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REVIEW PAPER

Solid-state Laser Rangefinders A Review

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ABSTRACT

Describes the development of solid-state laser rangefinders, during the last thirty years. The laser rangefinders using solid-state laser materials operating in visible, near and mid-infrared spectrum of light are in use. Considering the cost, efficiency, atmospheric transmission and detection capability, neodymium laser rengefinders operating in near-infrared region are still the state-of-the-art and are more in use as compared to rangefinders using other solid-state materials. The neodymium laser rangefinders in different configurations and use, developed in this Establishment are also described. The neodymium and diode lasers with improved detection capability in multiple pulse operation with pulse correlation techniques are under development to make these rangefinders eyesafe.

NOMENCLATURE

A_r	Receiver lens aperture
A_t	Target area
B	Amplifier bandwidth
B_o	Bandwidth of laser receiver
e	Electron charge
F	Noise factor of amplifier
G	Amplifier gain
H_s	Irradiance over detector response
$H_{\lambda s}$	Spectral irradiance at laser wavelength
I_d	Detector dark current
k	Boltzman constant
N	rms noise level of receiver output
P_t	Laser transmitter power
P_b	Background power in the laser receiver
P_s	Laser peak power received at detector
R	Range of target
R_L	Detector load resistance
$\hat{S}$	Peak level of signal at receiver output
T	Absolute temperature (°K)
T_r	Transmittance of receiver optics
T_t	Transmittance of transmitter optics
	Laser beam divergence (rads)
α_r	Receiver directivity (rads)
ß	Responsivity of detector' (A/W)
λ_s	Laser wavelength
χ	Tramsmittance of receiver optical filter outside its passband
σ	Atmospheric attenuation
σ_s	Atmospheric backscatter coefficient, and
ρ	Target reflectivity.

1. INTRODUCTION

With the development of first ruby laser[1] by Maiman and subseqtuent generation of giant pulse by Hellwarth[2] using Q-switching technique, the first ruby laser rangefinder weighing 90 lbs was developed and demonostrated[3] in 1961. This rangefinder had a rotating prism Q-switched transmitter operating at 0.6943μ wavelength and a photomultiplier tube with S-20 response in laser receiver to range a non-cooperative target up to maximum range of 10 km.

Since 1961, much development work has taken place in ranging techniques, i.e., operating at various wavelengths in visible, near- and mid-infrared using various types of laser materials, different pumping configurations, and various types of Q-switching and improved detection techniques. The range achievable is 20 km for ground targets and 150 km for air targets[4]. Till now, the laser rangefinders manufactured or in

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common use employ neodymium laser material doped in yttrium aluminium garnet (YAG) or in silicate or phosphate glass operating at 1.064μ or 1.054μ. The detectors used in a laser receiver are silicon avalanche photodiode for near-infrared lasers.

With the development of *InGaAs* avalanche detectors[5,6], much development work has been reported recently on eyesafe laser rangefinders using laser materials[7] operating at mid-infrared region.

2. BASIC PRINCIPLE

A laser rangefinder, like microwave radar works on the principle of time measurements of an optical-pulse travelling from the observation point to the target of interest and back. Since optical frequencies are 10^4 to 10^6 times higher than microwave frequencies, it has become possible for a compact transmitter giving a beamwidth or angular resolution of 10^{-4} rads to measure the ranges of target for ground-to-ground role. Since laser energy can be confined in a pulse duration of 10^{-9} s, a higher order of target range resolution can be achieved. But, the range compatibility of a laser rangefinder is limited due to higher background and high signal attenuation in the atmosphere at the optical wavelengths, i.e. due to absorption and scattering. The resolution is also limited due to the changes in the index of refraction along the optical path. Further, the drawback of a laser rangefinder is a potential eye hazard at higher energy densities and low generation efficiency.

2.1 Range Equation

For diffuse laser target of reflectivity ρ normal to laser beam, the echo power received at detector is:

$$P_s = \frac{P_t A_r T_t T_r \rho}{\pi R^2} e^{-2\sigma R}$$

For targets less than the beam size, the power received is:

$$P_s = \frac{4 P_t A_r T_t T_r \rho A_t}{\text{[illegible]}} e^{-2\sigma R}$$

3. DESCRIPTION

The majority of laser rangefinders in operation, use an optically-pumped solid-state laser as the source of transmitted power. The principles upon which these systems work are common to all, the difference between various instruments lie in the fine details of the optical design and of the electronic circuitry

The optical elements of a ranging system are shown in Fig. 1. Generally, the rangefinders have three optical channels, i.e. transmitter, receiver and sights. For near-visible laser rangefinders, the receiver and the sighting axes are combined through a beam splitter.

