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LASER SPECKLE AND ATMOSPHERIC SCINTILLATION DEPENDENCE ON LASER SPECTRAL BANDWIDTH: POSTPRINT

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Recent advances in low-cost high power diode lasers have made available a new type of illuminator source for LADAR remote sensing systems. These sources tend to be smaller more rugged, and have better power conversion efficiency than more conventional pumped crystal solid state lasers. They can be run in short pulse, or long pulse modes with pulse repetitions from DC to 10s of kilohertz. Although they don't have large optical band widths. These factors make them well suited to direct detection, as opposed to coherent detection, since the lower source coherence reduces detrimental atmospheric effects related to speckle noise and scintillation of the outgoing beam. In this paper we discuss these effects and situations where diode lasers provide an advantage when working through long slant paths.

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Laser speckle and atmospheric scintillation dependence on laser spectral bandwidth

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Recent advances in low-cost high power diode lasers have made available a new type of illuminator source for LADAR remote sensing systems. These sources tend to be smaller more rugged, and have better power conversion efficiency than more conventional pumped crystal solid state lasers. They can be run in short pulse, or long pulse modes with pulse repetitions from DC to 10s of kilohertz. Although they don't have the peak power of a Q-switched laser, they make up for it in higher average power. They also tend to have large optical band widths. These factors make them well suited to direct detection, as opposed to coherent detection, since the lower source coherence reduces detrimental atmospheric effects related to speckle noise and scintillation of the outgoing beam. In this paper we discuss these effects and situations where diode lasers provide an advantage when working through long slant paths.

1.0 INTRODUCTION

Recent advances in high power laser diode technology have lead to a significant new source for imaging LADAR systems. Originally designed as pump sources for solid state lasers, the diode laser devices have come into their own. Novel micro-optic coupling schemes allow for coupling the normally wide divergence of the diode output into multi-mode fiber optics, producing a well behaved spatially isotropic output with numeric aperture of about 0.22.

High power devices with from 10s to 100s of Watts average power are available in small off the shelf packages. The effective range of a LADAR system, with direct detection, is a strong function of the average power of the illuminator. Conventional laser sources with Q-switched crystal lasing media cost on the order of $100,000 per Watt of average power. On the other hand diode lasers costs are on the order of $200 per Watt average power.

2.0 FIBER COUPLED DIODE LASER

Figure 2.1 shows a 15 Watt average power fiber coupled diode laser produced by QPC laser. The dimensions of the laser head are 100 x 41 x 31 mm.

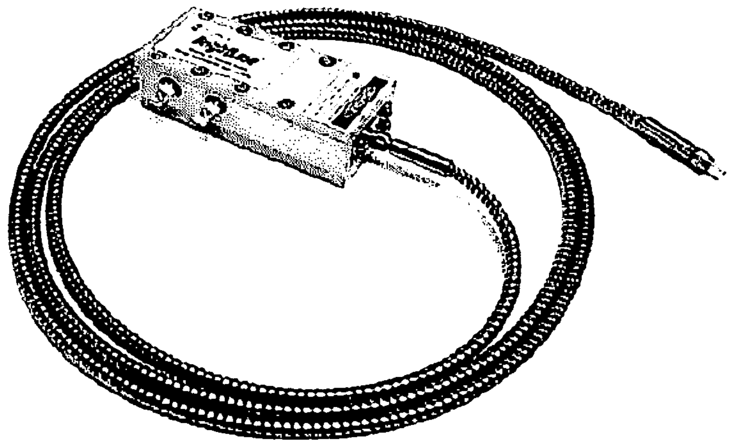


Fig. 2.1 Fiber Coupled Diode Laser

The laser is driven by a current source power supply with 0-60 amp D.C. to produce up to 15 Watts C.W. optical output power. The optical bandwidth is approximately 12 nano-meters wide. This wide bandwidth makes the output nearly incoherent. Specifications are given in Table I.

