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This work contributes to the Micropulse Laser Designation (MPLD) project. The objective of MPLD is to develop a 6-lb eye-safe micro-pulse laser system to locate, identify, range, mark, and designate stationary and moving targets. MPLD uses laser pulses of much lower energy and higher repetition rates than in existing laser designation systems. Because of this, MPLD presents a range of new circuit design and signal processing problems, and the present work seeks to address some of these problems.

Work to date has involved investigating techniques for increasing photodiode amplifier bandwidth, and reducing photodiode amplifier noise. Circuit simulations have indicated significant bandwidth and noise improvements compared with basic photodiode amplifiers. A basic calculation of visibility angles for designation in urban environments has also been made.

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**Monthly Progress Report on NSWC Grant N00178-08-1-9001**

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## I. Introduction

This work contributes to the Micropulse Laser Designation (MPLD) project. The objective of this project is to develop a 6-lb eye-safe micro-pulse laser system to locate, identify, range, mark, and designate stationary and moving targets.

MPLD uses laser pulses of much lower energy and higher repetition rates than in existing laser designation systems. Because of this, MPLD presents a range of new circuit design and signal processing problems, and the present work seeks to address some of these problems.

Work to date has involved investigating techniques for increasing photodiode amplifier bandwidth, and reducing photodiode amplifier noise. A basic calculation of visibility angles for urban environments has also been made. Details are given in Section II.

## II. Narrative and Research Accomplishments

A photodiode can be modeled as a current source in parallel with a capacitance, as illustrated in Figure 1.

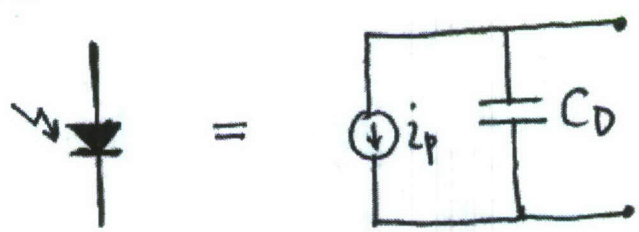


Figure 1. Photodiode equivalent circuit.

The photodiode envisaged for the present system has capacitance $C_D$ = 225 pF. Since the signal has a bandwidth of about 3 MHz and a gain of about 1000 is desired, this presents formidable problems to the circuit designer. Because of the low power of the laser pulses, the amplitude of the input signal is very small, and therefore a further important consideration is to minimize the noise of the circuit. Unfortunately, photodiode amplifiers have very complex noise response.

The appropriate amplifier for a photodiode is a current-to-voltage amplifier (transconductance amplifier), the basic form of which is illustrated in Figure 2.

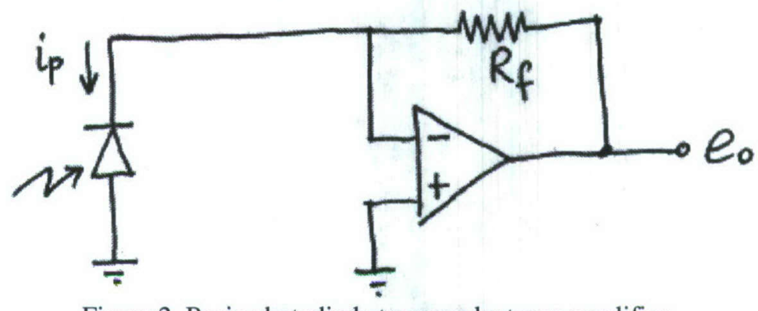


Figure 2. Basic photodiode transconductance amplifier

Because of the virtual ground at the op-amp's inverting input pin, the voltage across the diode is very small. This helps to ensure a large amplifier bandwidth by reducing currents through the diode capacitance $C_D$, thereby ensuring that almost all of the diode current passes through the feedback resistor $R_f$ rather than through $C_D$.

Bandwidth can be further increased by decreasing the closed-loop gain of the op-amp connected to the diode. If this is done, the overall gain can be brought up to the desired value by using more than one stage of amplification, as illustrated in Figure 3.

