Energy, Mines and Resources Canada
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On the Relative Merits of Using Either CW Helium-Cadmium or Pulsed Nitrogen Lasers as the Fluorescence excitation Source in Airborne Laser Fluorosensing System

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ABSTRACT

The relative merits of using either low power CW or high power pulsed lasers as the excitation source in airborne laser-fluorosensing systems are discussed. Using performance data for commercially available lasers, it is shown that for most airborne applications, pulsed nitrogen lasers provide significant advantages over CW He-Cd lasers.

1. INTRODUCTION

Considerable debate has been generated regarding the relative merits of two different types of lasers which are currently used in airborne laser-fluorosensor experiments being conducted by Federal Government Departments.

The Department of the Environment (DOE) is supporting the development of an airborne laser-fluorosensor which uses a modulated CW (Continuous Wave) Helium-Cadmium laser (see Table 1). The concurrent development of an airborne laser-fluorosensor by the Canada Centre for Remote Sensing (CCRS) of the Department of Energy, Mines and Resources, involves the use of a pulsed Nitrogen Laser (see Table 2).

The purpose of this note is not to add fuel to the debate, but rather to present a number of facts relating to the properties of these two laser types which are relevant to their application in the development of a commercially viable airborne laser-fluorosensor. Significant differences between these two lasers are discussed in the following five sections.

2. Ultimately all comparisons can be reduced to those of system sensitivity as limited by signal to noise considerations. For the purposes of this discussion, noise types are divided into two categories, viz. the inherent photon noise of the flurorescence signal under investigation and the background photon noise originating from sources independent of the laser stimulated fluorescence signal. As the two systems being discussed are assumed to employ identical receivers no reference is made to detector noise.

2.1. Noise in fluorescence signal results from the discrete quantum nature of light and it is described here as photon noise. The fluorescence signal power to photon noise power ratio for system i can be represented by (Ross, 1966)

$$\frac{S}{PN_i} = \frac{P_i\ T_i\ K_i}{(P_i\ T_i\ K_i)^{\frac{1}{2}}} \qquad (1)$$

where P_i = Peak laser power for system i,

T_i = Signal integration time for system i,

K_i = Laser duty cycle for system i.

In formulating this expression the following assumptions are made:-

a) Receiver field of view is coincident with and at least equal to laser beam field of view.

b) Detector is gated off during laser dead time.

c) Signal integration time T is an integral number of laser modulation or pulse periods such that T = n/f, where f is the laser modulation or pulse frequency and n is an integer. The maximum useful value of T or n is set by ground resolution requirements in relation to the ground speed of the airborne sensing platform.

and d) Receiver fluorescence power is proportional to the laser excitation power.

It is now possible to compare the performance of the pulsed and modulated CW laser fluorosensor systems under photon limited conditions in terms of the respective laser properties. A Signal to Photon Noise Advantage Ratio (SPNAR) can now be written as

$$\text{SPNAR} = \frac{(S/PN)_p}{(S/PN)_{cw}} \qquad (2)$$

Where $(S/PN)_p$ and $(S/PN)_{cw}$ are the signal to photon noise ratios for the pulsed and CW laser fluorosensors respectively.

For this comparison to be valid, the following assumptions must be made:-

a) Both laser fluorosensor systems employ identical receiver - detector systems,

b) Both systems view the same fluorescence spectral band,

and c) The fluorescent target has a flat spectral emission profile (See Section 3 for further discussion of this point).

Eq (2) can be written in terms of Eq (1) such that

$$\text{SPNAR} = \left(\frac{P_p \; K_p \; T_p}{P_{cw} \; K_{cw} \; T_{cw}} \right)^{\frac{1}{2}} \qquad (3)$$

In terms of the average power $\overline{P} = KP$, SPNAR can be given as

$$\text{SPNAR} = \left(\frac{\overline{P}_p \; T_p}{\overline{P}_{cw} \; T_{cw}} \right)^{\frac{1}{2}} \qquad (4)$$

and for equal signal integration times

$$\text{SPNAR} = \left(\frac{\overline{P}_p}{\overline{P}_{cw}} \right)^{\frac{1}{2}} \qquad (5)$$

The Nitrogen laser operating with pulses of 100 KW amplitude and 10 nsec width at a repetition rate of 100 H_z, has an average power of 100 mW, whereas the corresponding value for the modulated Helium Cadmium laser at 4416 Å is 10 mW (see Tables 1 and 2). For these W_{av} values, SPNAR for the Nitrogen laser over the He-Cd laser is 3.16. With the He-Cd laser operating in the ultraviolet at 3250Å with an average power of 1.5 mW, the advantage for the Nitrogen laser increases to 8.16. For nighttime operation of airborne laserfluorosensors, a photomultiplier detector operates under photon noise limited conditions, so that for a fixed aircraft altitude, it is advantageous to use the pulsed Nitrogen laser as the laserfluorosensor excitation source.

