

$$P_2 = P_1 \, e^{-2aR} \, \frac{r \, d^2}{R^2 \, \theta^2} \tag{3}$$

Taking $P_1 = 10^6 \, W$, $P_2 = 10^{-6} \, W$, $r = 0.4$ and $d = 2$ cm, we get $R = 60$ m from Eqn. (2).

Ideally the diffraction limited laser beam has a beam width dependent upon the cavity parameters and a divergence $\theta$ governed by diffraction effects. But in a scattering medium like water there is additional spreading due to scattering from suspended and dissolved particulate matter in the medium. Therefore a laser beam travelling in sea water would experience greater scattering losses as well as greater divergence. The exact value of divergence would however depend upon the extent and size of the particulate matter present in the medium but one could typically consider a divergence $\theta \sim 10$ m. rad in clear sea water as opposed to $\theta \leqslant 1$ m. rad in a homogenious medium like glass.

With $\theta = 10$ milli rad, Eqn. (3) gives

$R = 100$ m

With the existing technology, it is possible to obtain laser beam in the Blue Green region with peak power over a megawatt and pulsewidth from a few nanosec to a microsec at pulse rate upto 100 Hz corresponding to an average power of 4-5 watts.

At 1 ns per 30 cm of travel the to and fro time of travel for a 100 m target distance would be 60 ns and a pulsewidth of $< 1$ ns would be desired if a range resolution of $\sim 1$ m is required. For such a situation, a 1 MW beam of 1 ns duration at 1000 Hz would only correspond to an average power of 1 W.

Underwater detection and ranging upto 100 meters is thus a feasible proposition using the available blue green laser which may either be a *Q*-switched *Nd YAG SHG* system or UV laser pumped dye laser in the pulsed mode. Sub-nanosec pulse width can be obtained with mode locking.

### (*ii*) *Underwater Photography*

Recognition of underwater objects should be distinguished from detection or ranging. For recognition one needs information on the shape, size and distinguishing features of the object. For underwater illumination of the object blue green laser can be used. The requirements for estimating possible range include among other things, the sensitivity of the camera used for acquiring the image. One would expect this range to be smaller than the range for detection.

Photographing the objects underwater can be done either passively or by using artificial illumination. In the latter case one may use white light sources like flash bulbs or pulsed laser sources in the blue green. The advantages of using pulsed blue green laser would be that (i) short time high spectral brightness exposures can be given, and (ii) range gating can be adopted. Use of blue green laser will increase the availability of light in the desired band. The camera also will work in the high sensitivity region of its spectral response. When CW laser is used for photography, radiation around 500 nm is a good choice. Orthochromatic and normal panchromatic emulsion have sensitivity around this wavelength[13] (Fig. 4).

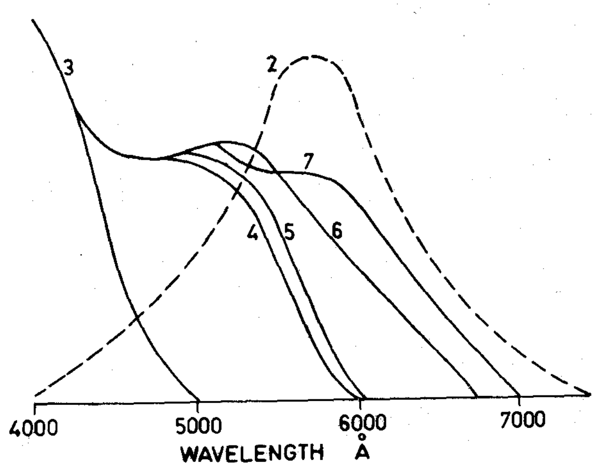


**Figure 4.** Sensitivity of different photographic emulsions over the visible spectrum (2)—Sensitivity of eye, (3)—Ordinary blue sensitive emulsion, (4)—Slow orthochromatic, (5)—Fast orthochromatic. (6)—Normal panchromatic and (7)—High speed pan emulsion with increased red sensitivity.

Fibre optic cables have recently been used for transmitting the data from the Submerged sensor to the monitoring station. These cables have the advantage of small size and less weight in comparison to the conventional coaxial cables for the same bandwidth capability. The advantage is particularly significant for large bandwidth video transmission.

The development of a system using active imaging with blue green laser and image transmission with fibre optic cables should be a step ahead from the conventional techniques.

