Development of Pulse Detection IC for LIDAR on Planetary Lander

By Takahide MIZUNO, Hirokazu IKEDA, Kousuke KAWAHARA

The Institute of Space and Astronautical Science, Sagamihara, Japan

ABSTRACT

In recent years, LIDAR has been used in remote sensing systems, obstacle avoidance systems on planetary landers, rendezvous docking systems, and formation flight control systems. A wide dynamic range is necessary for LIDAR systems on planetary landers and in rendezvous docking systems. For example, a dynamic range of 60 dB was required for the receiving system used in the Hayabusa mission in order to measure distances between 50 m and 50 km. In addition, an obstacle detection and avoidance system of a planetary lander requires a ranging resolution of better than 10 cm. For planetary landers, ISAS/JAXA is developing a customized integrated circuit (IC) for LIDAR reception. This report introduces the design of the customized IC and reports the results of preliminary experiments evaluating the prototype, LIDARX03.

1 Introduction

In recent years, planetary exploration missions aiming to elucidate the origin of the solar system have been conducted, such as Hayabusa (Japan) [1], NEAR (USA), and Rosetta (Europe). Many of the explorers currently in operation or planned for observation of the moon and planets, such as SELENE, the Lunar Reconnaissance Orbiter, Messenger, Bepi-Colombo, and the Mars Global Surveyor, incorporate LIDAR as a critical navigation sensor for long-range measurements. The LIDAR system enables planetary explorers to measure distance from the target planet.

The receiving circuit of Hayabusa's LIDAR consists of discrete electric devices. In the present study, we aim to reduce the circuit area and shorten the development period, by using techniques for fabricating sub-micron analog integrated circuits (ICs) that were developed in the field of high-energy physics.[2] The proposed device also incorporates a circuit for timing detection and an interpolator. In addition, the proposed device must cover the wide signal dynamic range that is particular to planetary explorers. In the case of Hayabusa mission, the required ranging coverage of LIDAR was 50 m to 50 km. The distance from 50 m to 50 km corresponds to a dynamic range of 60 dB for the power of the incoming optical signal. The wide dynamic range is required not only an asteroid lander, but also required in the lunar lander SELENE2 mission.

In this paper, we discuss the required performance and functionality for LIDAR receiving circuits of planetary explorers. After this introduction, we present the design of a customized IC and report the current state of its development.

2 Required Specifications

We assume that the transmitting power (P_t) is 5 mJ, the wavelength of the laser is 1.064 um, the transmitted pulse width is 10 ns, the target reflectivity is 5%, the diameter of the receiving antenna is 100 mm, the system efficiency is 70%, and the distance from the target is 50 m. In this case, the incoming signal power is 6.87×10^{-11} J[3]. The corresponding number of photons is 1.5×10^{10}. Under the conditions described above, the efficiency and the multiplication of the APD are 40% and 100, respectively. In the case of R=50 km, the incoming signal power becomes 6.87×10^{-17} J (1.5×10^{4} photons). When the target distance changes from 50 m to 50 km, the incoming electrical charge changes from 2400 pC to 0.0024 pC. We are developing a customized IC that has a dynamic range of 60 dB for planetary explorers.

Since Hayabusa's LIDAR does not have a clock interpolator, the resolution of the ranging is decided by the clock of the 75-MHz digital counter. For this reason, its resolution was ±1 m. Scientific observations and navigation systems require improved resolution; however, improvements in the time resolution by adopting a higher frequency digital clock are not possible considering chip fabrication, screening tests, and the power consumption of the digital device. Then, in order to obtain higher resolutions a new device that employs a moderate-frequency clock, e.g. 20 MHz, together with a clock interpolator is raised as a candidate.

