High-power photo-detection system for next-generation gravitational wave detectors

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Abstract. In next-generation interferometric gravitational wave detectors that are being designed, the power of their light sources will be larger than 100 W. As a consequence, the light power at the detection port of the interferometers must be increased by a factor of more than 10, compared with that of the current detectors; thus, a high-power photo-detection system is indispensable. Here, we present the photo-detection system which can detect the laser power of 500 mW at 1064 nm with a single photodiode of 3-mm diameter. Its response to DC and AC input signals are reported.

In order to detect gravitational waves (GWs) that were predicted by Einstein’s general relativity, large interferometers (LIGO in USA, VIRGO and GEO600 in Europe, TAMA300 in Japan) have been constructed and are being operated[1]. There are various noise sources limiting the sensitivity of the interferometers. Since the laser shot noise, which is inverse-proportional to the square-root of the laser power, is one of the main noises, high-power lasers have been developed (their output power was about 10 W); for example, an injection-locked laser-diode-pumped Nd:YAG laser was developed for TAMA300[2]. Although the sensitivity of the interferometers has now reached the design sensitivity at almost all frequency range[3], the probability that GWs can be observed is considered to be still low. Thus, the next-generation detectors that will have 10 times better sensitivity than the current one are designed such as Advanced LIGO[4] and LCGT[5].

In the next-generation interferometric detectors, the power of their light sources will be larger than 100 W[6]. As a consequence, the light power at detection ports of the interferometers must be increased by a factor of more than 10, compared with that of the current detectors.

For detecting such high laser power, several approaches have been done. One was to search for a suitable photodiode[7, 8]; the maximum power detectable with a single photo-diode was investigated under various conditions. The other was to develop the multiple photo-diode system[9]; here 16 photo-diodes were used to detect the power of about 2.3 W.

As for TAMA300, when the laser output power is 6 W, the typical power at the dark fringe is about 50 mW, which is detected with 4 photodiodes; InGaAs photodiodes of 1-mm diameter are used. We have shown that the diode is capable of detecting the light power higher than 100 mW[10].

Since LCGT will use the laser of 150-W output, we need to detect the dark-fringe power larger than 1.2 W if the same fringe contrast as that of TAMA300 is obtained. In order to
simplify the detection system, it is quite important to increase the power that can be detected by a single photodiode; if the number of the diodes is assumed to be 4, each diode is required to detect the light power of more than 300 mW.

Here, we describe the photo-detection system that can be used for the next-generation GW detectors; we have shown the maximum power of our system is about 500 mW with a single photodiode.

1. Photodiode selection

In order to enlarge the detectable power level, it is important to reduce the power density on the diode to avoid the saturation of photo-carrier generation, As is well known, the larger diameter is advantageous for detecting higher laser power[7]. In order to detect the light power as high as discussed above, we considered that a detection area should be almost ten times larger than that of the current photodiode. Thus, we decided to use a photodiode (InGaAs PIN type) of 3-mm diameter and looked for suitable products; table 1 shows commercially available photodiodes with their specifications. Since the response speed of photodiodes is predominantly limited by its capacitance, the response of large photodiodes is usually slow. From the data in table. 1, we decided to make further investigation of Hamamatsu G5125-30 because its capacitance was the smallest among them.

**Table 1.** List of InGaAs photodiodes of 3-mm diameter. Here, \( f_c \) is the cut-off frequency measured with 50-\( \Omega \) load, \( C_t \) is the capacitance of the diode, \( V_r \) is the reverse-bias voltage, respectively.

| Name     | Manufacture | \( f_c \) (MHz) | \( C_t \) (pF)          |
|----------|-------------|-----------------|-------------------------|
| G8370-83 | Hamamatsu   | 2               | 1000 \((V_r = 1 V, V_{r\text{ max}} = 2 V)\) |
| G5125-30 | Hamamatsu   | 4               | 500 \((V_r = 1 V, V_{r\text{ max}} = 5 V)\) |
| 30665G   | PerkinElmer  | 3               | 1000 \((V_r = 0 V, V_{r\text{ max}} = ?)\) |

In order to improve the response speed and the linearity of photodiodes, the reverse bias voltage \((V_r)\) is applied; the larger bias realize the smaller capacitance, the faster speed and the better linearity. According to the specifications given by the manufactures, the maximum bias voltage is 2 ~ 5 V. However, diodes can be operated under higher bias voltage than the specification[7].

We measured the capacitance \( C_t \) of G5125-30 as a function of \( V_r \); the measurement frequency was 200 kHz which was limited by the instrumental capability. We obtained the relation expressed as

\[
C_t = C_0 \left( \frac{V_r}{1 V} \right)^{-\beta} \quad (1 V < V_r < 10 V),
\]

where \( C_0 = (507.7 \pm 0.4) \text{ pF} \) and \( \beta = (0.2856 \pm 0.0006) \) for G5125-30. When \( V_r \) was 10 V, the capacitance was 263 pF; this value indicates that this photodiode can be used to detect the photo-signal with sufficient bandwidth.