## (*iii*) *Coastal Ocean Depth Survey*

Sea bed topography of shallow coastal areas can change within a few years after a bathymetric survey. This can happen due to erosion, growth of coral reefs, or submarine positioning. Accurate depth surveys are therefore needed from time to time for updating the depth charts.

Recently wavelengths 1.06 micron and 532 nm from a frequency doubled *Nd YAG* laser have been used for providing a quick depth chart[8e]. Both the IR and green beams from the aircraft borne laser are directed at sea surface. Most of the IR is reflected at the sea surface, while the green beam penetrates the water and is then reflected from the ocean floor. Water depth is inferred from the delay between the return of the two pulses to an airborne receiver (Fig. 5).

Coastal areas are characterised by turbid water conditions and therefore penetration is smaller compared to nearly clear water conditions of open sea. However, even in turbid water regions depths upto 30 m with one meter resolution should be measurable with a short pulse laser giving 1W average output. Larger output *Cu* vapour laser, giving 10W average output in the blue green (510 nm), could replace the 532 nm beam. This should be able to measure larger depths.

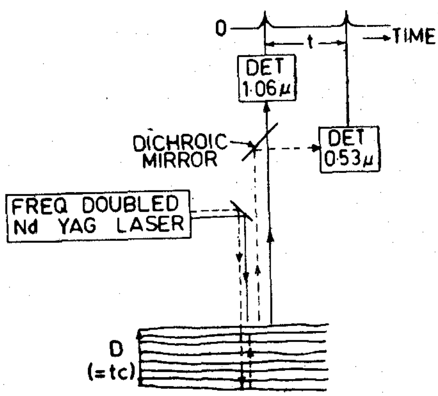


**Figure 5.** Schematic arrangement for sea depth profile measurement.

### (*iv*) *Aircraft of Satellite Communication with Submersible Objects*

Recent tests have shown that blue green laser radiation can not only penetrate through sea water but also through thick cloud covers[9b]. Therefore, communication between aircraft or satellite and submerged platforms using blue green lasers is both feasible and attractive[1-13&14]. Satellite to submarine communication by blue green laser (BGL) has been suggested as an alternative to the ELF and VLF for strategic communication in the year 1980-2000, Global coverage with high date rate is the advantage. Though ELF can have larger depth penetration, the environmental problems connected with high power large antenna fields cannot be dismissed. At the same time cost of blue green laser (BGL) development may be exceptionally high since the feasibility is dependent on the development of major advanced state-of-art systems. The availability of sustained funding by the R & D agencies to achieve early initial operational capability is also important. Experimental demonstration of the full system capability is yet to be proved and is likely to take another couple of years.

There are two schemes proposed for communicating with submerged submarines via a BGL beam (Fig. 6). In one case (Fig. 6a) a larger ground based transmitter sends the BGL beam to a steerable reflector mounted on the synchronous satellite and reflected onto a submarine holding area. The beam is sufficiently expanded after reflection to cover the intended area. Three symetrically spaced synchronous satellites can cover all of the submarine operational areas. In the other scheme (Fig. 6a) the pulsed BGL is mounted on the synchronous satellite and the beam is raster scanned over the submarine holding area. There is an *RF* link from the earth station for relaying the message to the Satellite. Both schemes have relative merits and demerits. In the former (ground based laser) the laser must be designed to operate at much higher power levels in order to compensate for atmospheric attenuation in uplink and to cater for a large coverage of the sub. holding area. In the latter scheme the *RF* link is likely to be jammed if caught in an EW envelope or exposed to EMP effect. Though the laser in this satellite can be of a smaller power yet its operational efficiency, life and reliability have to be high.

