Technical note

Distance image sensors
S15452/S15453/S15454-01WT
S16443/S16444-01WT

Contents

Distance image sensors are image sensors that measure the distance to the target object using the TOF (time-of-flight) method. Used in combination with a pulse modulated light source, these sensors output delay time signals on the timing that the light is emitted and received. The sensor signals are arithmetically processed by an external signal processing circuit or a PC to obtain distance data.

By developing a pixel structure capable of high-speed charge transfer in the CMOS process, we have made an image sensor product that can obtain the information required for distance calculation with a drive voltage of 5 V or less. With common CMOS image sensors, it takes microsecond order time to do charge transfer from the photosensitive area to the storage section, but Hamamatsu's distance image sensors can make the transfer in tens of nanoseconds order.

1. Features

- Wide spectral response range from visible to near infrared
- Reduced effect of background light
- Compact chip size package (CSP) type

[Table 1-1] Product lineup

Type	Linear			Area	
Type no.	S15452-01WT	S15453-01WT	S15454-01WT	S16443-01WT	S16444-01WT
Image size (H × V)	1.28 × 0.05 mm	5.12 × 0.05 mm	4.8 × 3.6 mm	2.6 × 1.6 mm	6.4 × 4 mm
Pixel pitch	20 µm		50 µm	20 (H) µm 201.5 (V) µm	20 (H) µm 201.5 (V) µm
Number of effective Pixels (H × V)	64	256	96 × 72	128 × 8	320 × 20
Video data rate	5 MHz		10 MHz		

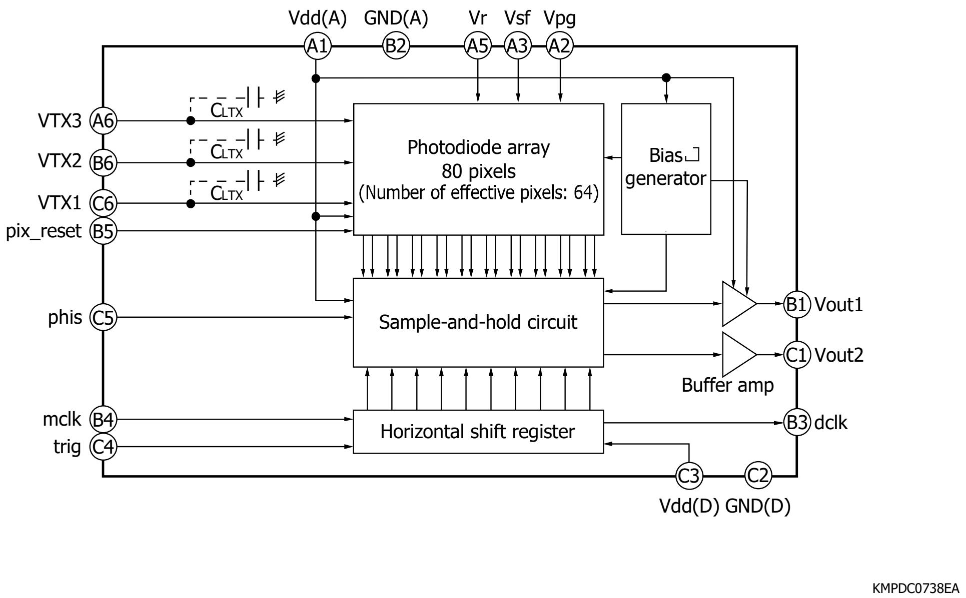
2. Structure

Distance image sensors consist of a photosensitive area, shift register, buffer amplifier, bias generator, timing generator, and so on. The block diagram is shown in Figure 2-1. Distance image sensors are different from typical CMOS image sensors in the following points.

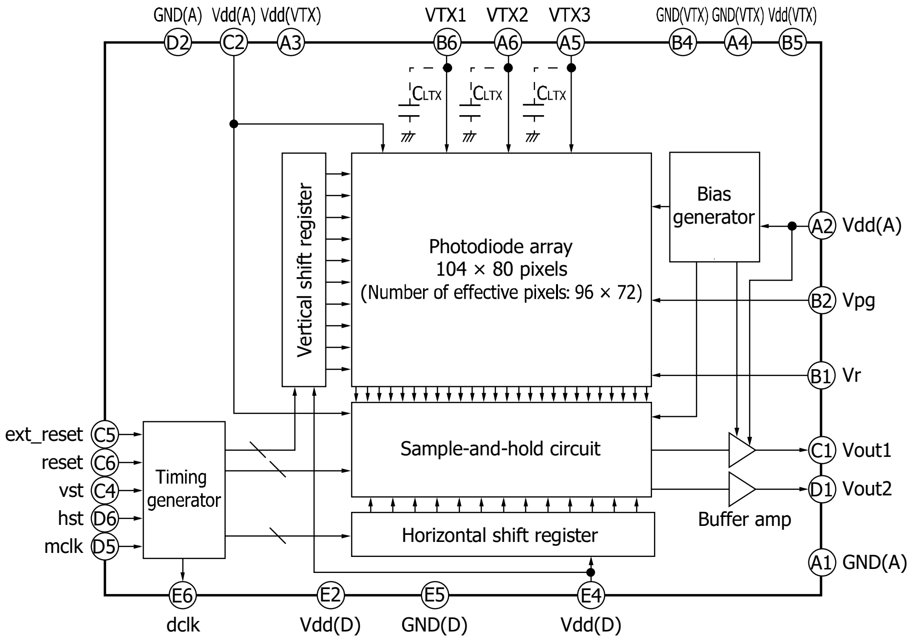
- Pixel structure that allows high-speed charge transfer
- Outputs from two output terminals the voltages needed to calculate the distance

[Figure 2-1] Block diagram

(a) S15452-01WT



(c) S15454-01WT



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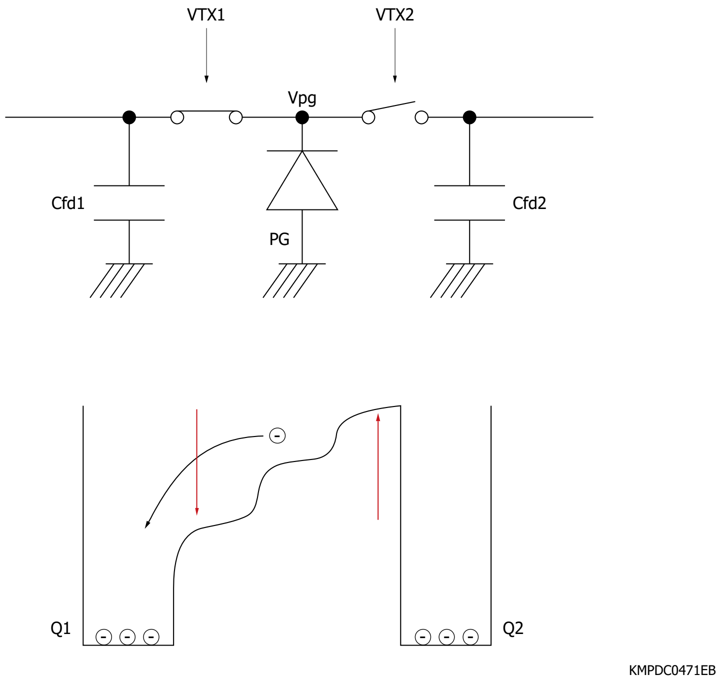
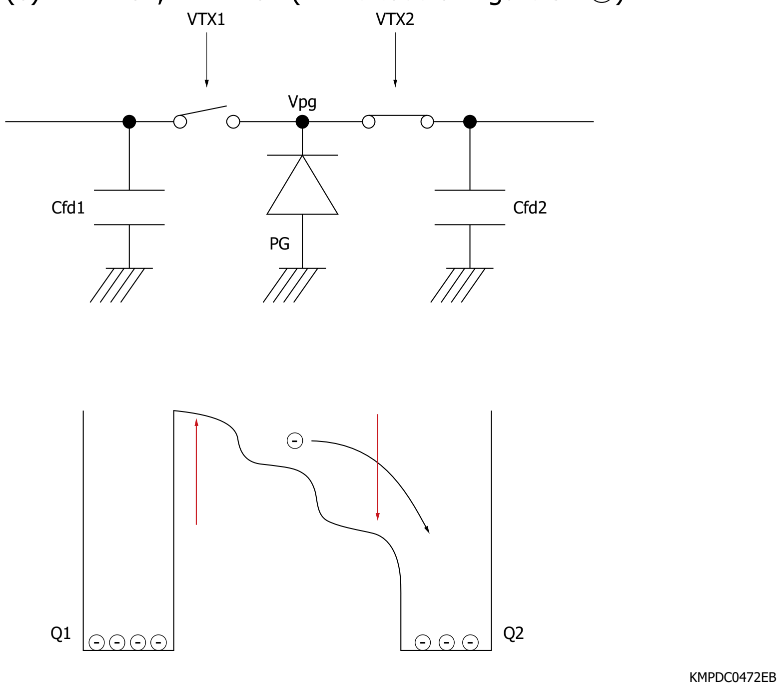
The distance image sensors have a pixel structure in which electrodes are formed on LOCOS (local oxidation of silicon), so they generate a fringe electric field like CCD image sensors and enable high-speed charge transfer [Figure 2-2]. The sample-and-hold circuit or column gain amplifier circuit performs required signal processing, and the shift registers scan the signal sequentially to output as voltage.
The number of electrons generated in each pulse emission is several e^-. Therefore, the operation shown in Figure 2-2 is repeated several thousand to several tens of thousands of times, and then the accumulated charge is read out. The number of repetitions varies depending on the incident light level and the required accuracy of distance measurement.