3 Design of Proposed Device

These procedures are fully conducted as a part of the in-house activity except for the third and fifth items. A photograph of the prototype bare IC chip referred to as LIDARX03 is shown in Figure 1. The procedure for fabrication is the Taiwan Semiconductor Manufacturing Company (TSMC) complementary metal-oxide semiconductor (CMOS) 0.35-um process that allows dependable manufacturing, with which we have considerable experience. The size of the bare chip is 3×3 mm^2. The package is a ceramic quad flat package (QFP) with a size of 14×14 mm^2 (80 pins). The following list is the development procedure:

Figure 2 shows the circuit structure of LIDARX03. LIDARX03 consists of a divider module, an integrator module, a timing detector module and a time-to-analog converter (TAC). The APD is located on an external test board and converts light signals to electrical charge. As mentioned above, there is a difference of about 60 dB between the signal levels of short-range and long-rang measurements.

The divider consists of a T-shaped circuit with a capacitor that is mounted on the outside of the device and divides a large quantity of electrical charge at short range into a suitable amount of charge. The dividing ratio of charge can be decided based on the ratio of internal and external capacitors. The combinations of external and internal capacitors are selectable with mechanical switches. Consequently, the device has five input channels through the various combinations of the dividers and the integrator. Therefore, the device has five steps of coarse adjustment for the gain. Each channel (CH0-CH4) has a gain range with a factor of 16, and the total dynamic range of the device reaches 60 dB ($16^5 \fallingdotseq 10^6$).

The integrator consists of a filter and amplifiers that can change the gain by changing the value of the feedback capacity. The feedback capacity can be changed with a 4-bit command. Using this function, the gain of the integrator can undergo fine adjustment. The compensation circuit of the pole/zero, PZC, is installed on the stage next to the integrator. The PZC circuit is to stablilize the DC level of the following leading/differential waves, and , hence, the influence of the input signal level on the detection timing is significantly mitigated.

The timing detector transforms the leading wave to a bipolar wave, which is referred to as a differential wave, and detects its zero-cross timing as the pulse detection timing. In order to prevent false detections caused by noise overlap on the differential wave, a threshold is set up for the leading wave; thus, only when the pulse height of the leading wave exceeds the threshold level that is set by external voltage, the HIT signal is generated at the zero-cross timing. The main functions of this device are its 60-dB dynamic range with the divider and the integrator and timing detection using the timing detector.

The TAC is activated by the HIT signal generated in the timing detector. A saw wave (about 4 mV/ns) begins to rise upon detection of the leading edge of the HIT signal. Then, the analog voltage of the saw wave is held at the timing of STOP signals synchronized with the digital clock and output the held voltage. The zero-cross point is estimated from the analog voltage of the TAC. In order to estimate the zero-cross timing, the inclination of the saw wave is highly important. However, the inclination has a non-negligible depencence on temperature, power-supply voltages and possibly drifts as a function of time. Therefore, the TAC produces an analog voltage twice. As a result of this function, the change in the inclination of the saw wave does not influence the estimation.

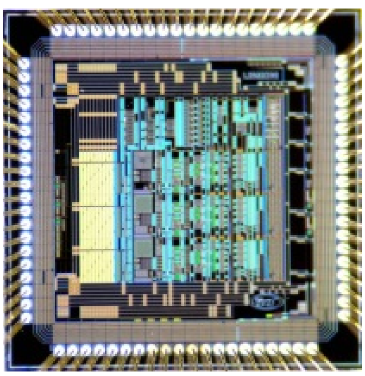


Fig. 1. Bare chip of prototype IC (LIDARX03)

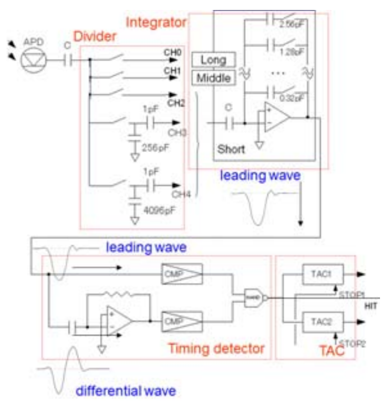


Fig. 2. Circuit outline (LIDARX03)

In the evaluation system, the clock of the digital controller is 15.625 MHz, and thus the interval time of STOP signals is 64 ns. Since the timing estimation uses analog voltage, the resolution of interpolation depends on the resolution and the accuracy of analog-to-digital converter (ADC) mounted on the test board.