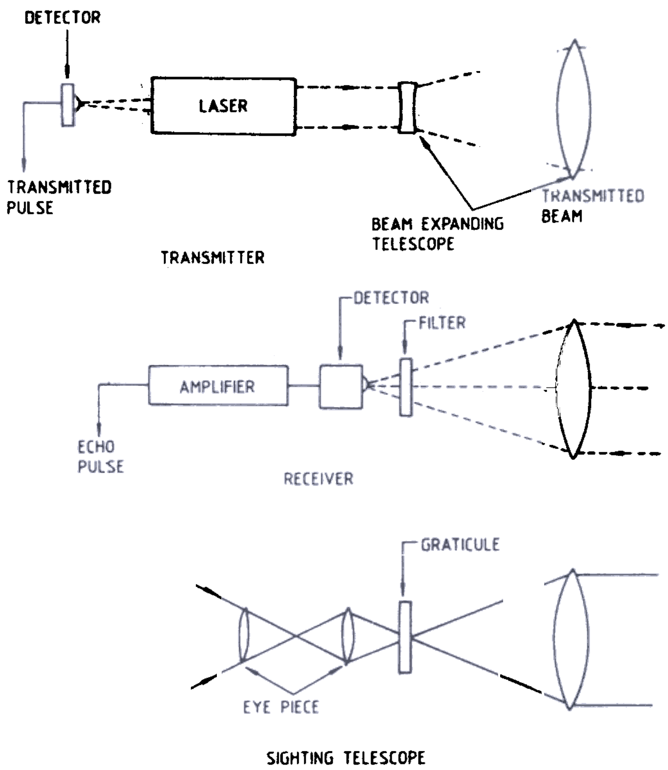

Figure 1. Optical elements of a ranging system.

Transmitter and receiver beams are combined using polarisation to separate the transmitted and received beams. Sometimes, all the three beams are combined using polarisation to separate the transmitted and received beams and a beam splitter to separate out the sighting channel. The beam divergence of laser beam from resonator is reduced to 0.5 to 1 mrads using beam expanding telescope. The field view of the receiver channel is determined by the ratio of the detector active area to the effective focal length of the receiver objective lens. The size of the transmitting beam and its image at detector is made equal or about 20 to 30 per cent smaller than the size of active area so as to cater for bore sighting inaccuracy between the three channels.

Figure 2 shows the block diagram of laser rangefinder electronics. Upon a command from an operator, electronic supplies are switched on and through a high voltage converter, energy storage condenser is charged to the required voltage. The aiming mark of the graticule is aligned to a point at the target and on pressing the laser fire switch, the laser pulse is transmitted within a few microseoonds or few milliseconds depending upon the Q-switching technique adopted. A portion of the transmitted pulse energy falls on a photodetector giving reference pulse to a range counter. The echo received on a sensitive detector placed at the focus of the receiving lens gives a stop pulse to the ranging counter. The ranging accuracy

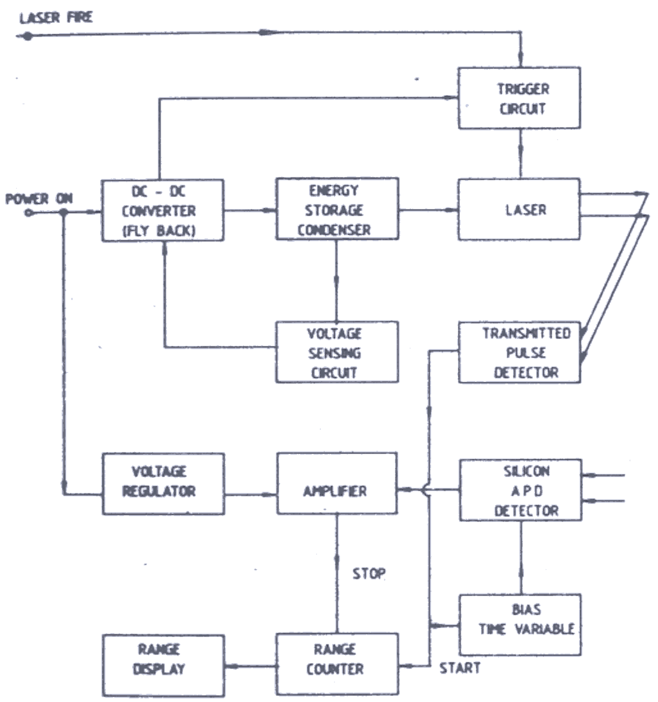

Figure 2. Block diagram of a laser rangefinder electronics.

depends on clock frequency of the counter and the laser transmittel pulsewidth; time variable gain on detector or amplifier is used to avoid damage of detector due to backscatter or false echo due to secondary reflections. Minimum blocking range or last echo logic is used to avoid ranges due to small objects in the path of the laser beam.