	6401-A
Output power	≥15 W
Operating current	< 60A
Operating voltage	< 1.5 V
Center wavelength	1532 nm
Wavelength tolerance	± 10 nm
Spectral width (FWHM)	< 12 nm
Wavelength temperature coefficient	0.35 nm/°C
Fiber core diameter (nominal)	400 μm
Fiber NA (nominal)	0.22
Fiber length	1 m
Fiber output connector	SMA
Operating/Test temperature	20° C
Internal thermister	NTC 10K Ω
Module size (L x W x H)	100mm x 41.5mm x 31.5mm

Table 1 Diode Laser Specifications

3.0 SPECKLE NOISE LIMITED SIGNAL TO NOISE RATIO

Many LADAR systems are illuminated with a narrow optical bandwidth coherent laser source. This gives rise to speckle noise corrupting the return signal. Idell and Webster[1] describe speckle noise limited SNR in a coherent imaging LADAR. Speckle noise is often the factor limiting SNR even in a direct detection system. In the spatial frequency domain, the SNR can be given by:

$$SNR = \frac{K|O(f)||T_p(f)|}{\{K + K^2[M(f)]^{-1}\}^{1/2}}. \tag{1}$$

In equation (1) K is the expected number of detected photons per image integration, O(f) is the modulus of the normalized spectrum of the observed scene, Tp(f) is the optical system incoherent pupil transfer function in the spatial frequency domain, and M(f) is a frequency domain space-bandwidth product parameter that modulates the excess noise produced by coherent speckle of the illuminator.

As K becomes large, the second term in the denominator dominates and we are in the high signal level regime. Then equation (1) becomes:

$$SNR = |O(f)||T_p(f)|[M(f)]^{1/2}. \tag{2}$$

Idell and Webster go on to show that the function M(f) can be approximated by:

$$M(f) \cong \frac{M_0}{T_p(f)}, \tag{3}$$

where M_0 is the number of coherent speckles across the image scene. This gives:

$$SNR \cong |O(f)|[M_0 T_p(f)]^{1/2}. \tag{4}$$

As a further simplification assume that the observed scene contains high spatial frequency information out to the Nyquist frequency of the imaging system. Then |O(f)|~1 and

$$SNR \cong [M_0 T_p(f)]^{1/2} \tag{5}$$

Depending on the shape of the imaging system aperture, $T_p(f)$ will decrease approximately linearly from 1 at f=0 to zero at the Nyquist frequency. This means that the signal to noise ratio for high spatial frequencies near the Nyquist frequency will always be less than or equal to one, no matter how high the illumination intensity. This is often a severely limiting factor in achieving high fidelity images with high spatial frequency content.

4.0 ILLUMINATOR SCINTILLATION

A second problem in LADAR systems is scintillation of the illuminator beam. After propagation over some path length through atmospheric turbulence, the plane wave laser illumination beam will experience intensity fluctuations known as scintillation[2,3]. Using the Rytov approximation to obtain solutions to the wave equation we can obtain the covariance of the log amplitude of the electric field for two point separated by r, after propagating over a path L, and at wave number k by:

$$B_\chi(\rho, L, k) = 4\pi^2 \int_0^L \int_0^\infty K J_o(K\rho) H_\chi(L-\eta, K, k)\Phi_n(K,\eta) dK d\eta, \tag{6}$$

where

$$H_\chi(x, K, k) = \{k \sin[K^2 x/(2k)]\}^2 \tag{7}$$

Evaluation of (6) at a point where $\rho \to 0$, and for a monochromatic wave with wave number k, gives the variance of the log amplitude as[2]

$$\sigma_\chi^2(L,k) = 0.56k^{7/6}\int_0^L C_n^2(\eta)(L-\eta)^{5/6}d\eta \qquad (8)$$

We next want to consider a non-monochromatic source made up of a number of partially coherent radiators spread over an optical wavelength band. In this case:

$$\sigma_\chi^2(L) = \int\int B\chi(0,L,k_1,k_2)MCF(k_1,k_2)dk_1dk_2 \qquad (9)$$

Where *MCF(k1,k2)* is the mutual coherence function between the radiator at wave number k_1 and the radiator at k_2. The effect of the MCF term in equation (9) is to act as a filter on the log amplitude spectrum and depending on the coherence of the radiators, reduce the log amplitude variance. Thus the wide bandwidth nearly incoherent diode laser illuminator beam can be expected to have a reduced level of scintillation when compared to that of a narrow band highly coherent illuminator.

5.0 LABORATORY COMPARISONS

We consider in this section laboratory image data showing a comparison between coherent narrow band laser illumination, and the diode laser illuminator with its wider band incoherent illumination.