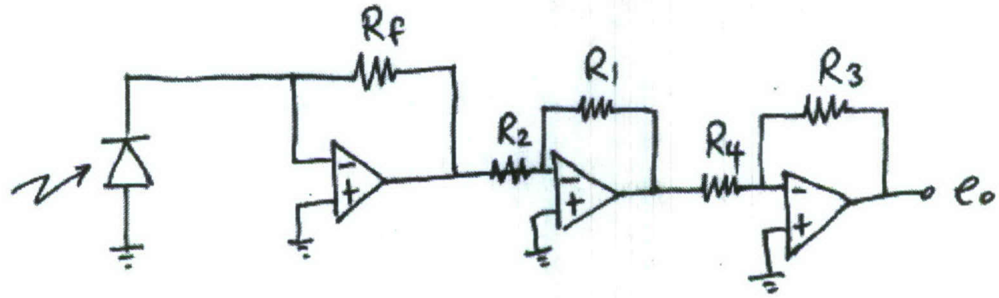


Figure 3. Three stage photodiode amplifier.

When used as a photodiode amplifier, the transconductance amplifier exhibits a complex noise behavior, in spite of the apparent simplicity of the basic circuit of Figure 2. The nature of this noise response and methods of reducing noise are presented in chapters 5 and 6 of reference [1]. The noise behavior of the photodiode amplifier has the following two undesirable properties that distinguish it from most other op-amp circuits:

1. There is "noise gain peaking" at high frequencies due to the interaction of parasitic capacitances within the amplifier. Above a certain frequency, the noise gain increases before eventually leveling off and then decreasing again once the op-amp's open-loop gain roll-off is reached, as illustrated in Figure 4 below.
2. The circuit amplifies the signal with a lower bandwidth than that with which the noise is amplified.

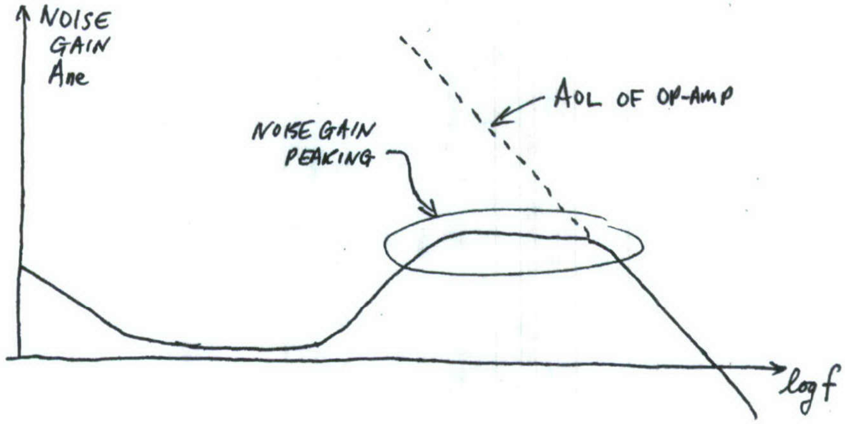


Figure 4. Photodiode amplifier noise gain, showing noise gain peaking.

This project is investigating several approaches to increasing the signal bandwidth of the amplifier, and limiting the adverse effects of noise caused by noise gain peaking and excessive noise-gain bandwidth.

**Bootstrapping the photodiode**

The signal voltage across the photodiode in the basic circuit of Figure 2 is very small, of order $e_0/A_{OL}$, where $A_{OL}$ is the op-amp open-loop gain. However, our application makes use of a photodiode with a high capacitance (225pF) and requires a bandwidth of about 3 MHz. This is a stringent requirement to satisfy, and it was found that even the small $e_0/A_{OL}$ signal voltage across the diode capacitance caused the bandwidth to be too low.

Bootstrapping reduces the voltage across the photodiode even further, by connecting a unity-gain buffer across it. The idea is illustrated in Figure 5, where an ideal unity-gain buffer is connected across the diode.