This device has a test port (TP) in order to evaluate the internal circuit without an APD. The TP is directly connected to the integrator by an internally mounted capacitor. Thus, a voltage step can be substituted for the signal from the APD.

4 Results of Evaluation

Figure 3 shows typical output waveforms from LIDARX03. The top waveform is a bipolar wave that is transformed from a leading wave. The timing detector detects the zero-cross timing of this waveform and generates a HIT signal (second waveform). The saw wave from the TAC starts rising upon being triggered by the leading edge of the HIT signal. The amplitude of the saw wave is generated twice according to the timing of the digital clock following the HIT signal. These two analog values are output as TAC1 (third waveform) and TAC2 (forth waveform). The HIT timing is estimated with TAC1 and TAC2. Therefore, stability and repeatability are important for measuring TOF. The zero-cross timing of bipolar waves must be stable, because this is the origin of the HIT signal.

The main function of the proposed device is timing detection of light pulses in a 60-dB dynamic range at the input level. In order to evaluate this function, we measured the behavior of this device by changing the input electrical charge. The amount of input charge changed from 0.001 pC to 3000 pC. Figure 4 shows the input charge dependence of the detected pulse (HIT) timing and the signal amplitude. In this figure, marks show coarse adjustment of CH and line styles show fine adjustments of gains. CH0 is designed for a long-distance measurement, and CH4 is designed for a short-distance measurement. The gain setting of “0000” means maximum gain of the integrator and “1111” means minimum gain of it. The vertical axis of Fig.4 (a) shows the time from the system trigger of the digital counter, thus, only the relative timings of each channels and gain settings are important.

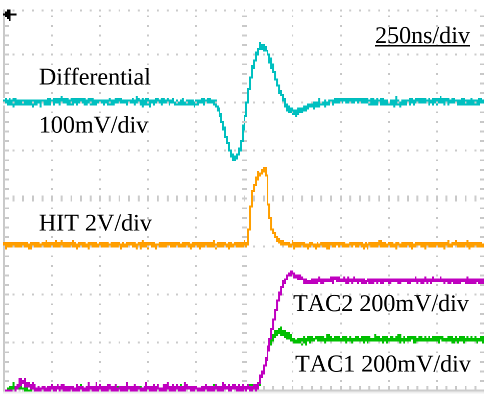
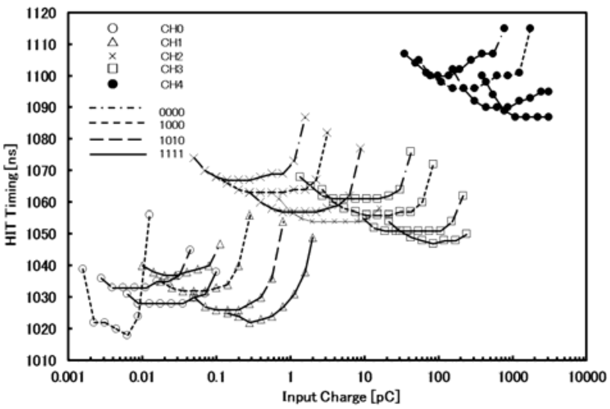
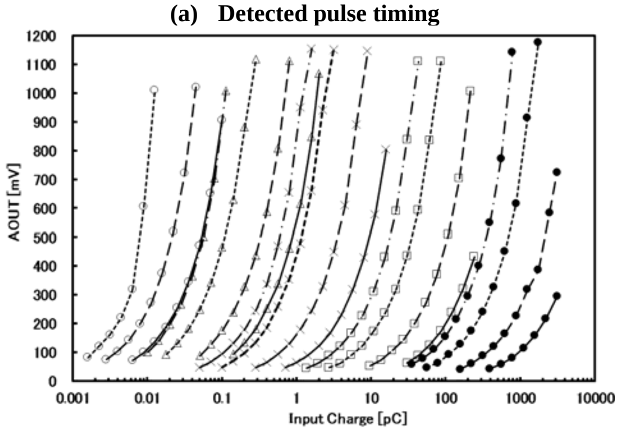