3.1 Atmospheric Transmission

In the range equation, the received power decreases by the factor $e^{-2\sigma R}$. The σ is atmosheric attenuation factor and can be divided into two components $\sigma=\sigma_s+\sigma_a$,

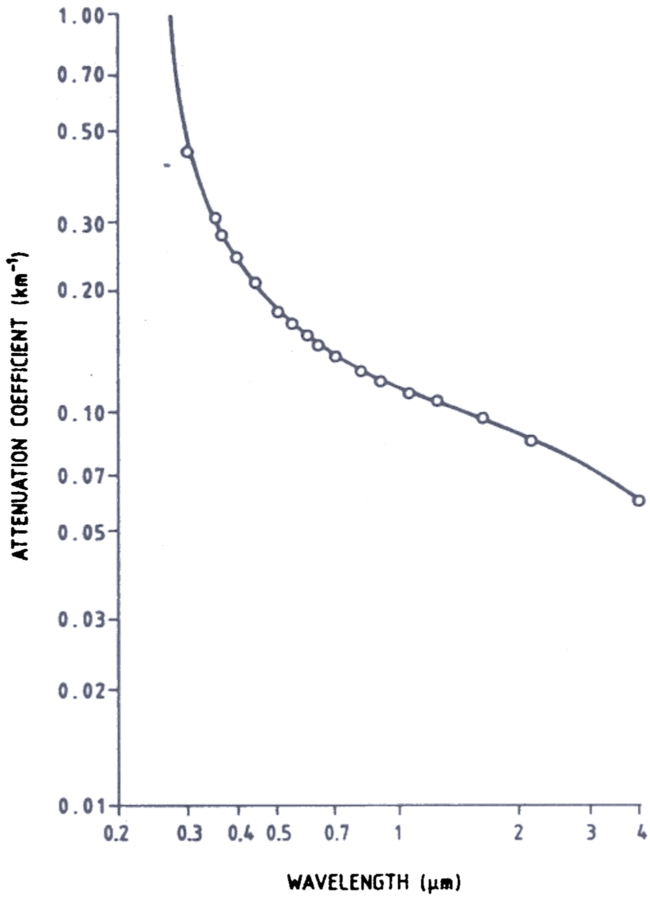

Figure 3. Transmission characteristics of visible and near-infrared spectra of optical energy in atmosphere under normal visible conditions.

which arises from scattering and absorption by the atmosphere. In the visible and near-infrared, the atmospheric attenuation is entirely due to scattering, which becomes increasingly severe as the wavelength is decreased. Thus, there is considerable advantage in using as long a wavelength as possible to reduce scattering. However, for some wavelength into the infrared, molecular absorption, particularly from H_2O and CO_2 becomes important. The performance of a rangefinder at the wavelength depends upon statistical knowledge of the distribution of temperature and humidity of the atmosphere. Figure 3 shows the transmission characteristics[8] of visible and near-infrared spectra of optical energy in atmosphere under normal visible conditions. The various factors affecting laser transmission and background noise in the atmosphere are well discussed by Zuev[9].

3.2 Target Returns

Generally the beam divergence of a laser rangefinder is controlled to fill the targets for ranging. The returns from the target depend on the reflectivity and cosine of angle of incidence and obey Lambert's law. The diffuse reflectivities of rough targets depend on the constitution of wavelength and to a lesser extent on the angle of incidence. They vary widely, values of a few per cent are often assumed. Smooth surfaces often show a marked variation with the angle of incidence. Targets have better reflectivity in visible and near-infrared. Generally for natural and extended targets it is taken as 0.4, while for military targets it is taken as 0.1 for wavelengths near-infrared. Target reflectance characteristics and reflection of various metals and natural targets are discussed by Jelalian[10] in the book titled the 'Laser Radar Systems'.

