

Distance image sensors

S15452/S15453/S15454-01WT

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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.

1. Features

- Wide spectral response range to near infrared
- Reduced effect of background light
- Compact wafer level package (WLP) type

[Table 1-1] Product lineup

Type	Linear		Area
Type no.	S15452-01WT	S15453-01WT	S15454-01WT
Pixel height	50 μm		50 μm
Pixel pitch	20 μm	20 μm	50 μm
Number of pixels	64	256	96 \times 72
Fill factor	80%		70%
Video data rate	5 MHz		10 MHz

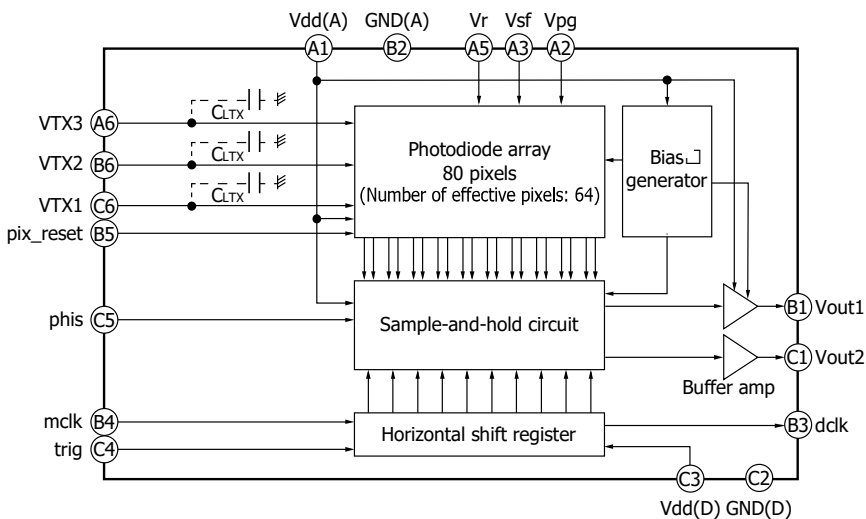
2. Structure

NIR-enhanced type distance image sensors consist of a photosensitive area, shift register, output 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 manner.

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

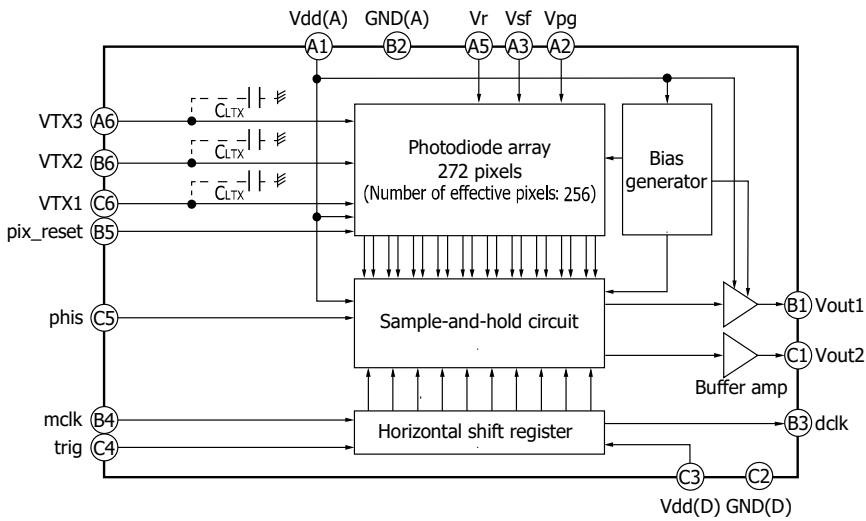
Like a typical CMOS image sensor, the output signal from the photosensitive area is processed by the sample-and-hold circuit or column gain amplifier circuit, scanned sequentially by the shift register, and read out as voltage output.

[Figure 2-1] Block diagram
(a) S15452-01WT



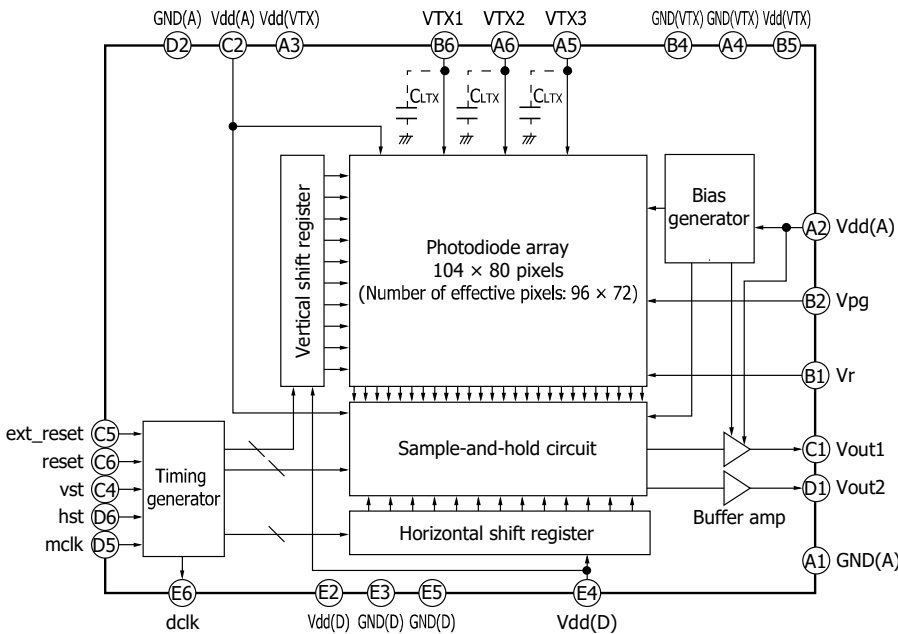
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(b) S15453-01WT