Fig. 3. Typical output waveforms from LIDARX03



(a) Detected pulse timing



(b) Signal amplitude

Fig. 4. Input charge dependence of the device outputs

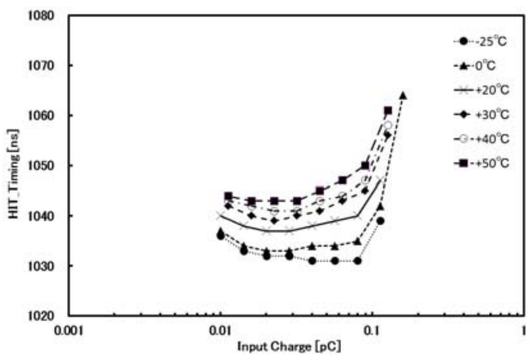


Fig. 5. Temperature dependence of detection timing

Since the result has high repeatability, the measurement can reach sub-nanosecond-level accuracy if we construct a suitable calibration curve. After constructing a calibration curve, it will be necessary to further improve the resolution of the measurement system and further evaluate the system. In addition, we consider it likely that we can achieve an accuracy level of several nanoseconds in a range of greater than 0.02 pC by constructing a calibration curve.

Figure 4 shows that the dynamic range of this device is about 60 dB; in fact, the minimum input charge level is 0.001 pC and the maximum level is 3000 pC. Furthermore, each channel has a dynamic range of over 10 dB and the channels overlap. Therefore, the device can conduct measurements over the entire 60-dB dynamic range. From Fig.4 (b), the amplitude of the signal is between 80 mV to 1000 mV. In this range, the HIT signal is output normally. The timing dispersion σ of the HIT signal is smaller than 3ns. When the signal amplitude is larger than 200mV, σ is smaller than 1ns. When the signal amplitude is between 80 mV to 800 mV, we can find that the HIT timing is comparatively uniform and independent from the input charge level. Therefore, in order to obtain a good quality timing signal, the gain settings must be adjusted to limit the signal amplitude within this range. If the amplitude of the leading wave is limited to the range of 80 mV to 800 mV, the coverage of each channel is overlapping and the device still obtains a 60-dB dynamic range.

The temperature dependency of HIT between -25 and +50 degree C is shown on Fig.5 for the case of CH1-0000. Other cases have more or less similar characteristics. The timing delay increases about 10 ns as the temperature increases from -25 to +50 degree C. We can find that low temperature brings good flatness of the timing curve. Because there is no thermal hysteresis, and reproducibility is good, the temperature dependency can be compensated by a table of correction-for-temperature. For this purpose, LIDARX03 has a bipolar transistor whose base-to-emitter voltage has a temperature dependency of -1.63 mV/degree.

5 Conclusion

The background, design and evaluation of a prototype IC for LIDAR pulse detection are reported in this paper. According to the evaluation results, all the main functions of the IC for pulse detection in a 60-dB dynamic range, the pulse timing generation, and the interpolation of the digital clock were confirmed to operate effectively. In the future, we plan to evaluate this device using light pulses.

References

1) *Mizuno, T., Tsuno, K., Okumura, E. and Nakayama, M.*: LIDAR for Asteroid Explorer Hayabusa: Development and Onboard Evaluation, JJSASS, Vol. 54 No. 634 (2006), pp. 514-521.
2) *Manobu, T., Hirokazu, I., Mitsuo, I. and Susumu, I.*: Performance of a Monolithic Time-to-Amplitude Converter for High Precision TOF Measurements, Nuclear Instruments and Methods in Physics Research A312 (1992), pp. 585-590.
3) *T.Mizuno, H.Ikeda, K.Kawahara*: Pulse Detection IC for a Laser Altimeter Using CMOS Technology, The 28th International Symposium on Space Technology and Science (2011), 2011-d-77

Correspondence

(Name) Takahide Mizuno
(Address) 3-1-1 Yoshinodai Chuo-ku Sagamihara Japan

(e-mail) tmizuno@isas.jaxa.jp