[Figure 2-2] Structure and surface potential of photosensitive area
(a) VTX1: on, VTX2: off (in the case of Figure 3-1①)



(b) VTX1: off, VTX2: on (in the case of Figure 3-1②)



3. Operating principle

3-1. Indirect TOF (time-of-flight)

Hamamatsu's distance image sensors output the phase difference information of light emission and light reception, needed for distance calculation, based on the principle of indirect TOF. Indirect TOF is a method in which the charge generated in the photosensitive area is transferred to the storage section in synchronous with the pulse light source, and the distance is calculated from the integrated charge.
The timing chart of the photosensitive area of the distance image sensor is shown in Figure 3-1. Output voltages Vout1 and Vout2 obtained by applying charge-to-voltage conversion on accumulated charges Q1 and Q2 based on their integration capacitances Cfd1 and Cfd2 are expressed by equations (3-1) and (3-2).

$$Vout1 = Q1/Cfd1 = N \times Iph \times \{(T_0 - Td)/Cfd1\} \quad ...(3\text{-}1)$$
$$Vout2 = Q2/Cfd2 = N \times Iph \times (Td/Cfd2) \quad ...(3\text{-}2)$$

Cfd1, Cfd2: integration capacitance of each output
N: charge transfer clock count
Iph: photocurrent
T_0: pulse width of output light
Td: delay time

Delay time Td when Cfd1=Cfd2 in equations (3-1) and (3-2) is expressed by equation (3-3).

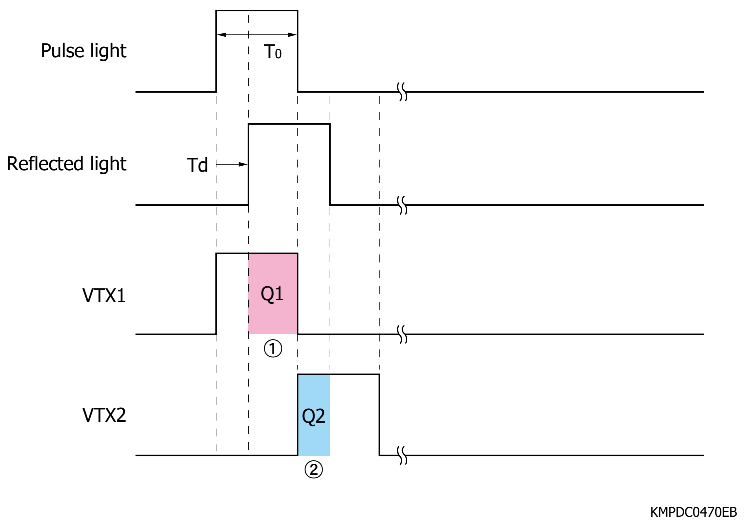
$$Td = \{Vout2/(Vout1 + Vout2)\} \times T_0 \quad ...(3\text{-}3)$$

Using the values (Vout1, Vout2) output according to the distance, distance D is expressed by equation (3-4).

$$D = 1/2 \times c \times Td = 1/2 \times c \times \{Vout2/(Vout1 + Vout2)\} \times T_0 \quad ...(3\text{-}4)$$

c: speed of light (3×10^8 m/s)

[Figure 3-1] Timing chart of photosensitive area



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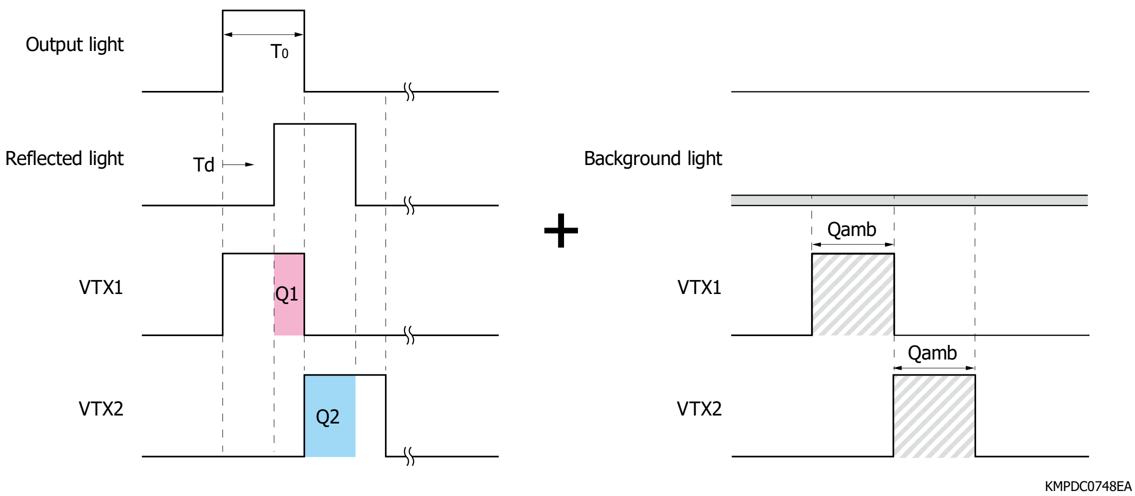
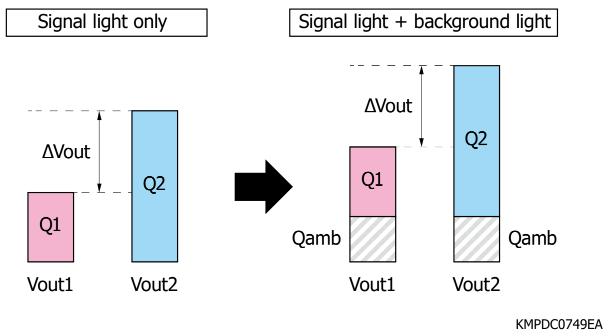
3-2. Background light elimination circuit

The distance image sensor outputs the sum of signal charge (Q1, Q2) and background light charge (Qamb) [Figure 3-2]. Distance is calculated with ΔVout, the difference between output voltages Vout1 and Vout2, so the distance can be measured when background light is present to some extent. However, if the charge generated by background light is large, the voltage range that can be output as signal charge will be reduced due to saturation of integration capacitance, which may narrow the dynamic range [Figure 3-3].

[Figure 3-2] Signal charge and background light charge



[Figure 3-3] Integrated charge when background light is incident



The distance image sensors are equipped with a background light elimination circuit [Figure 3-4] that suppresses saturation of output voltage when background light is incident. Figure 3-5 shows operation of the background light elimination circuit. When either integration capacitor Cfd1 or Cfd2 approaches saturation, the same amount of current flows to both Cfd1 and Cfd2 in the direction that reduces the integration charge. In this case, the difference value between Vout1 and Vout2 will not change, so it will have no effect on distance measurement.
In the background light elimination circuit, ON/OFF cannot be controlled since it automatically operates when the output voltage approaches saturation. We denote the current caused by the signal light flowing through Cfd1 and Cfd2 as Iac1 and Iac2 and the current caused by background light as Iamb. The charges caused by Iac1, Iac2, and Iamb are not distinguished and integrated simultaneously. We denote the current caused by the incident light (signal light + background light) flowing through Cfd1 and Cfd2 as Iph1 and Iph2. If Vout1 and Vout2 do not exceed the threshold [Figure 3-5 (a)], ΔVout1 (the amount of change in Vout1) is expressed by equation (3-5) and ΔVout2 (the amount of change in Vout2) by equation (3-6).

$\Delta Vout1 = (Q1 + Qamb)/Cfd1 = N \times [\{Iac1 \times (T_0 - Td)\} + (Iamb \times T_0)]/Cfd1$ ...(3-5)
$\Delta Vout2 = (Q2 + Qamb)/Cfd2 = N \times \{(Iac2 \times Td) + (Iamb \times T_0)\}/Cfd2$ ...(3-6)

When integration capacitance Cfd1 and Cfd2 are equal, ΔVout is expressed by equation (3-7).

$\Delta Vout = \Delta Vout1 - \Delta Vout2 = N \times [\{Iac1 \times (T_0 - Td)\} - (Iac2 \times Td)]/(Cfd1 \text{ or } Cfd2)$ ...(3-7)

If Vout1 or Vout2 exceeds the threshold [Figure 3-6 (b)], the larger of the two currents Iph1 and Iph2 is fed through Cfd1 and Cfd2. If Iph1 less than Iph2, Iph2 is fed. For Cfd2, because the incoming current is equal to the outgoing current, the change in Vout2 is zero, and the electric potential is equal to the threshold of the background light elimination circuit. From that point, as the incoming current becomes larger than the outgoing current, Vout1 increases, and Cfd1 accumulates charge corresponding to Iph1 - Iph2. After the operation of the background light elimination circuit, ΔVout1 (the amount of change in Vout1) is expressed by equation (3-8) and ΔVout2 (the amount of change in Vout2) by equation (3-9).

$$\begin{aligned}\Delta Vout1 &= \{(Q1 + Qamb) - (Q2 + Qamb)\}/Cfd1 = (Q1 - Q2)/Cfd1 \\ &= N \times [\{Iac1 \times (T_0 - Td) + Iamb \times T_0\} - \{(Iac2 \times Td) + (Iamb \times T_0)\}]/Cfd1 \\ &= N \times [\{Iac1 \times (T_0 - Td)\} - (Iac2 \times Td)]/Cfd1 \quad \text{...(3-8)}\end{aligned}$$

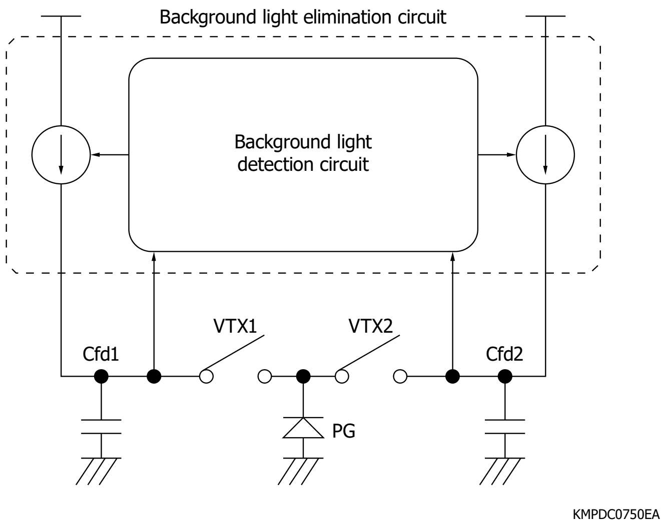
$\Delta Vout2 = \{(Q2 + Qamb) - (Q2 + Qamb)\}/Cfd2 = 0$ ... (3-9)

When Cfd1 and Cfd2 are equal, ΔVout is expressed by equation (3-10).