Alternatively, as the intensity of the received fluorescence signal falls off as $1/r^2$ with increasing target range r, it is possible to operate the pulsed nitrogen laser at twice the altitude of the He-Cd laser and achieve the same signal to photon noise ratio. This might constitute a significant aircraft safety factor for nighttime operations when investigating targets of low fluorescence conversion efficiency where the target range must be minimized in order to achieve an acceptable signal to photon noise ratio.

2.2

The second category is that of background photon noise, the principal source of which is solar radiation encountered during daytime operation of the laserfluorosensor. Under background photon noise limited conditions, the fluorescence signal power to background noise ratio for system i is represented by (Ross, 1966)

$$\frac{S}{\overline{B}N}_i = \frac{P_i \; T_i \; K_i}{(P_b \; T_i \; K_i \; \theta_i^{\,2})^{\frac{1}{2}}} \qquad (6)$$

Where P_i = Peak laser power for system i,

T_i = Signal integration time for system i,

K_i = Laser duty cycle for system i,

P_b = Background Photon Noise Power per steradian,

and θ_i = Laser Beam Divergence for system i.

In formulating Eq (6), the same assumptions are made as for Eq (1) except that in this case the receiver field of view is assumed to be coincident with and exactly equal to the laser beam field of view.

In order to compare the performance of the pulsed and CW laser-fluorosensor systems under background noise limited conditions in terms of the respective laser properties, a Signal to Background Noise Advantage Ratio (SBNAR) can be written such that

$$\text{SBNAR} = \frac{(S/BN)_p}{(S/BN)_{cw}} \tag{7}$$

where $(S/BN)_p$ and $(S/BN)_{cw}$ are the signal to background noise ratios for the pulsed and CW laser fluorosensors respectively. The assumptions made in formulating Eq (7) are the same as for Eq (2). Eq (7) can now be rewritten in terms of Eq (6) so that

$$\text{SBNAR} = \left(\frac{P_p/\Theta_p}{P_{cw}/\Theta_{cw}}\right) \cdot \left(\frac{T_p \quad K_p}{T_{cw} \quad K_{cw}}\right)^{\frac{1}{2}} \tag{8}$$

and for equal signal integration times

$$\text{SBNAR} = \left(\frac{P_p \quad /\Theta_p}{P_{cw} \quad /\Theta_{cw}}\right)\left(\frac{K_p}{K_{cw}}\right)^{\frac{1}{2}} \tag{9}$$

Comparing the Nitrogen laser (table 2) to the He-Cd laser (Table 1) at 4416Å, the SBNAR for the Nitrogen laser over the He-Cd laser is 420. For the He-Cd laser operating at 3250Å with CW power of 3mW, the advantage gained by using the Nitrogen laser increases to 2440.

The large advantage afforded by the pulsed Nitrogen laser due to its high peak power allows for the possibility of daytime operation of the laserfluorosensor, thereby realizing a 24-hour capability for the sensing system; acceptable signal to background noise ratios are possible for airborne detection and characterization of oil slicks provided that the return fluorescence signal is spatially filtered from the background solar radiation.

However, the relatively low brightness of the present pulsed Nitrogen laser as characterized by the far field beam divergence (see Table 2) in combination with undesirable beam mode structure present in the far field, does not provide for optimal discrimination against solar background noise. The ideal beam has low divergence and is Gaussian in cross section which allows for efficient spatial filtering of the solar background. Both the CW He-Cd laser (Table 1) and the new lightweight sealed off pulsed Nitrogen laser (Table 3) are acceptable in this respect.

3.

The Excitation wave length of the pulsed Nitrogen laser at 3371Å allows one to obtain complete fluorescence spectra from substances such as water pollution, pulpmill effluents and low viscosity crude oils, all of which have fluorescence spectra peaking below 4400Å. Clearly, as fluorescence spectra all occur at wavelengths longer than that of the excitation source, a large part of these spectra are not measurable with the DOE modulated CW laser fluorosensor operating at 4416Å. With a change of cavity mirrors the He-Cd laser can be made to operate at 3250Å in the near UV, but at the reduced power of 3 mW as against 20mW at 4416Å (UV operation has as yet not been undertaken by the DOE investigators). However, for remote sensing of certain substances such as chlorophyll (in algae), it may be advantageous to use the He-Cd laser at 4416Å as this lies close to the wavelength for peak excitation of chlorophyll pigment (~ 4400Å).

4.

The narrow pulses (~ 9 nsec) generated by the pulsed Nitrogen laser offer three advantages over a modulated CW system.