When a photo-current \((I_p)\) is extracted from the photodiode under high bias voltage, we must care for the dissipation power given by \( V_r I_p \), which generates heat and raises the temperature of the photodiode. Thus, the sufficient cooling is necessary for long term and stable operation.

2. Linearity measurement

First, we measured the linearity of the photodiode. In order to avoid the heat damage, the photodiode was cooled with dry ice as shown in figure 1. The photodiode was attached to an
aluminum base that was cooled with a piece of dry ice; pure aluminum was used owing to its high thermal conductivity. The use of dry ice made the system quite simple and was good for the first trial measurement. The optical system is shown in figure 2. We used a laser-diode pumped Nd:YVO₄ laser of 1-W output power at 1064-nm wavelength. The laser light was introduced to the photodiode through a lens, an acousto-optic modulator (AOM) and an attenuator; the AOM was used to give intensity modulation that was necessary to measure the AC response of the photodiode. A concave mirror (curvature radius: 3 m, reflectance: $R = 0.95$) was also used in order to make the appropriate beam size; its transmitted light was used for monitoring incident power. The photo-current from the photodiode was fed to a wide-band current-to-voltage converter; its maximum current and bandwidth were 500 mA and 5 MHz, respectively.

![Image of photodetection system](image)

**Figure 1.** Photo-detection system. The photodiode is attached to an aluminum base cooled with a piece of dry ice; pure aluminum is used owing to its high thermal conductivity. The electric circuit is installed in a black aluminum case.

We measured the linearity with different bias voltages and beam sizes. As previously reported[7], the linearity could be improved with higher bias voltages and larger beam sizes. We confirmed that the photodiode could be operated with 10-V bias voltage but had not tested it with higher voltage in order to avoid breaking the photodiode.

After several trial measurements, the beam diameter was set to be about 1.3 mm to obtain the optimum output. The AC response was measured when the laser intensity was modulated by the AOM at 1 MHz and the bias voltage was 10 V. The modulation frequency was limited by the bandwidth of the AOM. As is shown in figure 3, the linearity was confirmed within the power of 500 mW for DC. As for AC response, since small saturation was observed at 500 mW, we consider that the linearity was limited within 450 mW. The modulation index could be calculated from the efficiency of the AOM; when the amplitude of applied voltage is 0.1 V, intensity modulation of 3 % can be generated. These values satisfied the requirements mentioned above.

![Image of optical system](image)

**Figure 2.** Schematic diagram of the optical system. The light from a laser-diode pumped Nd:YVO₄ laser of 1-W output power at 1064-nm wavelength is introduced to the photodiode through a lens, an acousto-optic modulator (AOM) and an attenuator. A concave mirror (curvature radius: 3 m, reflectance $R = 0.95$) is also used in order to make the appropriate beam size.
0.1375Vp-p + 0.275Vp-p  
0.1375Vp-p + 0.275Vp-p  

Figure 3. DC and AC responses of the photodiode. The linearity is maintained within 500-mW incident power for DC (left) and 450-mW for AC (right). The voltages shown in the figures express the peak-to-peak amplitude of the applied voltage to the AOM for modulation; applied voltage of 0.1 V corresponds to 3 % intensity modulation.

3. Photodiode with electric cooling system

Although the use of dry ice was very simple and effective, it was not suitable for the actual use for continuous operation. Thus, we tested an electric cooling system that made use of a thermoelectric (TE) cooler; its schematic view is shown in figure 4. The photodiode was attached to a copper base, which was cooled by a TE cooler (dimension: 25 mm × 25 mm × 4 mm, maximum current: 4A, maximum heat transfer rate: 21 W). The TE cooler was provided on a heat sink having a cooling fan. A thermistor was attached the backside of the photodiode in order to monitor the temperature of the photodiode. The photo-current was fed to the circuit shown in figure 5, where the constant bias voltage (10 V) was applied with LM317T and LF356[11].

Figure 4. Electric cooling system of the photodiode (PD). PD is attached to a copper base, cooled by a TE cooler that is provided on a heat sink with a fan. A thermistor is attached for monitoring the PD temperature.

Figure 5. Electric circuit for the photodiode where the constant bias voltage (10 V) is applied with LM317T and LF356.

Figure 6 shows the DC output and the temperature of the photodiode as a function of the incident power. Although the temperature was changed from -10 °C to 20 °C, the linearity was
maintained when the incident power was lower than 500 mW; the straight line was obtained by least-square fit using the data measured when the incident power was lower than 500 mW. The quantum efficiency $\eta$ was calculated from the line slope as 0.83; this result was consistent with that given in the previous report[10].