$\Delta Vout = \Delta Vout1 - \Delta Vout2 = N \times [\{Iac1 \times (T_0 - Td)\} - (Iac2 \times Td)]/(Cfd1 \text{ or } Cfd2)$ ...(3-10)

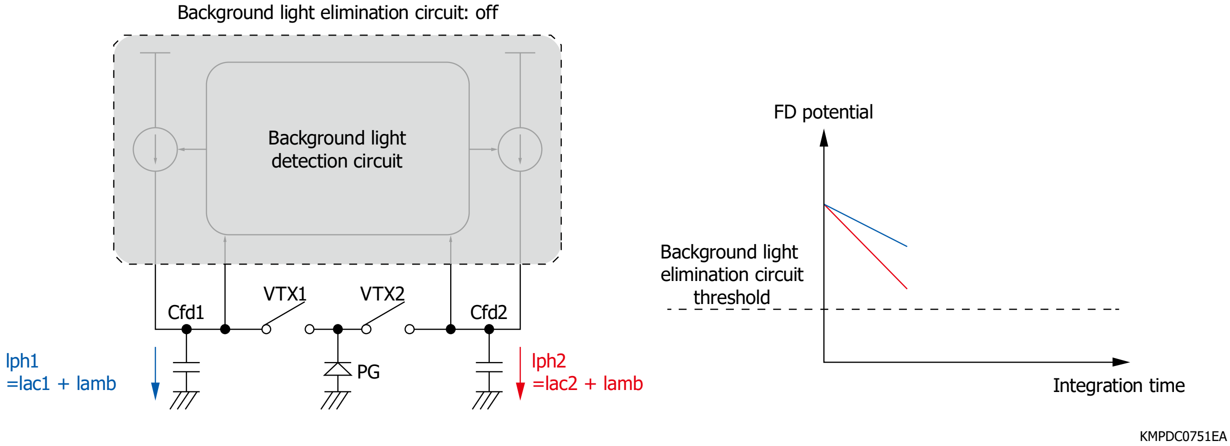
With the operation of the background light elimination circuit, charge Qamb (caused by the background light) is subtracted in equations (3-7) and (3-10).

[Figure 3-4] Background light elimination circuit

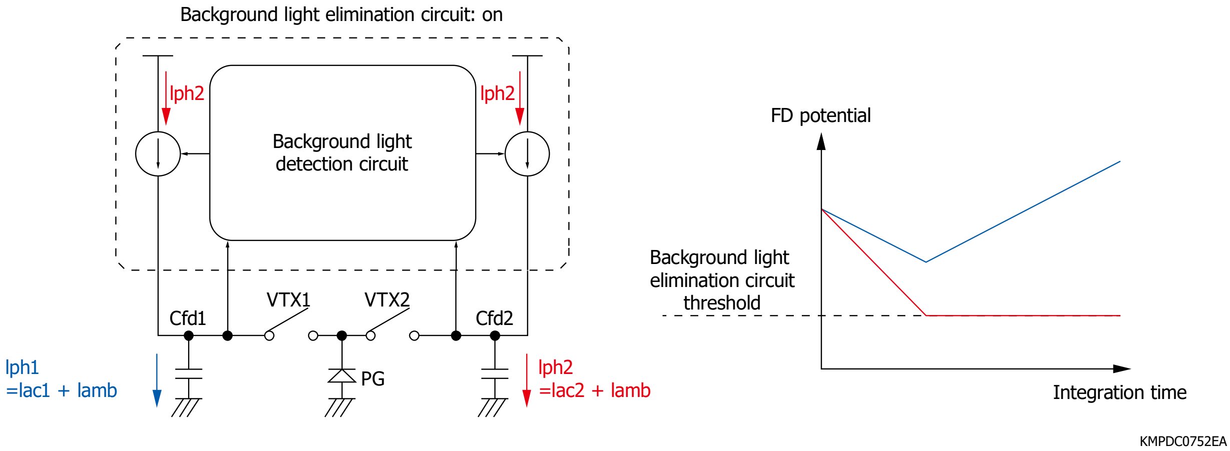


[Figure 3-5] Operation of background light elimination circuit

(a) Background light elimination circuit: before operation



(b) Background light elimination circuit: after operation (Iph1<Iph2)

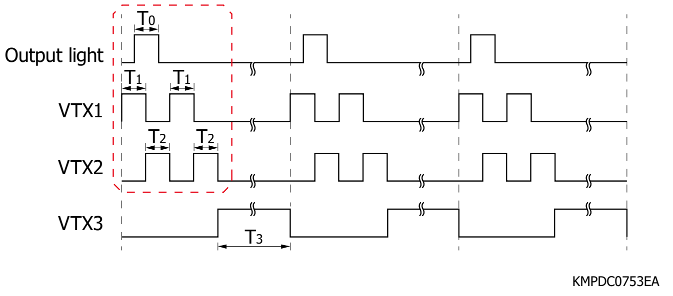


3-3. Distance calculation

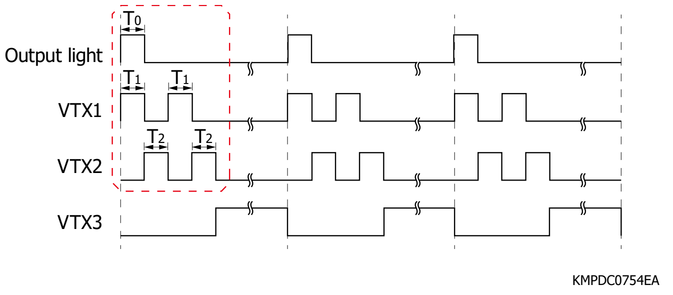
This section explains how to calculate distances by using ΔVout, which is the difference between output voltages Vout1 and Vout2 of Cfd1 and Cfd2. Four outputs Vout1(F1), Vout2(F1), Vout1(F2), and Vout2(F2) for two gate drive timings (F1 and F2) are used to calculate a distance [Figure 3-6]. Set pulse widths T_1 and T_2 of VTX1 and VTX2 the same as pulse width T_0 of the output light, and drive VTX1 and VTX2 alternately twice.
With a single gate drive timing, ΔVout is equal to zero when Vout1 and Vout2 are the same, and the distance cannot be calculated.
F1 in Figure 3-7 has a time shift of $T_0/2$ between the output light and the VTX1 drive timing (F2 has no shift). If we normalize the total charge that is produced during light reception to 1, even when either ΔVout(F1) or ΔVout(F2) is zero, the other will be 1 or -1 because of time shift $T_0/2$. Driving VTX1 and VTX2 alternately twice using pulse light allows total charge 1 to be calculated over the delay time 0 to $2T_0$ range. Figure 3-7 shows the difference signal levels for delay time Td of the reflected light for gate drive timings F1 and F2 and Figure 3-8 the absolute values of the difference signal levels. Total charge 1 can be calculated by adding |ΔVout(F1)| and |ΔVout(F2)|. Figure 3-9 shows a calculation example of total charge (Td = $1/3T_0$, Td = $13/8T_0$). Total charge 1 is used to determined delay time Td, and the distance is calculated.