4.1 Fluorescence lifetimes of environmental substances have values which typically extend from 5 nsec to 50 nsec depending upon the nature of the target material. The Nitrogen laser, having pulse widths in the region of 10 nsec, is therefore able to produce fluorescence decay times which are readily converted into characteristic lifetime values. This fluorescence lifetime information when used in conjunction with the fluorescence emission spectra, provides an added degree of specificity to the process of characterizing and identifying the environmental substance under investigation; it is not possible to employ this technique using a CW laser when it is modulated at frequencies in the kilohertz region.

4.2. Range gating can be performed whereby targets at any desired range can be sampled.

4.3. The laser (UV) backscattered pulse can be employed to give direct and accurate values for the altitude of the aircraft above the target.

5.

The main disadvantages of the pulsed Nitrogen laser currently being used in the CCRS laser-fluorosensor, when compared to the modulated CW He-Cd laser used in the DOE laser fluorosensor, are the system size, weight and power consumption; the respective figures for the two lasers are given in Tables 1 and 2. However, with a view to future developments, a high performance, sealed off, pulsed Nitrogen laser has recently become available, weighing 12 lbs., requiring 200 watts of line power and with dimensions of 18" x 4" x 6"; other performance figures for this new laser are given in Table 3. These figures are a considerable improvement over those for both the present pulsed Nitrogen laser and the CW He-Cd laser.

6.

The output power of CW lasers such as the Helium-Cadmium laser is critically dependent upon the mechanical alignment of the optical cavity. Consequently vibrations, mechanical shock and temperature fluctuations encountered in aircraft environments can produce significant fluctuations in laser power.

In contrast, the output pulse of the superradiant Nitrogen laser generally occurs within two, or at the most three, passes of the optical cavity. Operation of the Nitrogen laser therefore does not demand critical alignment of the optical cavity (if one is employed) and is consequently an ideal laser for airborne remote sensing applications.

REFERENCE

Ross, Monte (1966). Laser Receivers. Wiley.

TABLE 1

CHARACTERISTICS OF RCA LD 2148
HELIUM CADMIUM (HE-CD) CW GAS LASER

CENTRE WAVELENGTH	4416 A°	3250 A° (with UV mirrors)
C W POWER	20 mw	3 mw
BEAM DIAMETER	0.9 mm	0.9 mm
BEAM DIVERGENCE (FULL ANGLE)	0.8 mrad	0.7 mrad
POLARIZATION	POLARIZED, 10^3:1	
OVERALL WEIGHT LASER HEAD WEIGHT	50 lbs. 33 lbs.	
POWER CONSUMPTION	400 VA at 114V/60 Hz	
LASER HEAD DIMENSIONS	30 in x 7 in x 6 in	

TABLE 2

CHARACTERISTICS OF THE AVCO C - 950

NITROGEN/NEON LASER

	NITROGEN LASER	NEON LASER
CENTRE WAVELENGTH	3371.1 Å	5400.56 Å
BANDWIDTH	1 Å	10^{-2} Å
PULSE WIDTH (FWHM)	10 nsec	3 nsec
MAXIMUM PULSE PEAK POWER	100 kW	20 kW
PULSE REPETITION RATE	1 to 100 pps (continuously variable) or single shot.	
POLARIZATION	UNPOLARIZED	
OUTPUT BEAM DIMENSIONS	2 in x 1/8 in	
FULL ANGLE FAR FIELD BEAM DIVERGENCE USING LENS	13.5 mrad x 3.6 mrad	
OVERALL WEIGHT	450 lbs	
LASER HEAD WEIGHT	150 lbs	
POWER CONSUMPTION	1300 VA at 115V/60Hz	
LASER HEAD DIMENSIONS	48 in x 21 in x 13 in	

TABLE 3

CHARACTERISTICS OF THE LASER ENERGY N2-50

NITROGEN/NEON LASER

	NITROGEN LASER	NEON LASER
CENTRE WAVELENGTH	3371.1 Å	5400.56 Å
BANDWIDTH	1 Å	10^{-2} Å
PULSE WIDTH (FWHM)	6 nsec	3 nsec
MAXIMUM PULSE PEAK POWER	30 kW	2 kW
PULSE REPETITION RATE	1 to 100 pps (continuously variable)	
POLARIZATION	POLARIZED, 10:1	
BEAM DIAMETER	3 mm	
FULL ANGLE FAR FIELD BEAM DIVERGENCE USING LENS	1 mrad	
OVERALL WEIGHT	50 lbs	
LASER HEAD WEIGHT	12 lbs	
POWER CONSUMPTION	200 VA at 115V/60 Hz	
LASER HEAD DIMENSIONS	18 in x 6 in x 4 in	