3.3 Laser Receiver

The maximum range capability of a laser rangefinder depends on receiving lens aperture, transmission of laser filter, quantum efficiency of detector and noise. For visible and near-infrared laser, the detector used is photomultiplier tube with S-20 response or a silicon avalanche photodiode. A field-stop aperture or detector active area and receiver lens focal length is chosen such that directivity of the receiver is 20-30 per cent more than the directivity of laser beam to keep the background noise minimum. The peak signal-to-rms noise ratio in a laser receiver[11], when ranging a target in the Earth atmosphere is given by

$$\frac{\hat{S}}{N} = \frac{\beta^2 P_s^2 R_L G^2}{(2eB(\beta P_b + I_d)R_L G^2 + 2kFTB)}$$

where

$2eB\beta P_b R_L G^2$ = Noise due to background illuminated of target by Sun.

$2eBI_d R_L G^2$ = Noise due to detector dark current.

$2FkTB$ = Noise due to amplifying system.

$$P_b = \frac{(H_{\lambda s}B_o + H_s\chi)\alpha^2 A_r T_r}{4}\left[\rho e^{-2\sigma R} + \frac{\sigma_s(1-e^{-2\sigma R})}{4\sigma}\right]$$

If the noise due to detector dark current and preamplifier noise is much smaller than the background noise due to sunlight then,

$$\frac{\hat{S}}{N} = \frac{\beta P_s^2}{2eB\beta P_b}$$

For less background noise, P_b, the detector should have high quantum efficiency at laser wavelength and the laser receiver should be highly directive with narrow bandwidth B_o.

The Sun irradiance H at a point outside the Earth's atmosphere is

$$H = \int_0^\infty H_\lambda d_\lambda$$

$= 1345\ \mathrm{Wm^{-2}}$ at aphelion

$= 739\ \mathrm{Wm^{-2}}$ over detector response.

The spectral irradiance at sea level is H_λ

at 6943 A° = $0.12\ \mathrm{Wm^{-2}A^{-1}}$

at 1.06 μ = $0.06\ \mathrm{Wm^{-2}A^{-1}}$

at 2.06 μ = $0.01\ \mathrm{Wm^{-2}A^{-1}}$

Therefore, while working at higher wavelength, not only the background radiation due to the Sun is less, but its contribution due to backscatter from atmospheric particles will also be less.

For pulse laser rangefinder, direct detection techniques, i.e., detection of intensity and variation of the intensity of light on photodetector are used. The amplifiers used have bandwidth of 15 to 40 MHz depending upon the pulsewidth with lower cut-off frequency at 0.1 MHz.

For continuous wave and frequency stable lasers optical heterodyne detection techniques[12] are used. In this, optical signal is mixed with a stable coherent optical local oscillator by a beam splitting mirror or other optical summing devices as shown in Fig. 4.

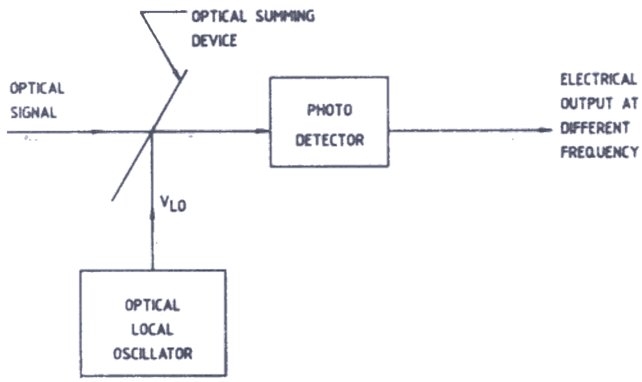

Figure 4.

Both are then directed towards the input of a photodetector where mixing action takes place between the signal and the local oscillator fields. Optical mixing has become practical because the narrow emission with the intermediate frequency in the microwave region or lower is well within the bandwidth of fast photodetectors, the photomixing is called optical heterodyne. For this purpose, the laser frequency should be highly stable. One such laser radar has been described by Kene[13].

3.4 Laser Sources

The majority of laser rangefinders being manufactured use an optically-pumped solid-state laser source[14] as the source of transmitting power. The laser materials commonly used are ruby-0.6943μ, *Nd*:silicate glass-1.06μ, *Nd*:phosphate glass-1.054μ, *Nd*:YAG-1.064μ. Now with the development of *InGaAs*-avalanche photodiode, laser rangefinders in mid-infrared, i.e. *Nd*:YAG Raman shifted-1.540μ, *Er*:Glass laser-1.535μ, *Er*:YLF-1.730μ, *Ho*:YLF-2.06μ, *CrTm*:*Ho*:YAG-2.060μ, have been reported[7,15].