Since the cooling fan was found to be very noisy, we have to replace the fan with a water tiller or a large heat sink. We also found the switching regulator for the current source of the TE cooler was quite noisy but the series regulator was almost harmless. These issues must be considered when the electric cooling system is used in actual interferometers.

![Figure 6](image-url)

**Figure 6.** DC output and the temperature of the photodiode as a function of the incident power. The straight line is obtained by least-square fit using the data measured at the power of lower than 500 mW. The quantum efficiency $\eta$ is calculated from the line slope as 0.83.

### 4. RF response

If the RF modulation technique is used in the interferometer, the photodiode must have sufficient bandwidth (10-20 MHz). Thus, we have measured the RF response of the photodiode at small signal level using a high-speed LED (Hamamatsu, L7558-01); its typical output powers was about 5 mW when the forward current was 50 mA. The intensity-modulated light from the LED was incident on the photodiode and the output was led to a wide-band and low-noise amplifier. The circuit diagram of the amplifier is shown in figure 7; its input equivalent voltage noise was 1.15 nV/$\sqrt{\text{Hz}}$ at 1 MHz, which was predominated by the voltage noise of MAX4106 and the thermal noise of the resistors.

The response of the photodiode is presented in figure 8 as a function of frequency; this response function, normalized with the DC signal response, can be expressed as the following complex function,

$$G(\omega) = \frac{1}{1 - \omega^2 LC + i\omega RC}. \quad (2)$$

By fitting the above equation to the data, we obtained $LC = 7.06 \times 10^{-17}$ s$^2$ and $RC = 5.13 \times 10^{-9}$ s. We used a twisted-pair wire in order to connect the photodiode and the amplifier; the wire had the capacitance of 8.9 pF and the inductance of 0.25 $\mu$H. If $C$ is given by the sum of the diode capacitance and that of the wire, namely, $C = 263 + 8.9 = 272$ pF, we obtain $L = 0.260 \mu$H and $R = 18.9 \Omega$. Since the value of $L$ is almost same as that of the wire, we
consider that $L$ originated from the inductance of the wire. The value of $R$ was different from the apparent load resistor (10 $\Omega$); the difference was due to the AC loss of the diode capacitance and the equivalent series resistor of the diode.

Since the load resister of the circuit was 10 $\Omega$, which was not so high, the equivalent noise current was about 60 mA, which was calculated from the amplifier noise and the gain function. This value was quite large compared with the previous one[10] because the RF resonance was not adopted. If the RF modulation signal should be detected with much better signal-to-noise ratio, a resonance mechanism should be introduced in detection circuit.

![Figure 7. Wide-band and low-noise amplifier. The input equivalent voltage noise of the amplifier is about 1.15 nV/\sqrt{Hz} at 1 MHz, which is predominated by the voltage noise of MAX4106 and the thermal noise of the resistors.](image)

![Figure 8. RF response of the photodiode measured with a high-speed LED. The curve is obtained by fitting the gain function given in eq.(2) to the data.](image)

5. Conclusions
We have measured the linearity of the InGaAs photodiode Hamamatsu G5125-30 that has 3-mm diameter. We confirmed that the photodiode can be operated for 500-mW incident power under 10-V bias voltage with a appropriate cooling system. As for the response speed, we found that the diode had the sufficient speed for AC signals (< 1 MHz). However, we need further circuit design improvement in order to use this diode for detecting RF (10-20 MHz) signals.

References
[1] Hough J, Rowan S and Sathyaprakash BS 2005 J. Phys. B: At. Mol. Phys. 38 S497.
[2] Yang ST, Imai Y, Oka M, Eguchi N, and Kubota S 1996 Opt. Lett. 21 1676.
[3] Waldman SJ 2006 Class. Quantum Gravity 23 S653.
[4] http://www.ligo.caltech.edu/advLIGO/
[5] Kuroda K 2006 Class. Quantum Gravity 23 S215.
[6] Takeno K, Ozeki T, Moriwaki S, and Mio N 2005 Opt. Lett. 30 2110.
[7] Caron B, Dominjon A, Flaminio R, Hermel R, Lacotte JC, Marion F, Massonet L, Morand R, Mours B, Verkindt D and Yvert M 1995 Nucl. Instr. and Meth. in Phys. Res. A 360 379.
[8] Csatorday P, Marin A, Zucker M 1998 http://www.ligo.caltech.edu/docs/G/G980022-00.pdf.
[9] Jennrich O, Newton G, Skeldon KD and Hough J 2002 Opt. Commun. 205 405.
[10] Mio N, Ando M, Heinzel G, and Moriwaki S 2001 Jpn. J. Appl. Phys. 40 426.
[11] Rollins J, Ottaway D, Zucker M, Weiss R and Abbott R 2004 Opt. Lett. 29 1876.