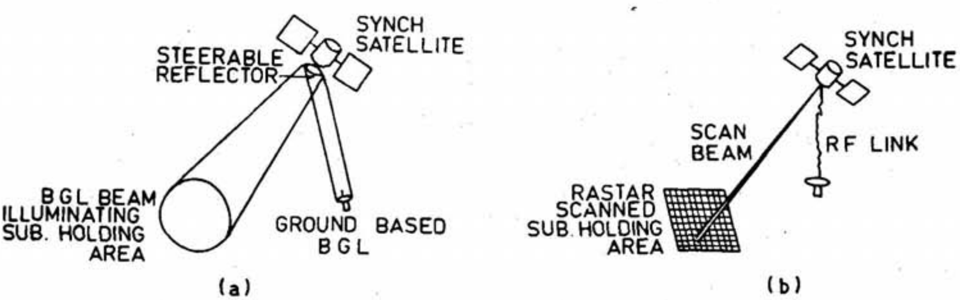


**Figure 6.** Two proposed schemes for satellite to submarine communication with blue green laser.

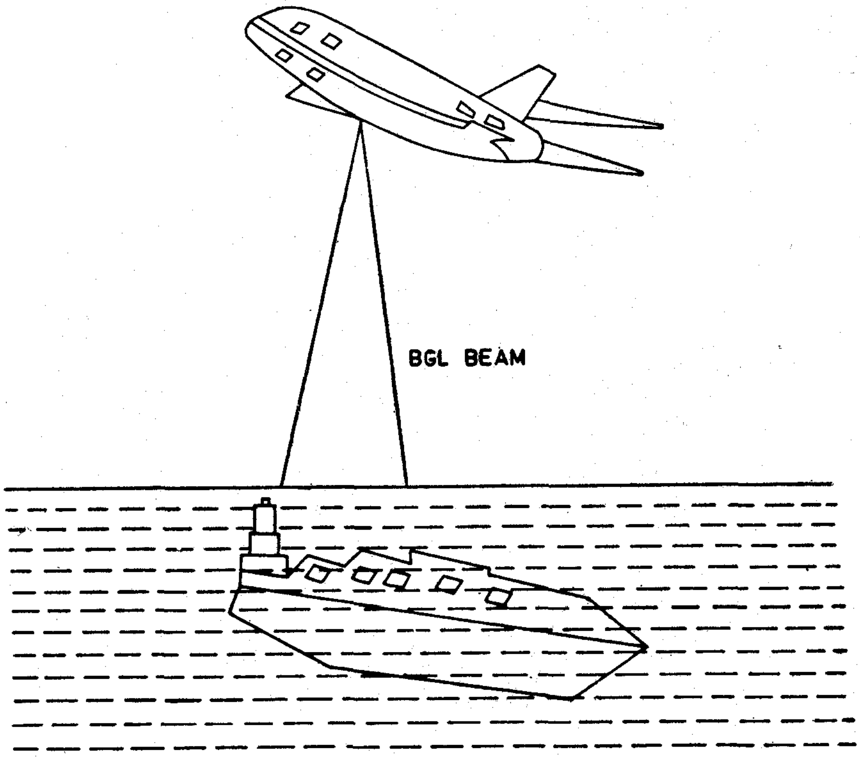


**Figure 7.** Aircraft mounted BGL for communication with submarine.

The receiver, in both the schemes, would be mounted on the submarine and would be tuned to the BGL wavelength. The important design parameters for receiver are angle of view and sensitivity, the submarine depth and speed. If the laser is aircraft mounted instead of ground based (Fig. 7) the aircraft speed and altitude are also important since they are directly associated with laser power requirements, scan rates and effective broadcast range. One of the issues under current investigation is the effect of bioluminance on signal reception. Many ocean organisms emit light, some of it within the blue green window where the underwater receiver is sensitive.

A fully operational system would include a submarine mounted laser uplink transmitter as a standby capable of immediately responding to IFF interrogation. Once the acknowledgement is completed the encoded messages could be transmitted in a short burst via the BGL carrier. Operational requirements of BGL for satellites to submarine communication are very demanding. Frequency doubled *Nd YAG* may suffice powerwise for airborne systems but not for satellite use. Also there is a limit on the operational life due to limited life of flash lamps which need replacement. *Cu* vapour laser may be having higher efficiency and good average output power yet it does not have the required pulse energy nor the long life required for this application. Dye lasers in the blue green have upto 200W (average) and are quite satisfactory in terms of power, yet their low efficiency and poor life of flash tube and dye[15] make them unsuitable for this application. Of the two promising candidates (Raman shifted *XeCl* and *HgBr* lasers) the *XeCl* BGL has also fallen from favour. *HgBr* is now the only type to receive second phase funding from the Defence Advanced Research Projects Agency in USA for this application.

## 4. Conclusion

Good transmission through water and availability of high power lasers in the Blue Green region of the spectrum can provide detection, range and communication with submersible objects. A workable range of upto 100 m is possible under clear waters and 30-50 m under turbid conditions. Coastal depth measurement and communication with submarines are considered useful applications. These have military potential for quick hydrographic surveys and communication of emergency messages with submarines on global scale. Though a number of lasers are available in the blue green region, the stringent requirements for the satellite to submarine communication is generating further R & D activity to provide a viable laser to serve this purpose.

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