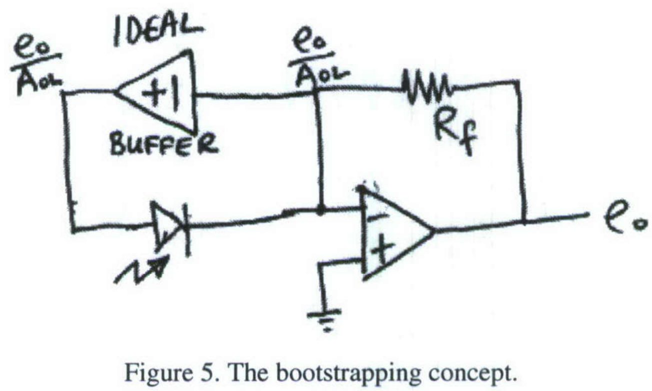


Figure 5. The bootstrapping concept.

The ideal buffer ensures that the voltage across the diode is exactly zero at all times, and of course this eliminates all influence upon the circuit by the diode capacitance $C_D$. This was verified by simulating the circuit of Figure 5 using a voltage-dependent voltage source for the ideal buffer.

In the real world, of course, an ideal buffer does not exist. For bootstrapping to be successful, the buffer must satisfy four stringent requirements:

1. low input capacitance (buffer input capacitance must be much less than photodiode capacitance)
2. low noise (buffer noise must be less than op-amp input noise)
3. wide bandwidth (buffer bandwith must be much higher than op-amp bandwidth)
4. low output impedance

Figure 6 shows a modified version of the 3-stage circuit of Figure 3, where bootstrapping has been implemented using a fourth op-amp connected as a unity-gain follower.

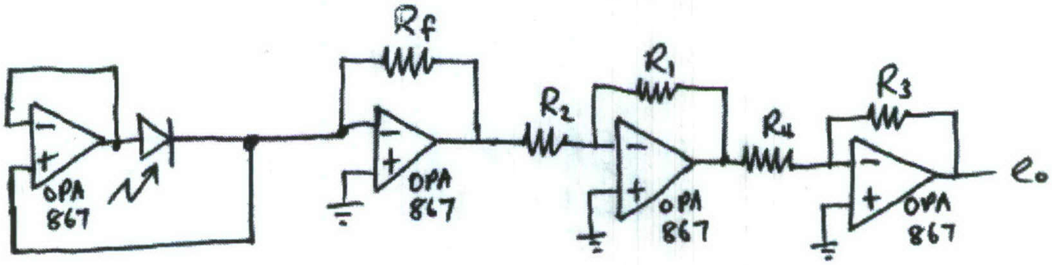


Figure 6. Bootstrapped three-stage photodiode amplifier using unity-gain op-amp buffer.

Simulation showed that the bandwidth of this amplifier did not increase to the extent anticipated. This was initially surprising, but it clearly demonstrated just how stringent the above 4 requirements upon the buffer actually are. Essentially, what was going wrong was that the buffer did not have a wide enough bandwidth in spite of the op-amp's large crossover frequency, because the crossover frequency of the OPA687 is not stable to low closed-loop gain.

The op-amp follower circuit was then replaced with a specialized unity-gain follower, the MAX4200, as shown in Figure 7.

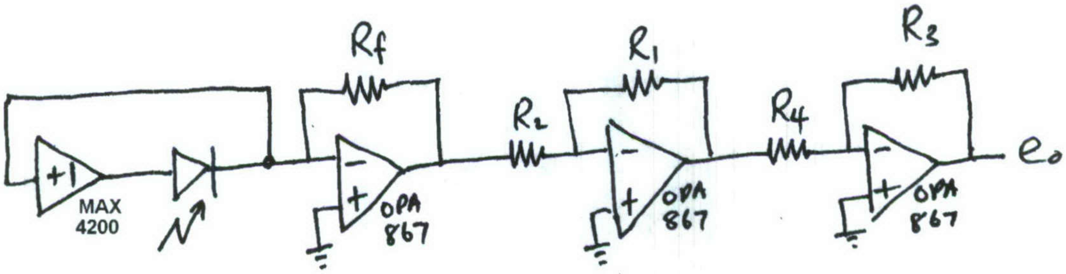


Figure 7. Bootstrapped photodiode amplifier using MAX4200 buffer.