[Figure 3-6] Gate drive timing

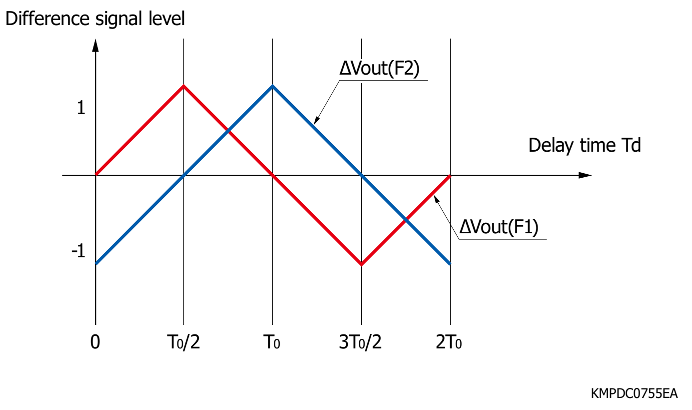
(a) F1



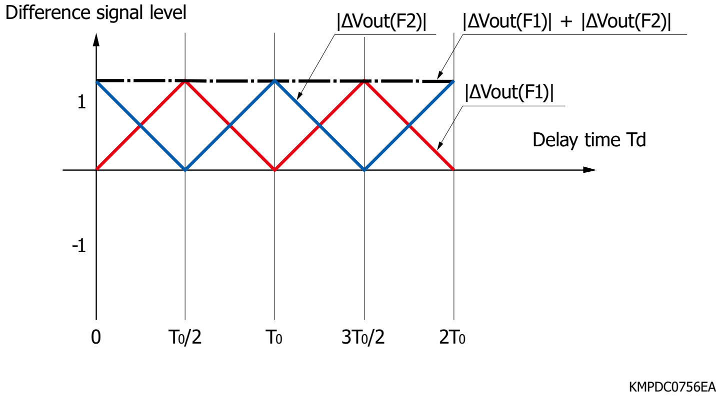
(b) F2



[Figure 3-7] Difference signal level vs. delay time

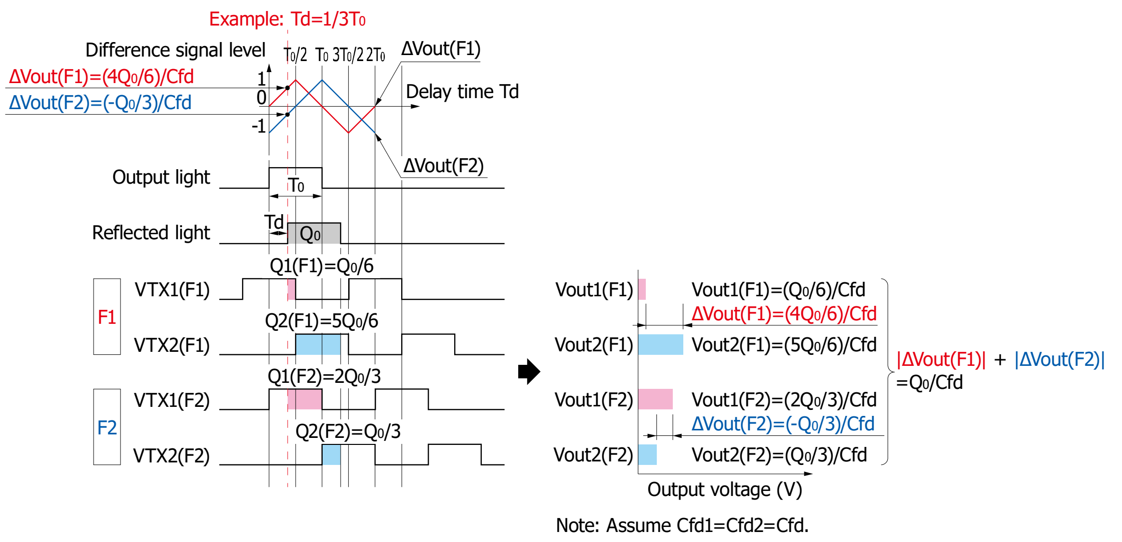


[Figure 3-8] Difference signal level (absolute value) vs. delay time



[Figure 3-9] Calculation examples of total charge

(a) Td = 1/3T_0



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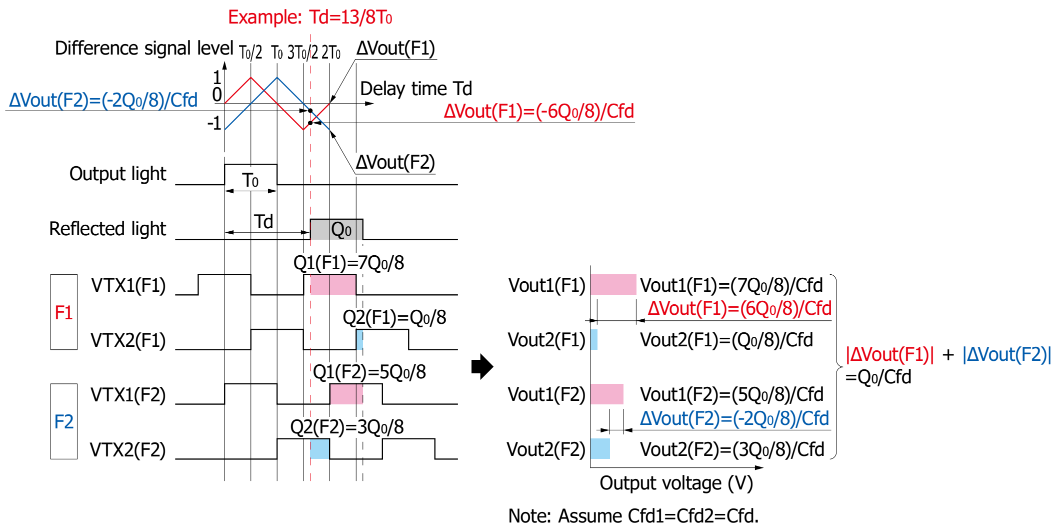
(b) Td = 13/8T_0



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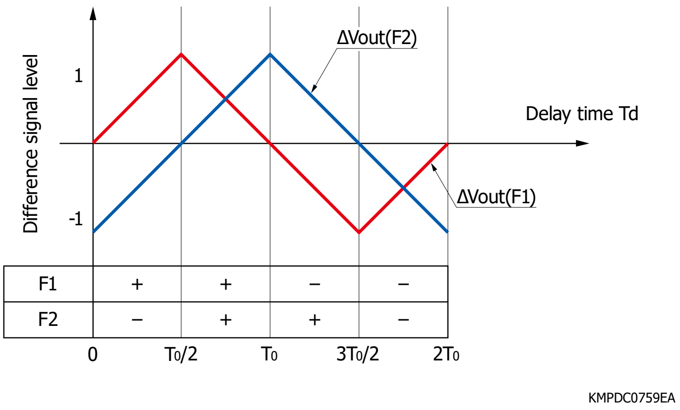
Distance D can be calculated from the ratio of the total charge and the charge after delay time Td [equation (3-11)]. For delay time 0 to 2T_0, correct equation (3-11) so that the above ratio changes linearly from 0 to 1, and calculate the distance.

D = {(Charge after delay time Td)/(Total charge)} × CT_0 ...(3-11)

The delay time of light reception timing is determined to be greater than or less than T_0 based on whether ΔVout(F1) is positive or negative. Correct ΔVout(F2), and determine the amount of change in the delay time with respect to the total charge [Figure 3-10].

[Figure 3-10] Polarity of difference signal level



F1	+	+	−	−
F2	−	+	+	−

Distance is calculated by correcting ΔVout(F2) separately for the cases when ΔVout(F1) is positive and negative. Correct ΔVout(F2) so that it changes from 0 to 1 in response to Td changing from 0 to $2T_0$.

(1) When ΔVout(F1) is positive

When ΔVout(F1) is positive, delay time Td is less than T_0 [Figure 3-11]. ΔVout(F2) is corrected so that it changes from 0 to 0.5 in response to Td changing from 0 to T_0. When Td is less than T_0, ΔVout(F2) changes from -1 to 1, and the amount of increase is 2 [Figure 3-11]. To make the amount of increase to 0.5, multiply a factor of 1/4 to ΔVout(F2). To make the amount of change start from zero, add an offset of 1/4. Distance D when ΔVout(F1) is positive is expressed by equation (3-12).

$$D = [\{\Delta Vout(F2)/4\}/\{|\Delta Vout(F1)| + |\Delta Vout(F2)|\} + 1/4] \times CT_0$$
$$= [\Delta Vout(F2)/\{|\Delta Vout(F1)| + |\Delta Vout(F2)|\} + 1] \times (CT_0/4) \qquad \dots (3\text{-}12)$$

(2) When ΔVout(F1) is negative

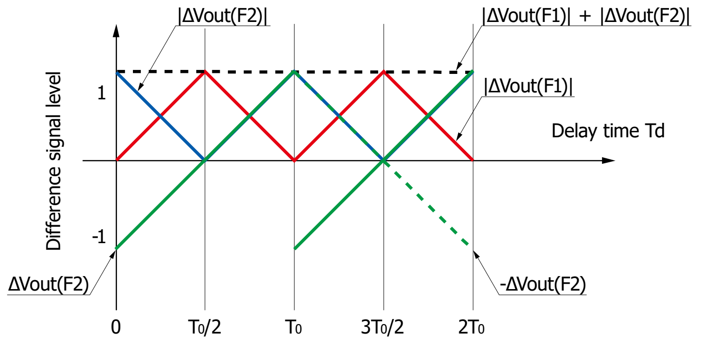
When ΔVout(F1) is negative, delay time Td is greater than T_0 [Figure 3-11]. Correct ΔVout(F2) so that it changes from 0.5 to 1 in response to Td changing from T_0 to $2T_0$. When delay time Td is greater than T_0, ΔVout(F2) changes from 1 to -1 [Figure 3-11]. If we multiply this by a factor of -1 to invert the slope, ΔVout(F2) will change from -1 to 1, and the amount of increase will become 2. To make the amount of increase to 0.5, multiply a factor of 1/4 to ΔVout(F2). Then, add an offset of 3/4 so that ΔVout(F2) changes from 0.5 to 1. Distance D when ΔVout(F1) is negative is expressed by equation (3-13).

$$D = [\{-\Delta Vout(F2)/4\}/\{|\Delta Vout(F1)| + |\Delta Vout(F2)|\} + 3/4] \times CT_0$$
$$= [-\Delta Vout(F2)/\{|\Delta Vout(F1)| + |\Delta Vout(F2)|\} + 3] \times CT_0/4 \qquad \dots (3\text{-}13)$$

Figure 3-11 shows the distance calculation process of (1) and (2). The green line in Figure 3-11 (c) corresponds to the amount of charge after the delay time Td.