KMPDC0742EA

(c) S15454-01WT



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3. Operating principle

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

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).

$$V_{out1} = Q1/C_{fd1} = N \times I_{ph} \times \{(T_0 - T_d)/C_{fd1}\} \dots(3-1)$$

$$V_{out2} = Q2/C_{fd2} = N \times I_{ph} \times (T_d/C_{fd2}) \dots(3-2)$$

Cfd1, Cfd2: integration capacitance of each output

N: charge transfer clock count

Iph: photocurrent

T0: 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).

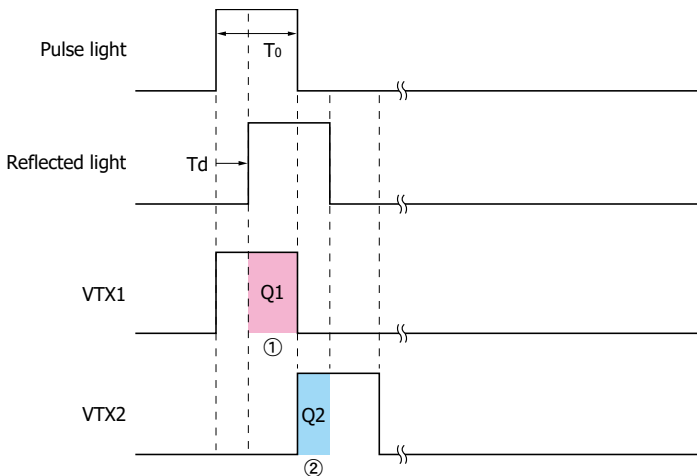
$$T_d = \{V_{out2}/(V_{out1} + V_{out2})\} \times T_0 \dots(3-3)$$

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

$$D = 1/2 \times c \times T_d = 1/2 \times c \times \{V_{out2}/(V_{out1} + V_{out2})\} \times T_0 \dots(3-4)$$

c: speed of light (3×10^8 m/s)

[Figure 3-1] Timing chart of photosensitive area



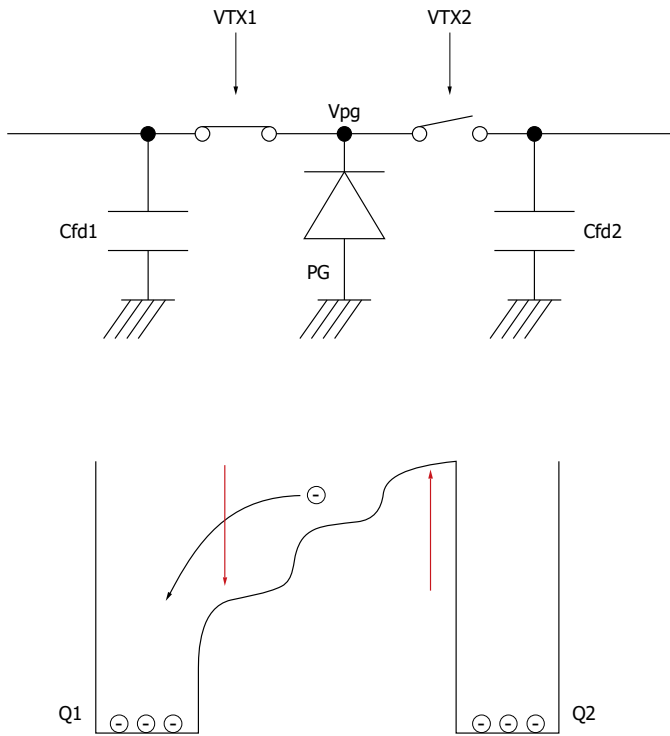
The structure and surface potential of the photosensitive area of the distance image sensor are shown in Figure 3-2. Typical CMOS image sensors can be driven with a single power supply, but the transfer time needed for the charge to move from the photosensitive area to the integration area is in the microsecond order. On the other hand, high-speed charge transfer (nanosecond order) is possible on CCD image sensors, but they require multiple voltage inputs including high voltage.

To achieve the high-speed charge transfer (several tens of nanoseconds) needed to acquire distance information, we have developed a pixel structure that enables high-speed charge transfer like the CCDs in the CMOS process. This has allowed distance image sensors to achieve the high-speed charge transfer needed for distance measurement.

The number of electrons generated in each pulse emission is several e-. Therefore, the operation shown in Figure 3-2 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.