Under simulation, the circuit of Figure 7 provided greatly improved bandwidth and lower noise as compared with Figure 3. This is to be expected, because the MAX4200 has 2pF input capacitance, low noise, 660 MHz bandwidth, and 8Ω output impedance, and therefore satisfies the four very stringent requirements listed earlier.

Another approach is to use a discrete circuit rather than an integrated circuit for the unity gain buffer. Shown in Figure 8 is a bootstrapped photodiode amplifier using a discrete unity gain buffer. The buffer consists of the three JFETs, one BJT and associated resistors.

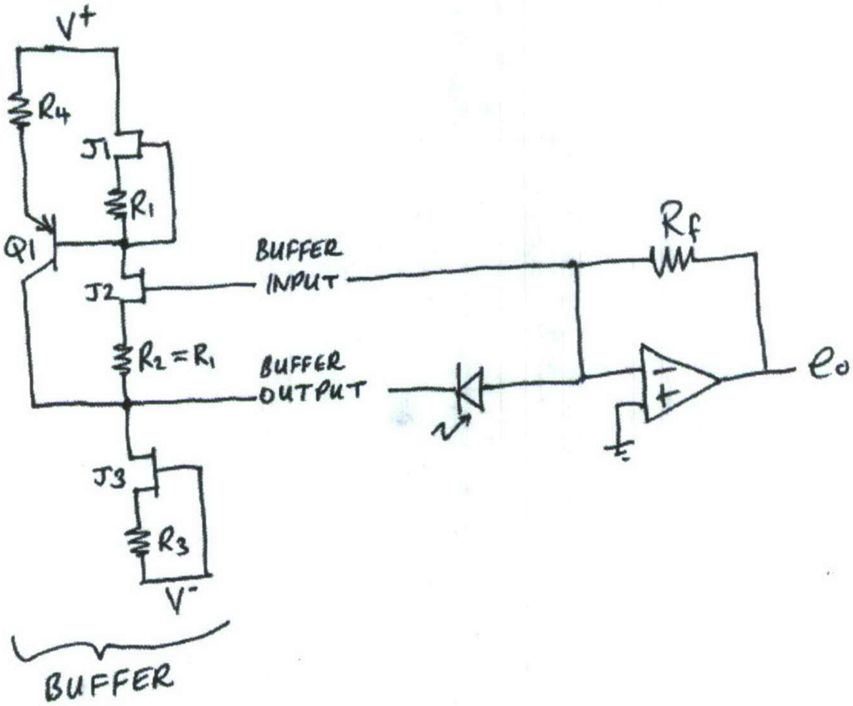


Figure 8. Bootstrapped photodiode amplifier using discrete buffer.

## Approaches to reducing noise

The bootstrapped three-stage amplifier circuit of figure 7 has potential for further noise reduction because the problems of noise-gain peaking and inequality between signal and noise-gain bandwidth.

To reduce noise peaking: One way of reducing noise is to put a capacitance across the feedback resistor $R_f$ of the transconductance amplification stage. This functions by reducing the magnitude of the noise-gain peaking, i.e. it reduces the height of the high-frequency "bump" in the noise gain curve of Figure 4.

To reduce noise-gain bandwidth: A pole in the signal gain response causes it to start rolling off at a lower frequency than the noise gain response. The result is that there is a range of frequencies where the op-amp is amplifying noise and not signal. This can be dealt with by reducing the open-loop gain of the op-amp so that the roll-off in open-loop response prevents the unnecessary amplification of noise within this range of frequencies.

Figure 9 shows a variation of the basic photodiode transconductance amplifier where a second op-amp $A_2$ is placed within the feedback loop in order to modifying the open-loop response of op-amp $A_1$. Examination of Figure 9 shows that the modified open-loop response has the following behavior:

1. At low frequencies, $C_1$ is open circuit, so that the full open-loop gain of $A_2$ is contributed to the composite amplifier.
2. At high frequencies, $C_1$ is short circuit, so that $A_2$ contributes a gain of $R_2/R_1$ to the composite amplifier. (By choosing $R_2<R_1$, we ensure that this contribution is in fact an attenuation).