[Figure 3-11] Distance calculation process

(a) Change to the slope polarity (only when delay time Td is greater than T_0)



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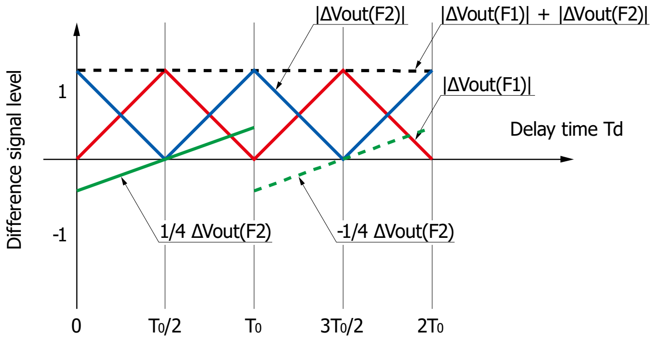
(b) Change to the slope [multiple 1/4 to ΔVout(F2)]



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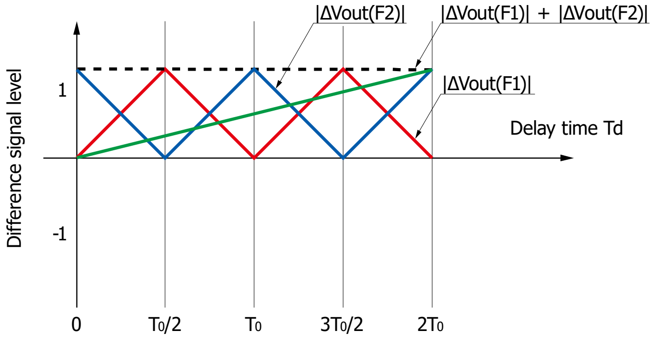
(c) Addition of offset (Td<T_0: 1/4, Td>T_0: 3/4)



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3-4. Charge drain function

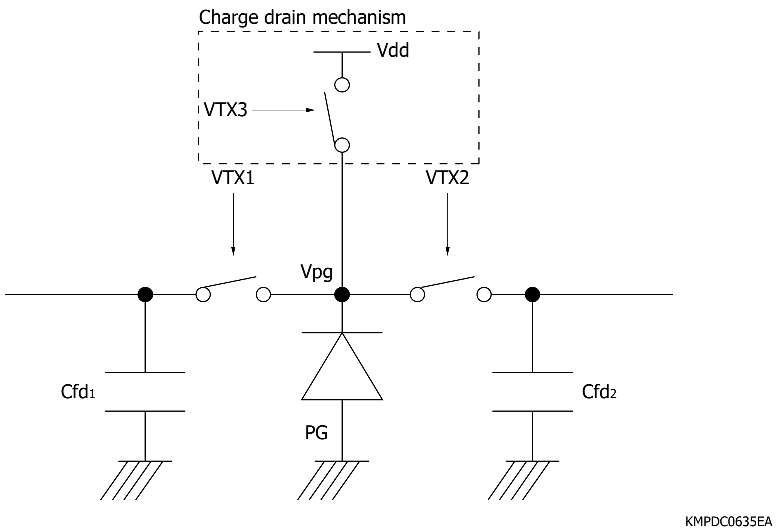
A distance image sensor has charge transfer gates VTX1, VTX2, which transfer the charges that are generated at the photosensitive area, and a charge drain gate VTX3, which discharges unneeded charges [Figure3-12]. When VTX1 and VTX2 are off and VTX3 is on, the charge drain function is turned on. This makes it possible to drain unneeded charges caused by background light during the non-emission period. The charge drain function enables the following:

①Detection of high-speed pulses

Signal charges from pulse laser diodes and other high-speed pulse light sources can be integrated efficiently.

②Shutter operation

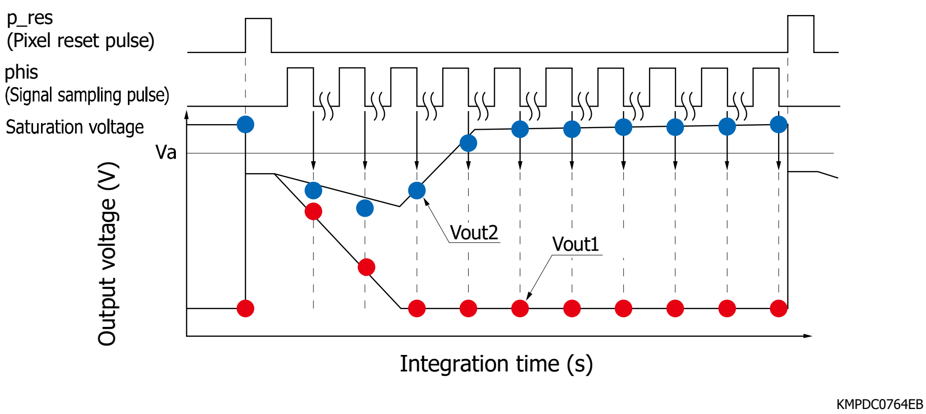
[Figure 3-12] Structure of photosensitive area



3-5. Non-destructive readout

Non-destructive readout is a method of outputting voltages at different integration times without resetting the integration capacitors Cfd1 and Cfd2 in the pixel (without destroying integration charge). Distance accuracy is improved with the adjustment of integration time (e.g. shortening the integration time when the incident signal is strong in order to avoid saturation; lengthening the integration time when the incident signal is weak). Using non-destructive readout, a large signal suitable for distance measurement can be selected from the signals read out with different integration times, and a wide dynamic range can be realized.
Figure 3-13 shows a schematic diagram of non-destructive readout (relationship between output voltage and integration time). Set the threshold voltage Va lower than the saturation voltage. The output voltage immediately before exceeding Va is the optimum value for achieving high measurement accuracy. By taking the difference between any two points with different integration times, it is possible to cancel the noise generated when Cfd1 and Cfd2 are reset. One disadvantage of non-destructive readout is that the readout is performed several times in each frame, so the frame rate decreases as the number of readouts increases.

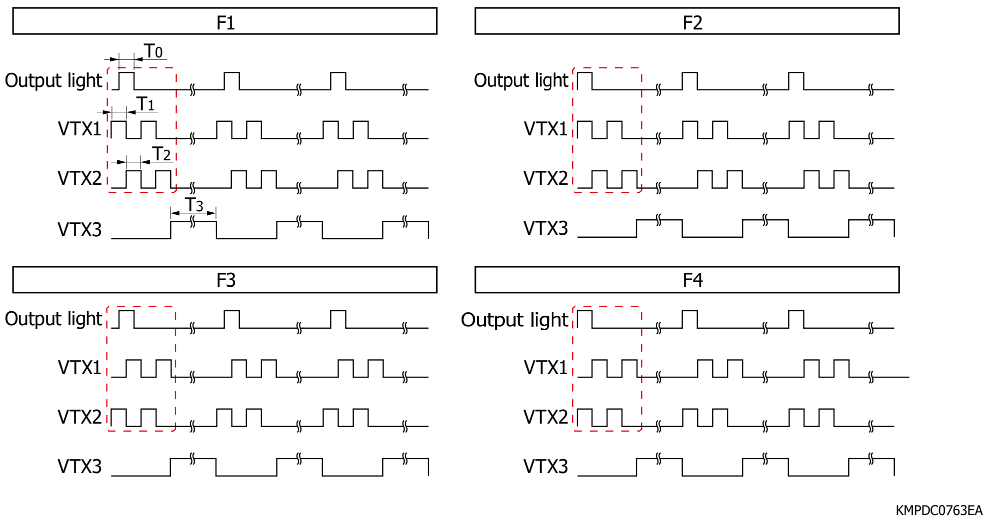
[Figure 3-13] Schematic diagram of non-destructive readout



3-6. Drive timing

In the ideal case, distance measurement is possible by using the gate drive timings of F1 and F2. However, Vout1 and Vout2 have intrinsic variation components (Verr), and this error remains in the difference signals, which prohibits distances from being calculated accurately. To overcome this problem, calculate the distance by also using F3 and F4, which have the VTX1 and VTX2 of F1 and F2 swapped, to eliminate Verr [Figure 3-14].

[Figure 3-14] Timing chart



F3 is F1 with the timings of VTX1 and VTX2 swapped. Ideally, Vout1(F1) is equal to Vout2(F3) and Vout2(F1) is equal to Vout1(F3). If intrinsic variation components Verr1 and Verr2 exist in Vout1 and Vout2, ΔVout(F1) is expressed by equation (3-14) and ΔVout(F3) by equation (3-15).

$$\Delta Vout(F1) = \{Vout2(F1) + Verr2\} - \{Vout1(F1) + Verr1\} \quad ...(3\text{-}14)$$
$$\Delta Vout(F3) = \{Vout2(F3) + Verr2\} - \{Vout1(F3) + Verr1\} \quad ...(3\text{-}15)$$

Assuming Vout1(F1) is equal to Vout2(F3) and Vout2(F1) is equal to Vout1(F3), subtracting equation (3-14) from equation (3-15) produces equation (3-16). By using F3 along with F1, Verr1 and Verr2 can be eliminated.

$$\begin{aligned} &\Delta Vout(F1) - \Delta Vout(F3) \\ &= [\{Vout2(F1) + Verr2\} - \{Vout1(F1) + Verr1\}] - [\{Vout2(F3) + Verr2\} - \{Vout1(F3) + Verr1\}] \\ &= 2\{Vout2(F1) - Vout1(F1)\} \quad ...\ (3\text{-}16) \end{aligned}$$

F4 is F2 with the timings of VTX1 and VTX2 swapped. By using F4 along with F2, Verr1 and Verr2 can be eliminated [equation (3-17)].

$$\begin{aligned} &\Delta Vout(F2) - \Delta Vout(F4) \\ &= [\{Vout2(F2) + Verr2\} - \{Vout1(F2) + Verr1\}] - [\{Vout2(F4) + Verr2\} - \{Vout1(F4) + Verr1\}] \\ &= 2\{Vout2(F2) - Vout1(F2)\} \quad ...\ (3\text{-}17) \end{aligned}$$

Equations (3-18) and (3-19) are distance calculation equations that use gate drive timings F1 to F4.