The laser materials are pumped[16] by xenon flash lamp. The laser materials are in the form of a rod, but recently slab geometries with laser diode pumping are under development and may find application in high repetition[17] rate laser rangefinders. The optical energy of the flash lamp is coupled to the laser material using elliptical gold-plated reflectors, silver or dielectrically-coated glass elliptical reflectors with laser rod and flash lamp placed at foci. $BaSO_4$ diffuse reflector on Samarium filters with sensitiser ions in close pumping chamber developed[18] by Kigre, Ifc, USA, absorbs one micron and unwanted UV radiation while transmitting and reinforcing at the wavelength corresponding to the neodymium pump bands, when used improves operating efficiency of laser materials. The laser resonators are formed by a partially reflecting dielectric mirror, or resonant reflector at one end and TIR prism, corner cube prism or total reflecting dielectric mirror at the other end. The part of flash lamp energy stored in laser material as population inversion is released in a single giant pulse by Q-switching techniques for solid-state lasers[19] used are mainly rotating prism, electrooptics, and passive Q-switching.

In rotating prism Q-switching techniques[3,20] TIR prism used as total reflector of laser resonator is mounted on a shaft of permanent magnet DC high speed or 400 Hz hysteresis synchronous motor. The TIR prism position and flashing of lamp is synchronised in such a way that when all the energy from the flash lamp is absorbed by the laser material, TIR prism gets aligned to a partial mirror at the instant of optimum population inversion to generate a single giant pulse whose duration is 30 to 50 ns, depending upon laser material gain, motor speed and resonator length. This type of Q-switching has an advantage since the alignment is not very critical, only TIR edge has to be placed exactly at resonator axis. Here, 70 to 80 per cent of the stored energy is released in a well collimated beam with divergence between 2 to 3 mrads.

In electrooptics Q-switching, polariser, lithium neobate or polariser, lithium neobate and quarter wave plate in a laser resonator forms electrooptics shutter. This electrooptics shutter is kept closed till the flash lamp energy is absorbed and optimum population inversion in the laser material is achieved. In this type of Q-switching, the laser output is available either from partial reflector or from polarising beam splitter. If TIR prisms form both ends of the resonator, a quarter wave plate is used. In this type of Q-switching, 5 to 20 ns pulses are obtained depending upon the mode of operation, i.e., cavity dumping mode or pulse reflection mode. This type of Q-switching is complex and costly for rangefinders, but in this type of Q-switching, precise time-control for the generation of pulse is easily achievable.

The passive Q-switching is mainly used in compact or hand-held laser rangefinders[14,21,22] the type of material consists of an organic reverse bleachable infrared dye dissolved in organic solvent or dispersed in acetate sheet. Recently, $LiF{:}F_2$ colour centre laser crystal[23] and tetravalent chromium-doped solid-state as passive Q-switching elements for *Nd*:YAG lasers have been reported[24]. In this type of Q-switching, pulse is very sharp with pulse duration of 4 to 10 ns resulting in high peak power with low-energy loss in passive Q-switched element.

3.5 Laser Electronics

The laser electronics for laser rangefinders can be divided into three heads:

3.5.1 Power Supply and Flash Lamp Driving Circuit

The power supply mainly consists of high voltage flyback convertor[25] for charging of energy storage condenser with voltage sensing circuit to switch off the converter as soon as the required electrical energy is stored on condenser with over voltage protection, ± 5 V switching or series regulator with over voltage protection and 10 to 12 V or ± 5 V supply protected from electromagnetic interference for amplifier and low-level detection circuit.

The flash lamp driving circuits of energy storage condenser and inductor or pulse forming network[26] to match with the lamp impedance for optimum flash output and duration to match with absorption band and mean fluorescence life-time[27] of laser material. For high repetition rate operation of flash lamp, the flash lamp is operated in simmer mode, while for single pulse operation shunt or series trigger modes are used for producing initial ionisation in the lamp. These circuits are well shielded and placed close to flash lamp to avoid radiative interference on detection circuits.