We see that the effect of including op-amp $A_2$, we are reducing the open-loop gain of the composite amplifier for high frequencies. By appropriate choice of $R_1$, $R_2$, and $C_1$, we can control the open-loop response such that the noise-gain bandwidth is made equal to the signal-gain bandwidth. Details are in reference [1], pages 117-118.

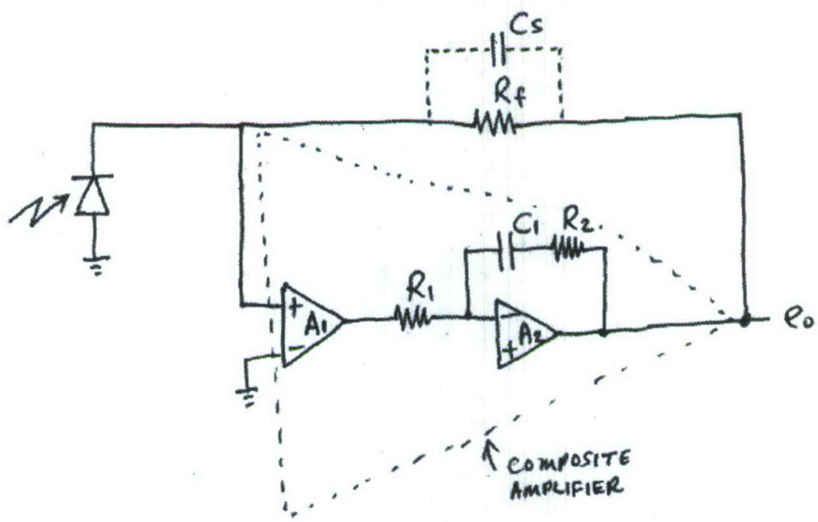


Figure 9. Noise-gain reduction using a composite amplifier.

## Visibilty of laser designation in urban areas

Assume that a laser spot is positioned at ground level against the wall of a building of height h in a street of width w. It is assumed that all buildings are of the same height h on both sides of the street. We calculate the visibility of the laser spot from the air.

Figure 10 shows a plan view of the situation. T is the location of the laser spot, and E is the vertical projection of the position of the viewer in the sky. $\Phi$ is the azimuth angle, the angle between the viewing direction and the perpendicular to the direction of the street.

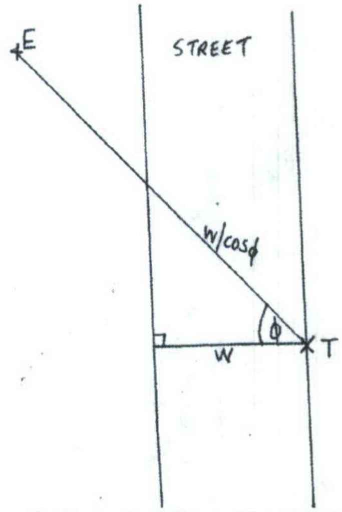


Figure 10. Plan view of street of width w. T is the designated target, E is the eye in the sky, φ is the azimuth angle.

Figure 11 shows a side view in the vertical plane through ET, i.e. the vertical plane at azimuth angle Φ. The angle θ is the angle between the vertical and the line ET. The Visibility Angle θmax is the maximum value of θ for which the laser spot would be visible.

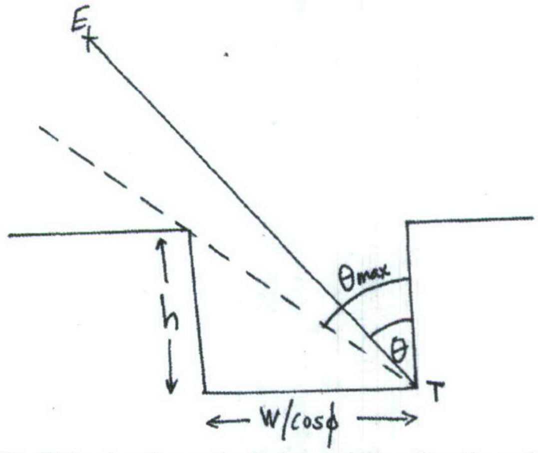


Figure 11. Side view in vertical plane of the azimuth angle φ.