(1) When $\Delta Vout(F1) - \Delta Vout(F3)$ is positive

$$D = [\{(\Delta Vout(F2) - \Delta Vout(F4))/4\} / \{|\Delta Vout(F1) - \Delta Vout(F3)| + |\Delta Vout(F2) - \Delta Vout(F4)|\} + 1/4] \times CT_0$$
$$= [\{\Delta Vout(F2) - \Delta Vout(F4)\} / \{|\Delta Vout(F1) - \Delta Vout(F3)| + |\Delta Vout(F2) - \Delta Vout(F4)|\} + 1] \times CT_0/4 \quad ...(3\text{-}18)$$

(2) When $\Delta Vout(F1) - \Delta Vout(F3)$ is negative

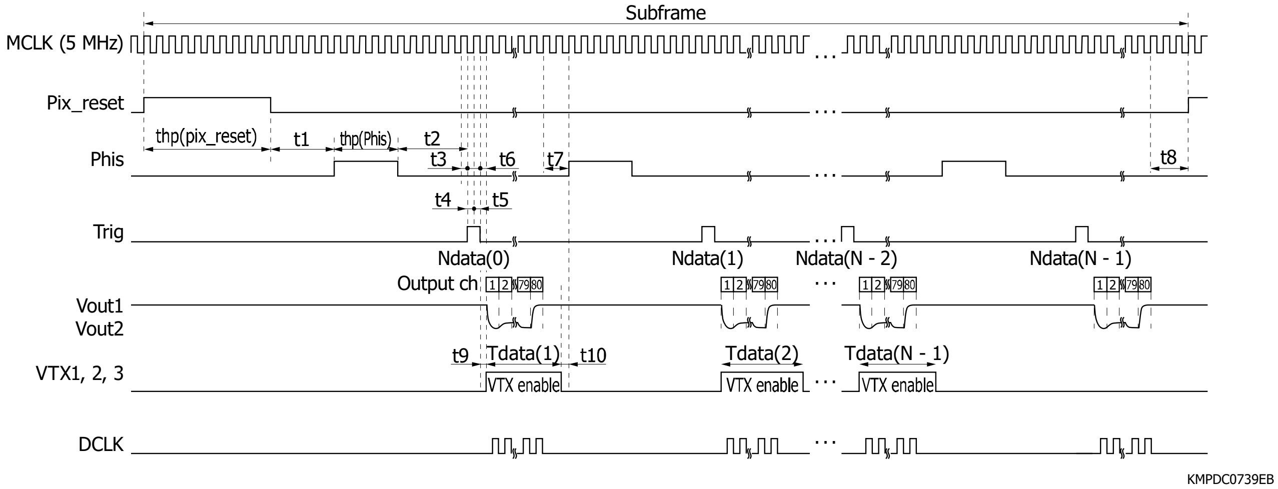
$$D = [-(\Delta Vout(F2) - \Delta Vout(F4))/4\} / \{|\Delta Vout(F1) - \Delta Vout(F3)| + |\Delta Vout(F2) - \Delta Vout(F4)|\} + 3/4] \times CT_0$$
$$= [-\{\Delta Vout(F2) - \Delta Vout(F4)\} / \{|\Delta Vout(F1) - \Delta Vout(F3)| + |\Delta Vout(F2) - \Delta Vout(F4)|\} + 3] \times CT_0/4 \quad ... (3\text{-}19)$$

3-7. Timing chart

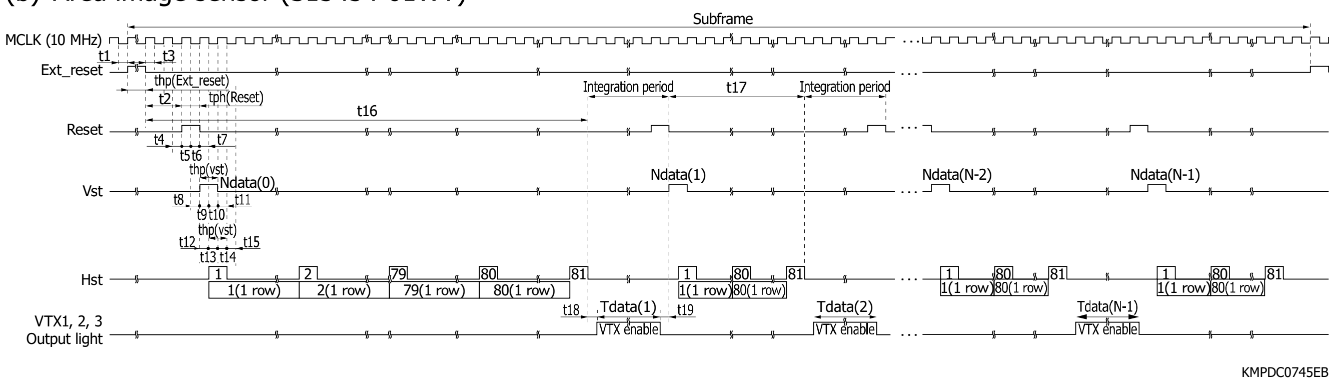
Figure 3-16 shows the signal readout timing chart. When the distance is measured once, readout is performed four times using different gate timings. F3 and F4 are gate drive timings of F1 and F2 but with the VTX1 and VTX2 timings swapped.

[Figure 3-15] Timing chart (subframe*)

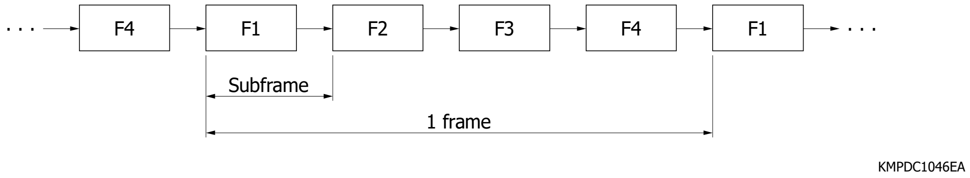
(a) Linear image sensor (S15452-01WT)



(b) Area image sensor (S15454-01WT)



*Data with different phase timing. One frame consists of four subframes (F1, F2, F3, F4).



3-8. Calculating the frame rate

Frame rate=1/{4 (Time per subframe)}

=1/{(Integration time + Readout time) × 4} ...(3-20)

The integration time setting is necessary to be changed by the required distance accuracy and usage environment factors such as fluctuating background light.

[Linear image sensor (S15453-01WT)]

$$\text{Readout time} = \frac{1}{\text{Clock pulse frequency}} \times \text{Number of horizontal pixels}$$

=Time per clock (Readout time per pixel) × Number of horizontal pixels... (3-21)

Calculation example of readout time (clock pulse frequency=5 MHz, number of horizontal pixels=272)

$$\text{Readout time} = \frac{1}{5 \times 10^6\ [\text{Hz}]} \times 272$$

$$= 200\ [\text{ns}] \times 272$$

$$= 0.0544\ [\text{ms}] \ldots (3\text{-}22)$$

When operating in non-destructive readout mode:

Time per subframe = Integration time + (Readout time × Non-destructive readout count) ... (3-23)

[Area image sensor (S15454-01WT)]

$$\text{Readout time} = \frac{1}{\text{Clock pulse frequency}} \times \text{Horizontal timing clock} \times \text{Number of vertical pixels}$$

$$= \text{Time per clock (Readout time per pixel)} \times \text{Horizontal timing clocks} \times \text{Number of vertical pixels} \ldots \text{(3-24)}$$

Calculation example of readout time
(clock pulse frequency=10 MHz, horizontal timing clocks=141, number of vertical pixels=80)

$$\text{Readout time} = \frac{1}{10 \times 10^6 \text{ [Hz]}} \times 141 \times 80$$

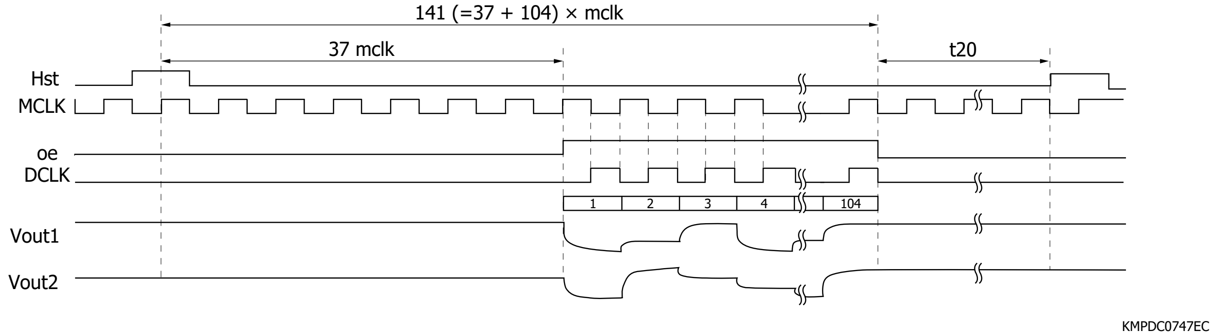
$$= 100 \text{ [ns]} \times 141 \times 80$$

$$= 1.128 \text{ [ms]}$$

When operating in non-destructive readout mode:
Time per subframe = Integration time + (Readout time × Non-destructive readout count) … (3-25)

The integration signal can be read out without doing readout of the reset level. In this case, there will be more random noise, as well as degradation of photoresponse nonuniformity in the photosensitive area.