3.5.2 Low-Level Detection Circuits

Detection electronics mainly consist of a photomultiplier tube or silicon avalanche photodiode with its bias circuits, and trans-impedance amplifier. The gain of the amplifier or silicon avalanche photodiode multiplication is varied with time with minimum gain as the time of laser pulse transmission and maximum after 10 to 20 μs to avoid false echo or backscatter from atomsphere which may damage the detector. Temperature compensation in bias circuit is introduced since breakdown voltage of silicon avalanche photodiode varies with temperature, and hence varies the gain which is maximum near avalanche breakdown.

3.5.3 Timing Circuits and Ranging Electronics

The ranging counter measures the time of travel of laser pulse from the observation point to the target and back. The accuracy of range of time interval depends on clock frequency and pulse rise time. For range accuracy of ± 5 m, the clock frequency used is 30 MHz. For better accuracy, the rise time of the pulse should be fast or laser pulsewidth should be narrow and fast detection circuits are to be used. The range counter generally consists of crystal-controlled oscillator, gates and decade or binary counter with numeric display. Further, it has facilities for minimum blocking range, multiple target discrimination or last echo logic depending upon its use in a particular environment.

4. RANGING SYSTEM

Starting with ruby laser rangefinders developed at the Instruments Research & Development Establishment (IRDE), Dehradun, in early seventies, the various other types of rangfinders developed till now are as follows :

4.1 Portable Laser Rangefinder

Figure 5 shows a ruby laser rangefinder mounted on a tripod. It consists of a transreceiver unit with detection and counting electronics and a power supply unit with energy storage condenser bank. Rotating prism Q-switching has been used with three plate sapphire

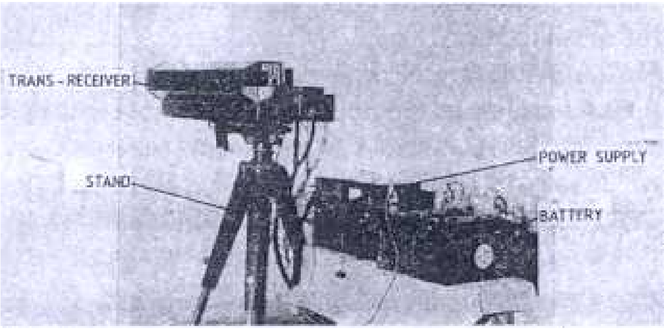

Figure 5. Ruby ' ·r rangefinder.

resonant reflector as partial mirror. The divergence of laser has been reduced to 0.5 mrads by using beam expanding telescope. A photomultiplier tube RCA type 7265 with S-20 response has been used in laser receiver having common axis with sighting telescope of magnification ×7 and field of view 7°.

Figure 6 shows *Nd*:glass laser rangefinder with built-in power source, i.e., *Ni-Cd* batteries. The objective lens of aiming sight also acts as receiver lens. A cube beam splitter is incorporated in the sight to separate laser echo which is focused on the detector after passing through interference filter. It can measure

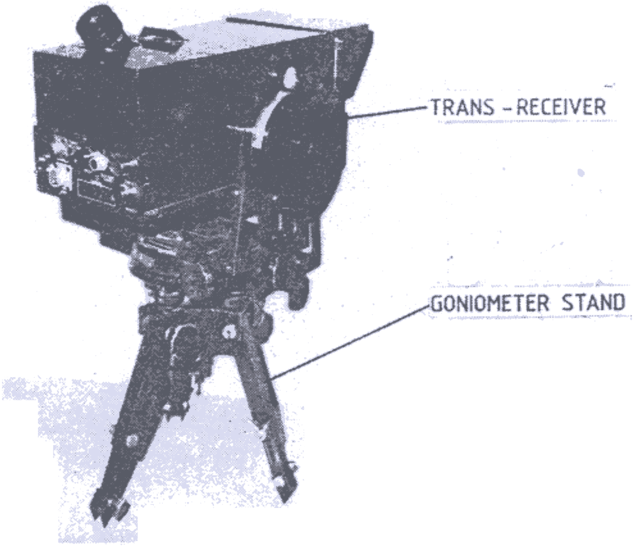

Figure 6. *Nd*:Glass laser rangefinder.

target range up to 10 km in clear visibility conditions with an accuracy of ± 10 m. The range counter can measure two target ranges in the same line of sight with a resolution of 30 m. Goniometer can give target bearing in 360° azimuth and 30° in elevation with an accuracy of ± 2 min.

4.2 Laser Rangefinders for Armoured Vehicle

Figures 7, 8 and 9 show *Nd*:glass laser rangefinder developed in various configurations to be used with the gunner's sight of an armoured vehicle.