From Figures 10 and 11, we see that $\tan\theta_m = \dfrac{w/\cos\phi}{h} = \dfrac{w}{h\cos\phi}$, so that

$\theta_m = \tan^{-1}\dfrac{w}{h\cos\phi}$. Figure 12 plots the maximum visibility angle versus building height for various azimuth angles.

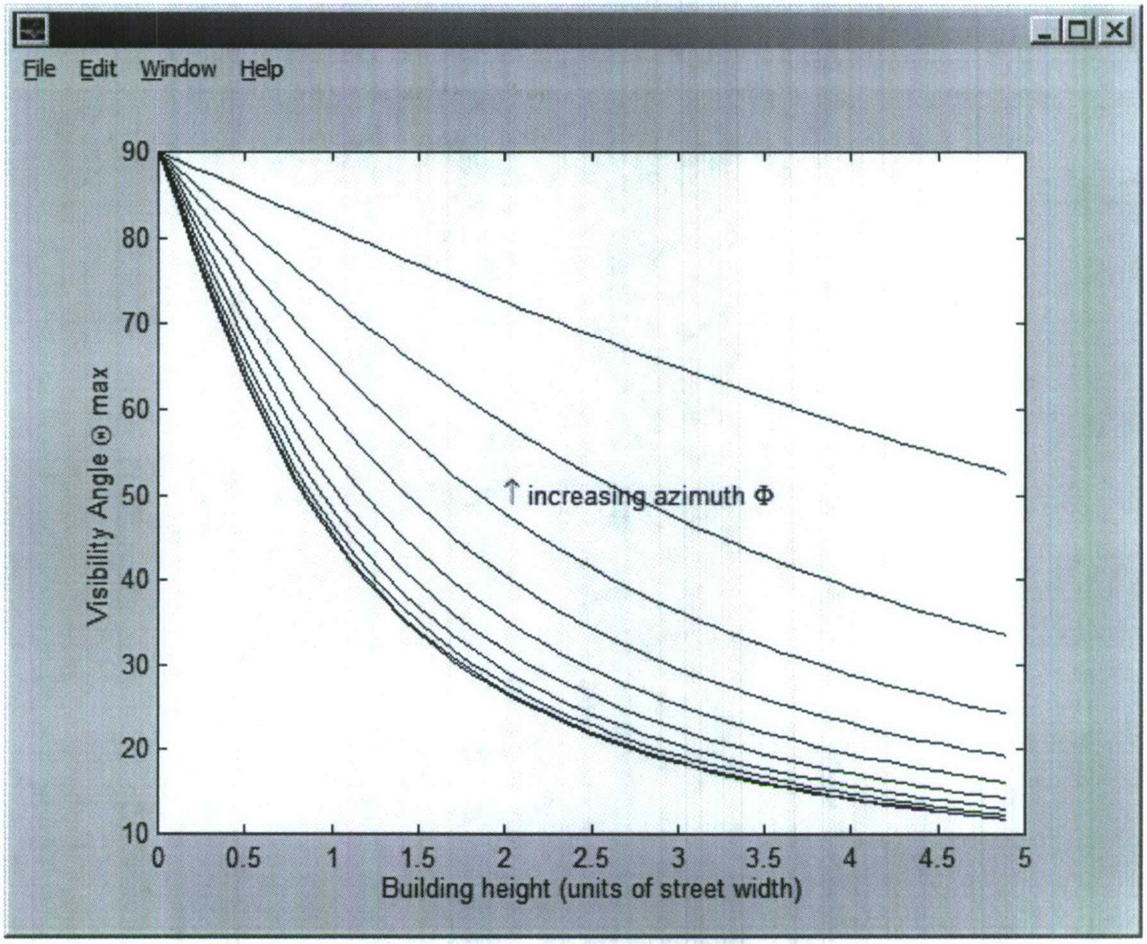


Figure 12. Visibility angle as a function of building height.

## References


1. Jerald Graeme, "Photodiode amplifiers – Op Amp Solutions", McGraw Hill 1996.
2. MAX4200 data sheet, Maxim Integrated Products, 120 San Gabriel Drive, Sunnyvale, CA 94086