[Figure 3-16] Horizontal timing

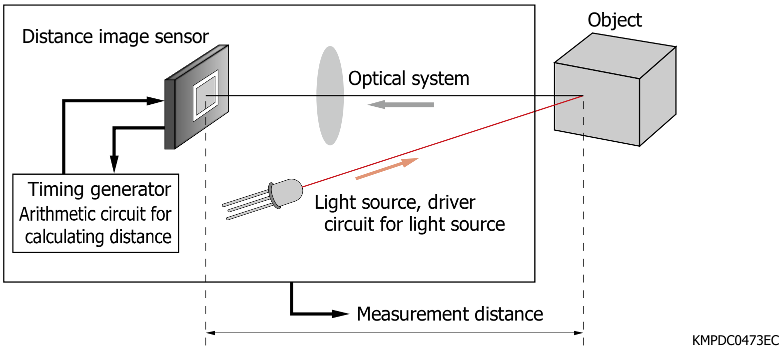


4. How to use

4-1. Configuration example

A configuration example of a distance measurement system using the distance image sensor is shown in Figure 4-1. The system consists of the distance image sensor, light source and its driver circuit, light emitting/receiving optical system, timing generator, and arithmetic circuit for calculating distance. The distance accuracy depends greatly on the light source emission level and the light emitting/receiving optical system.

[Figure 4-1] Configuration example of distance measurement system



4-2. Light source selection

When the distance image sensor is used to measure distance, a light source (LED or pulse laser diode) suitable for the pulse width of the distance image sensor's charge transfer clock must be selected. In addition, the pulse width of charge transfer clock and the light emission pulse width must be set according to the distance. The response speed of the light source needs to be around 10 ns or less for rise and fall times. Since the light source must be irradiated in a line in the case of the S15452-01WT, S15453-01WT distance linear image sensors and over an area in the case of the S15454-01WT, S16443-01WT and S16444-01WT distance area image sensors, large output power is required. For this, multiple light sources are sometimes used. When multiple light sources are used, a driver circuit for driving the multiple light sources at high speeds and high output is also required.

5. Calibration

After the distance image sensor and the light source are combined, distance calibration is necessary. Make sure to do calibration because the following variations will occur.

- Delay in the light emission timing
- Delay in the wiring between the sensor and light source
- Shape of the light emission pulse of light source
- Delay in the peripheral circuits

The following shows an example of the calibration method.

Distance D is given by equations (5-1)(5-2).

(1) When $Td \leq T_0$

$$D=\alpha\left(\frac{VoutB}{|VoutA| + |VoutB|}+1\right) \times \frac{CT_0}{4} - Dofs \quad \dots (5\text{-}1)$$

(2) When $T_0 < Td \leq 2T_0$

$$D=\alpha\left(\frac{-VoutB}{|VoutA| + |VoutB|}+3\right) \times \frac{CT_0}{4} - Dofs \quad \dots (5\text{-}2)$$

α: slope
c: speed of light
T_0: light emission pulse width
Dofs: distance offset

You need to set the light emission timing delay (Light_pulse_delay), distance offset (Dofs), and slope (α).

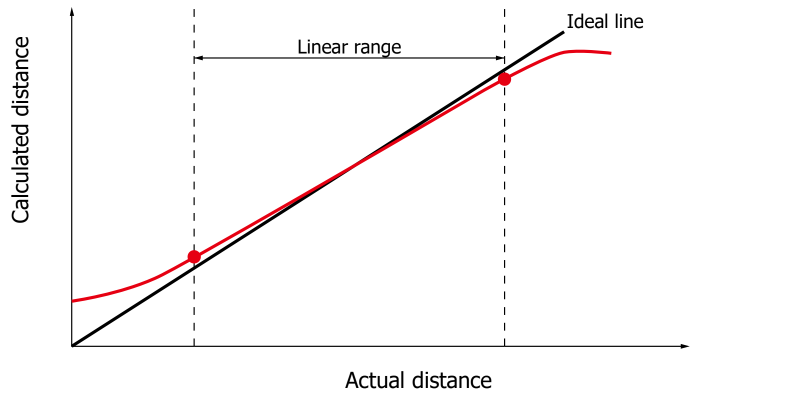
Setting the light emission timing delay, distance offset, and Dofs

The calculated distance is shifted by changing the light emission timing delay and distance offset so that the calculated distance matches the actual distance.

Setting the slope α

Select two points in the linear range of distance, and calculate α to match the ideal line [Figure 5-1].

[Figure 5-1] Calculated distance vs. actual distance



6. Calculating the incident light level

If you want to construct a camera module using a distance image sensor, you need to set the parameters according to the operating conditions to maximize the performance of the sensor. For example, when outdoors under strong sunlight, various measures need to be taken such as reducing the integration time or suppressing the incident sunlight using a band-pass filter to avoid pixel saturation.

How much to reduce the integration time or which band-pass filter is most suited in reducing the sunlight to the appropriate level varies depending on the operating conditions. To make things easier, we created a model of the camera module configuration and derived an equation that simply calculates the incident light level (signal light, background light) per pixel. Please use this when designing camera modules.

Camera module parameters

The following are main parameters of a camera module that uses a distance image sensor. In addition, Figure 6-1 shows the schematic diagram. We assume that the light from the light source is shaped into a rectangle by the angle of view (θ_H, θ_V) determined by the lens and directed on the sensor.

(1) Target object
• Distance to the target object L [m]
• Reflectance of the target object R [%]

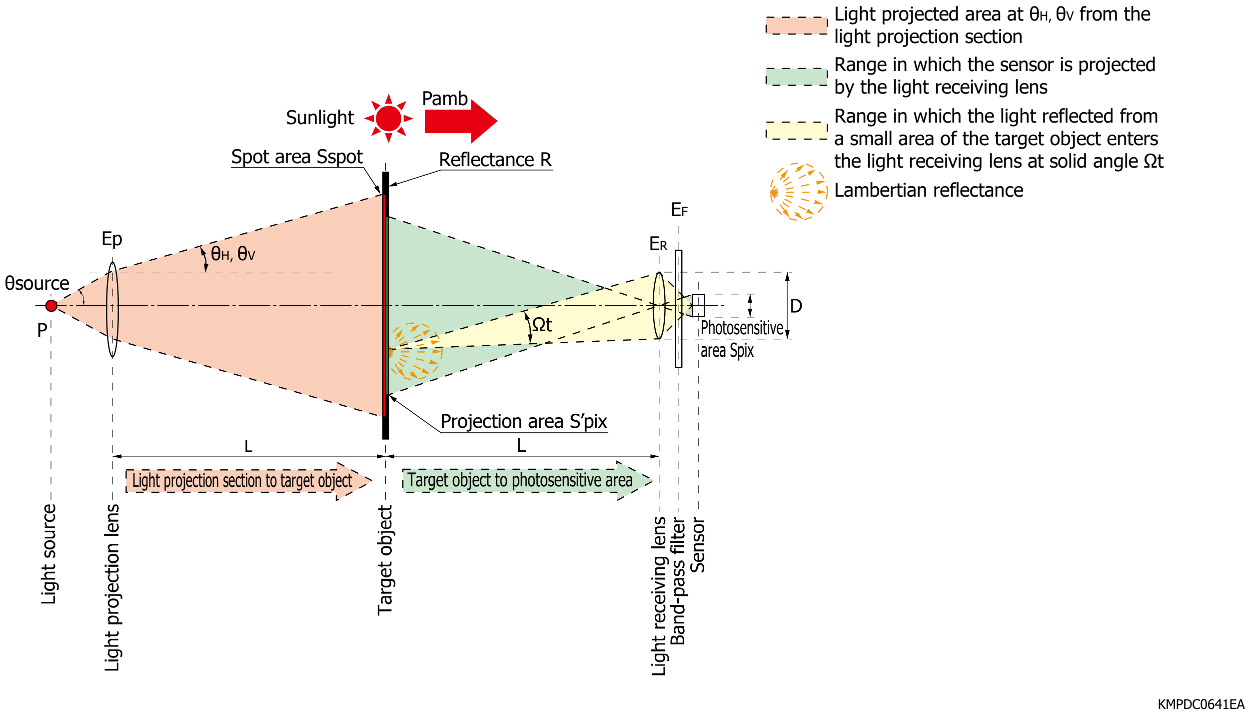
(2) Light projection section
- Light source output P [W/sr]
- Light projection efficiency E_P [%]
- Duty ratio "duty"
- Integration time Tacc [s]
- Light emitter's angle at half maximum θsource [V]
- Light projection angle (horizontal, vertical) θ_H, θ_V [°]