Figure 7 shows the production model of laser rangefinder, where the laser trans-receiver unit is mounted on mantlet of tank with gunner's and

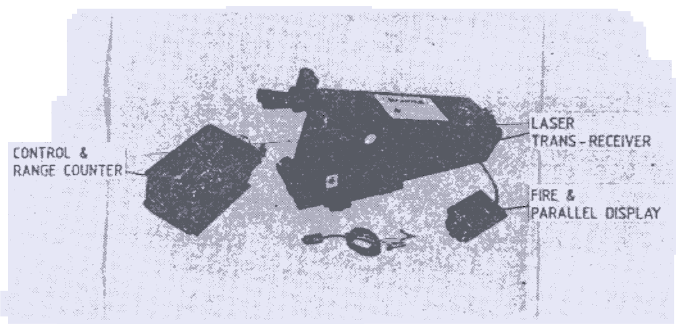

Figure 7. Laser rangefinder with separate transmitter, receiver and sighting channels.

commander's control units alongwith digital range display mounted inside the turret. The ranging counter has minimum blocking range variable from 400 to 4000 m and can measure range of two targets intercepted by a laser beam.

Figure 8 shows the laser trans-receiver having common lens for transmitter collimator and receiver. The transmitted beam is sent through the central portion of the lens while the received beam is sent to the detector through a special beam splitter with a hole in the centre.

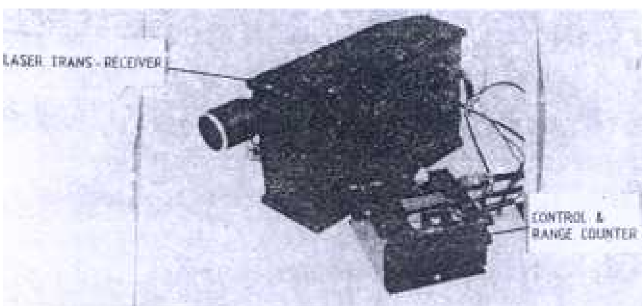

Figure 8. Laser rangefinder with common receiver and transmitter axis.

This unit has been coupled to the sighting axis of gunner's sight by a special beam splitter. Due to backscatter, silicon avalanche photodiode is biased after laser transmission, and the minimum blocking range is 600 m.

Figure 9 shows the laser rangefinder with receiver and aiming sight on same axis, while laser transmission on separate axis. The laser echo from the target is collected by the objective lens of sighting telescope incorporating a cube beam splitter which transmits the visible portion of light to graticule, and eyepiece for sighting of target and laser aiming purpose. The laser

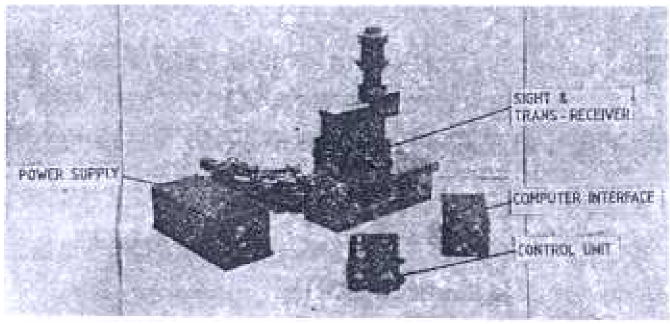

Figure 9. Laser rangefinders with receiver common to sighting-axis.

echo in near-infrared (1.054 μ) is reflected by this beam splitter and after passing through interference filter is focused on silicon avalanche photodiode (APD) biased at low voltage. This bias voltage is increased to a value just below breakdown voltage in 20 μs from laser transmission to provide time variable gain for laser echo from target at different ranges. The minimum blocking range for this rangefinder can be kept at 200 m.

All these rangefinders have minimum pulse energy of 40 mJ in a pulse duration of 30 ns.

4.3 Hand-held Laser Rangefinder

Figure 10 shows the hand-held laser rangefinder developed by IRDE using *Nd*:YAG laser material with passive Q-switching with minimum pulse energy of 15 mJ in a pulse duration of 8 ns. This rangefinder measures a range of extended targets up to 10 km in clear conditions. This rangefinder has a bracket and can be coupled to night sight.