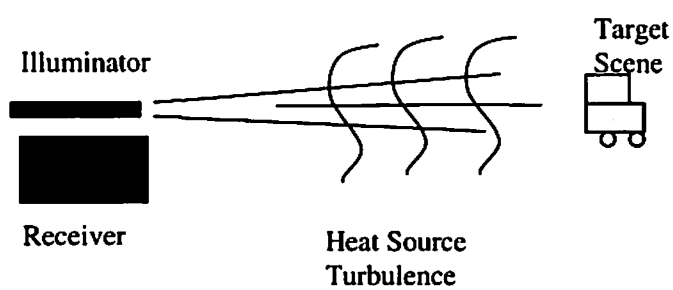
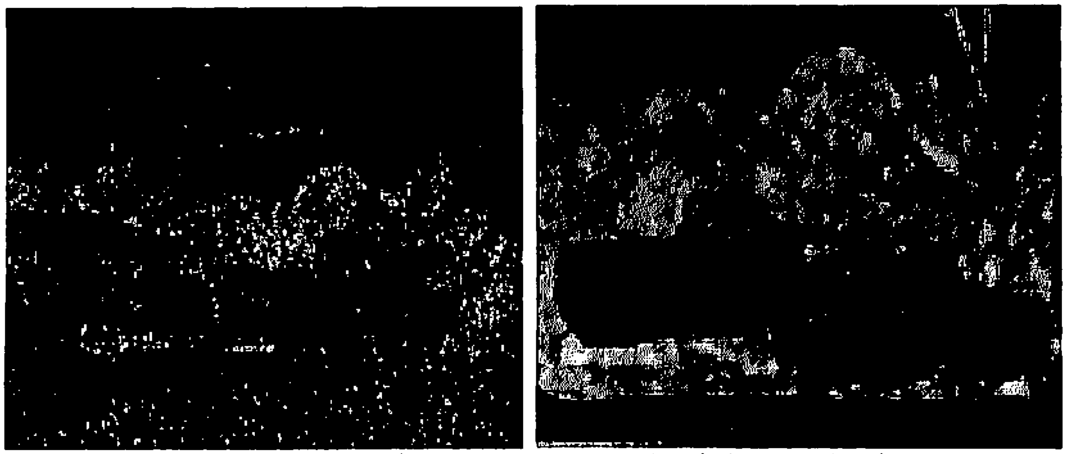


Figure 4.1 Layout of Laboratory Experiments

The layout for laboratory experimentation is shown in figure 4.1. A heat source with a fan blowing across it is used to generate turbulence along the beam path from the illuminator to a target. The target is constructed from model trucks, and natural vegetation. Light then scatters from the target back to the receiver.

Figure 4.2 shows a comparison between images taken in the laboratory with the highly coherent laser illuminator and the nearly incoherent diode laser illuminator.



a) Highly Coherent Laser Illuminator b) Diode Laser Illuminator

Figure 4.2 Comparison of Imagery Produced with a Coherent Laser and a Diode Laser Illuminator.

Figure 4.2 a) illustrates the effect of the coherent speckle noise and illuminator scintillation on the signal to noise ratio of the received image. At high spatial frequencies, near Nyquist, the SNR drops below one. On the other hand figure 4.1 b), with the scene is illuminated with the nearly incoherent diode laser, shows a much better SNR at the high spatial frequencies.

6.0 CONCLUSIONS

Recent advances in high power laser diode technology make them attractive for both CW and QCW LADAR imaging systems. They have higher average power but lower peak power than short pulse Q-switched crystal lasers. They also have a much smaller weight and volume and better overall efficiency than the type of pulsed lasers we have been working with, making them suited for integration into smaller ball turrets. These lasers have the advantage of a wide optical bandwidth and so the output is nearly incoherent which greatly reduces speckle noise in the resulting imagery. However they must be used with cameras with low dark current so that exposures on the order of 1/30 second can be obtained without appreciable dark noise. The cost per Watt of average output is a small fraction of that of a conventional Q-switched laser.

We have tested a 15 Watt fiber coupled diode laser from QPC lasers. The fiber coupled output has nearly diffraction-limited divergence when used in conjunction with collimator optics. Imaging tests were conducted in the lab in Albuquerque using an INDEGO/FLIR camera with 1/30 second exposures. Images using the diode illuminator were compared with those from a Q-Switched laser. At high spatial frequencies, the signal to noise ratio was much greater when using the diode illuminator because of the lower speckle noise and illuminator scintillation.

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