(3) Background light
- Sunlight intensity Pamb [W/m^2]
- Band-pass filter's transmission wavelength range (short-wavelength side, long-wavelength side) λshort , λlong [nm]

(4) Photosensitive area
- Light receiving lens efficiency E_R [%]
- Band-pass filter's signal light transmittance E_F [%]
- Light receiving lens F value
- Light receiving lens focal distance f [m]

(5) Distance image sensor
- Pixel size (horizontal, vertical) Hpix, Vpix [m] (area Spix)
- Fill factor FF [%]
- Photosensitivity Ssens [A/W]
- Pixel capacitance Cfd [F]
- Random noise RN [V]
- Dark output V_D [V/s]

[Figure 6-1] Schematic diagram of camera module with built-in distance image sensor



Calculation method

First, we calculate the light spot level Pspot [W/m²] on the target object [equation (6-1)].

$$\text{Pspot} = \text{P} \times \frac{\text{A}}{\text{L}^2} \times \text{Ep} \times \frac{1}{\text{Sspot}} \quad \text{...(6-1)}$$

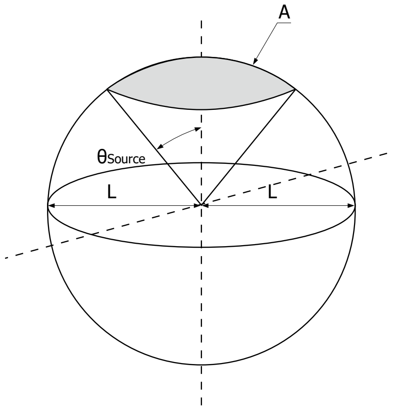
P: Light source output [W/sr]
A: Area of a spherical surface obtained by cutting a sphere with radius L at an angle of θsource

$\frac{A}{L^2}$: solid angle of the projected light [sr]

EP: light projection efficiency [%]

Sspot: area of the light spot projected on the target object $[m^2]$

[Figure 6-2] Area A on the spherical surface



Sspot is given by equation (6-2).

$$\text{Sspot} = 2\text{L} \tan \theta_H \times 2\text{L} \tan \theta_V \quad ...\ (6\text{-}2)$$

A is given by equation (6-3).

$$A = 2\pi \{1 - \cos(\theta\text{source})\} \times L^2 \quad ...\ (6\text{-}3)$$

Next, we calculate angle of the reflected light from a small area of the target object that enters the light receiving lens. If the diameter of the light receiving lens is D [m], the angle θ_R formed between a given point on the target object and the edge of the light receiving lens is given by equation (6-4).

$$\theta_R = \tan^{-1}\left(\frac{D}{2L}\right) \quad ...\ (6\text{-}4)$$

If we use θ_R, solid angle Ωt [unit: sr] is given by equation (6-5).

$$\Omega t = 4\pi \sin^2 \frac{\theta_R}{2} \quad ...\ (6\text{-}5)$$

θ_R varies depending on the position on the target object, but here it is approximated to a fixed value. Of the reflected light diffused in all directions from the target object, we assume the portion corresponding to Ωt to enter the lens.

The region on the target object that the distance image sensor can receive the reflected light of corresponds to the projection plane of the pixels displayed on the object through the light receiving lens. The relationship between pixel area Spix and the pixel projection area S'pix on the target object is given by equation (6-6).

$$S'pix = \left(\frac{L}{f}\right)^2 Spix \quad . . . (6\text{-}6)$$

We determine the level of signal light and background light that hit and reflect off the target object and enter a single pixel through the lens. To simplify the calculation, we assume the target object to be a perfect diffuser. If the incident light level is I [W], the reflected light level is I/π [W/sr] for a point light source and I [W/sr] for an extremely wide surface light source such as sunlight. The signal light level Ppix [W] entering a single pixel is given by equation (6-7).

$$Ppix = Pspot \times R \times \frac{1}{\pi} \times \Omega t \times S'pix \times E_R \times E_F(sig) \times FF \quad . . . (6\text{-}7)$$

The background light level Ppix(amb) [W] entering a single pixel is given by equation (6-8).

$$Ppix(amb) = Pamp \times R \times 1 \times \Omega t \times S'pix \times E_R \times E_F(amb) \times FF \quad . . . (6\text{-}8)$$

$E_F(sig)$: band-pass filter transmittance for signal light
$E_F(amb)$: band-pass filter transmittance for background light

Output voltage Vpix [V] generated from the signal light is given by equation (6-9).

$$Vpix = Ppix \times Tacc \times duty \times (Ssens/Cfd) \quad . . . (6\text{-}9)$$

Tacc: integration time [s]
duty: duty ratio
Ssens: photosensitivity [A/W]
Cfd: pixel capacitance [F]

Output voltage Vpix(amb) [V] generated from the background light is given by equation (6-10). Equation (6-10) has "× 2" because background light is incident at the two gate drive timings.

$$Vpix(amb) = Ppix(amb) \times Tacc \times duty \times (Ssens/Cfd) \times 2 \quad ...(6\text{-}10)$$

Distance accuracy

Using the levels of signal light and background light entering a single pixel determined above, we calculate the distance accuracy of the camera module. Photocurrent Ipix [A] per pixel generated by the signal light is given by equation (6-11).

$$Ipix = Ppix \times Ssens \quad . . . (6\text{-}11)$$

The number of electrons Qpix [e^-] per pixel generated by the signal light is given by equation (6-12).

$$Qpix = Ipix \times Tacc \times duty/e \ . . . (6\text{-}12)$$
$$= Ppix \times Ssens \times Tacc \times duty/e$$

e: quantum of electricity=1.602×10^{-19} [C]

The number of electrons Qpix(amb) [e^-] per pixel generated by the background light is given by equation (6-13).

$$Qpix(amb) = Ppix(amb) \times Ssens \times Tacc \times duty/e \times 2 \ \ldots (6\text{-}13)$$

Noise components are given by the following equations. Calculate the distance using four gate drive timings in the background light elimination circuit.

$$N_L = \sqrt{4 \times Qpix + 8 \times Qpix(amb)} \ . . . (6\text{-}14)$$

N_L: light shot noise
Qpix: number of signal electrons (4 ×: 4 timing charts)
Qpix(amb): number of background light electrons (8 ×: 4 timing charts, output at Vout1 and Vout2)

$$N_R = 8 \times RN \times Cfd/e \ . . . (6\text{-}15)$$

N_R : random noise [e^-]
RN: random noise [V] (8 ×: 4 timing charts, output at Vout1 and Vout2)

$$N_D = \sqrt{16 \times V_D \times Tacc \times Cfd/e} \ . . . (6\text{-}16)$$

N_D: dark current shot noise [e^-]
V_D: dark output [V/s] (16 ×: 4 timing charts, output at Vout1 and Vout2, 2 gate pulses)

Total noise N [e^-] is given by equation (6-17).

$$N = \sqrt{N_L^2 + N_R^2 + N_D^2} \ . . . (6\text{-}17)$$

The S/N is the ratio of the number of signal electrons Qpix to N.

Distance accuracy σ [m] is given by equation (6-18). Double the number of signal electrons Qpix in order to calculate the distance from the output of Vout1 and Vout2 in the background light elimination circuit.

$$\sigma = \frac{N}{2 \times Qpix} \times \frac{cT_0}{2} \ . . . (6\text{-}18)$$

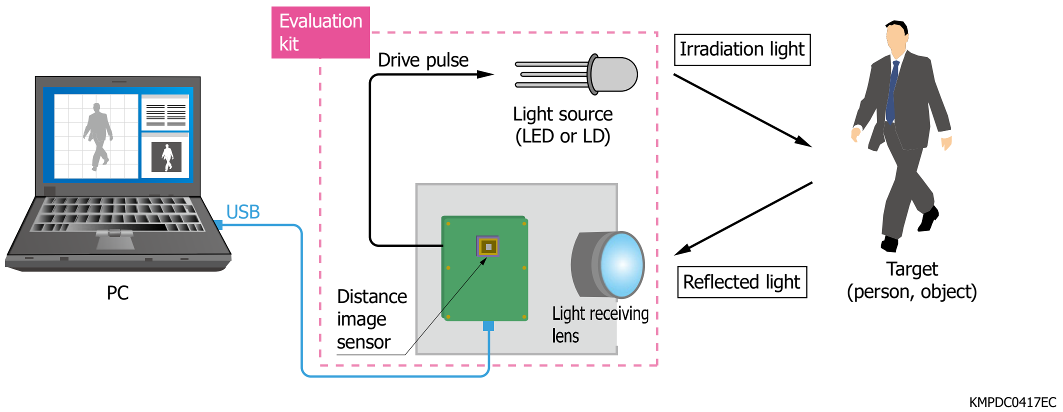
c: speed of light
T_0: light emission pulse width

Increasing the incident signal level helps to improve the distance accuracy. As the temperature rises, dark current shot noise increases and distance accuracy worsens, so it is necessary to consider the heat dissipation design of the distance image sensor.

7. Evaluation kit

Figure 7-1 shows a configuration example using the evaluation kit for the distance image sensor. This evaluation kit can generate sensor drive timing with an FPGA and sensor bias voltage with a DAC-IC, perform A/D conversion on the sensor output signal, and transfer data to a PC via USB 3.0. This evaluation kit can be driven with only a 5 V power supply.
Hamamatsu provides evaluation kits (with LED array and light receiving lens) for the S15452-01WT, S15453-01WT, S15454-01WT, S16443-01WT, and S16444-01WT.

[Figure 7-1] Configuration example of distance measurement using the evaluation kit



[Figure 7-2] Evaluation kit examples

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