4.4 High Repetition Rate Laser Rangefinder

Figure 11 shows *Nd*:YAG laser rangefinder with pulse repetition rate of 10 pulses per second for ranging

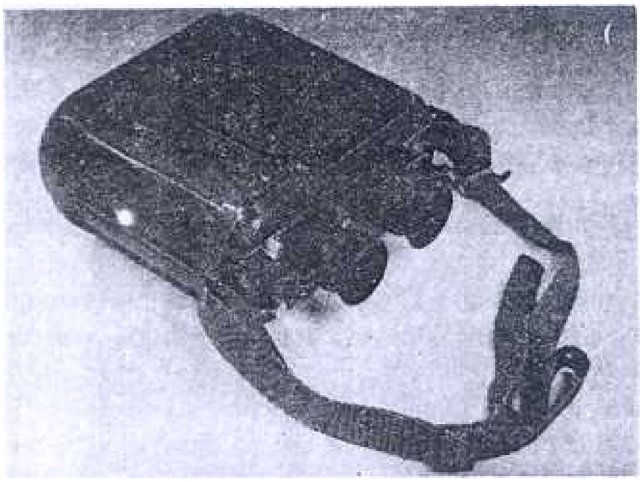

Figure 10. ***Nd*****:YAG hand-held laser rangefinder.**

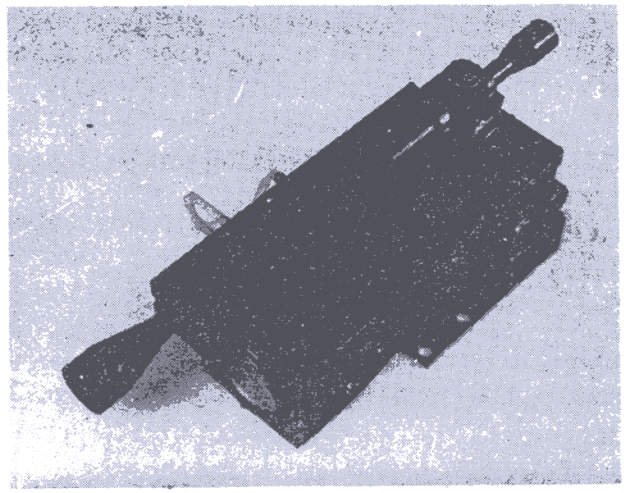

Figure 11. ***Nd*****:YAG high repetition laser rangefinder.**

military aircraft targets up to 8 km range in clear visible conditions. It uses electrooptical Q-switching with a transmitter energy of 60 mJ, a beam of divergence of 2 mrad. This unit has aligning aid and can be coupled with radar, IR or TV tracking device.

Table 1 gives the specifications of various rangefinders developed at IRDE.

5. CONCLUSION

The compact *Nd*:YAG laser rangefinders ranging up to 4 km with range accuracy ± 2.5 m under clear visible conditions with pulse energy as low as 2-3 mJ, have been reported[21,22]. For mid-infrared laser

Table 1. Specifications of laser rangefinders

Details	Portable		Armoured Vehicle	Hand-held	High rep rate
Laser material	ruby	*Nd*:glass (silicate)	*Nd*:glass (phosphate)	*Nd*:YAG	*Nd*:YAG
Output energy (mJ min)	70	40	40	15	60
Pulsewidth (nscc)	50	30	30	9	16
Type of Q-switching	rotating prism	rotating prism	rotating prism	passive	electro-optics
Beam divergence (mrad)	1	1	1	1.5	2
Receiver bandwidth (A°)	50	100	100	100	100
Detector directivity (mrad)	2	2	2	2	3
Receiver aperture (mm)	50	50	39	45	70
Maximum range (km)	0.2-15	0.4-10	0.4-4	0.2-10	0.4-10
Accuracy (m)	± 10	± 10	± 10	± 10	± 5
Sight					
(a) Magnification	× 7	× 7	–	×7	
(b) Field of view	7°	7°	–	6.5°	–
Weight (kg)	25	8	12	3	11
Operating temperature (°C)	0-+70	−20- + 50	−20- + 50	− 30-50	− 20- + 50

rangefinders which are under development as eyesafe laser to replace *Nd*:YAG working in near-infrared, the detection efficiency of *InGaAs* avalanche photodiode at high temperature is less than silicon avalanche photodiodes, and these detectors are much costlier as compared to silicon detectors. Therefore, considering all these factors, *Nd*:YAG laser rangefinders will be still in operation, further due to their compactness and low-cost value.

As suggested in a paper[28], multi-pulse operation of *Nd*:YAG lasers in compact size alongwith pulse correlation technique will make them less hazardous, as their pulse power can be reduced; and at the same time it will keep them immune from electrooptics countermeasure.

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