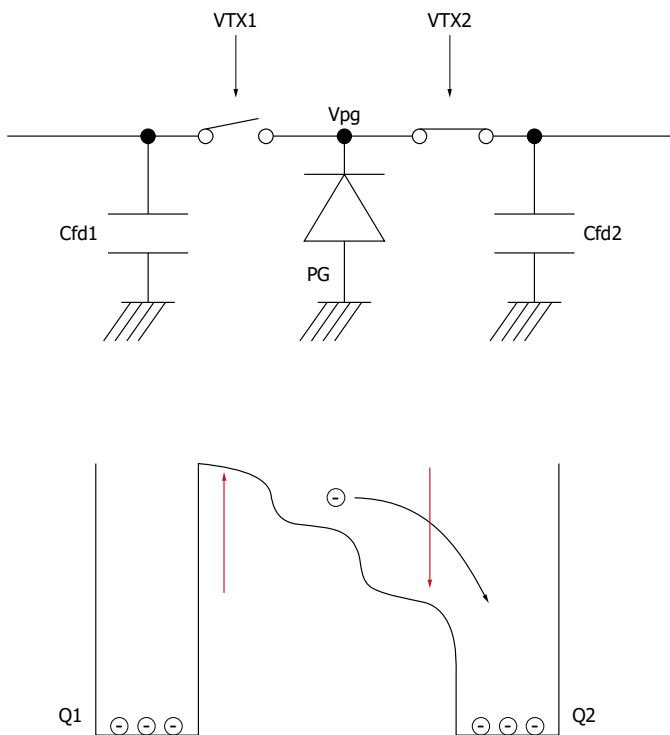
[Figure 3-2] Structure and surface potential of photosensitive area

(a) VTX1: on, VTX2: off (in the case of Figure 3-1①)



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

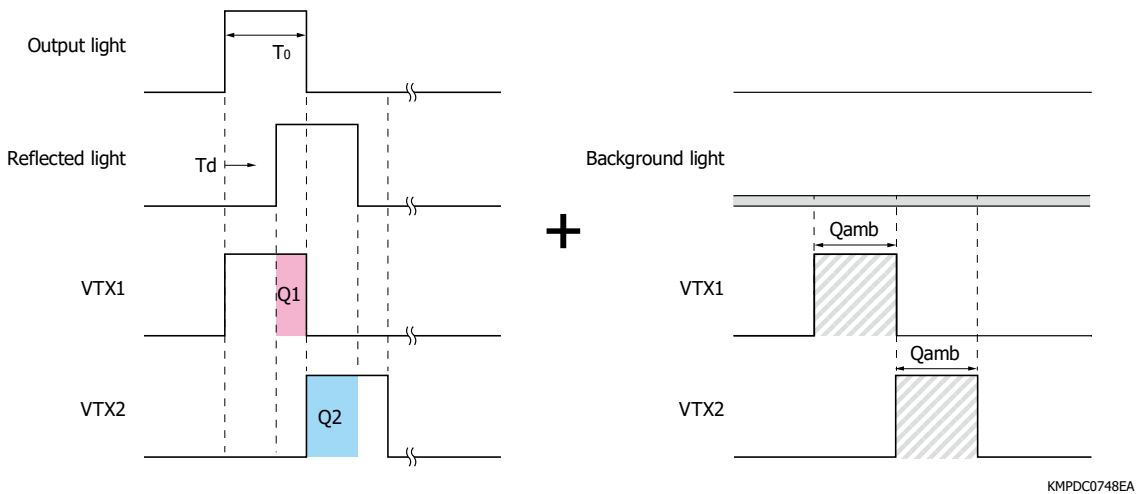


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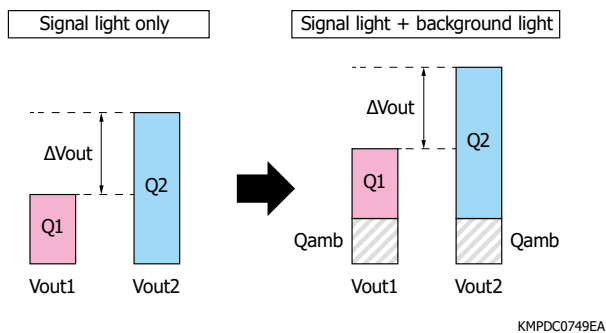
3-2. Background light elimination circuit

The distance image sensor outputs the sum of signal charge (Q_1 , Q_2) and background light charge (Q_{amb}) [Figure 3-3]. Distance is calculated with ΔV_{out} , the difference between output voltages V_{out1} and V_{out2} , 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 3-4].

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



[Figure 3-4] Integrated charge when background light is incident



The distance image sensors S15452/S15453/S15454-01WT are equipped with a background light elimination circuit [Figure 3-5] that suppresses saturation of output voltage when background light is incident. Figure 3-6 shows operation of the background light elimination circuit. When either integration capacitor C_{fd1} or C_{fd2} approaches saturation, the same amount of current flows to both C_{fd1} and C_{fd2} in the direction that reduces the integration charge. In this case, the difference value between V_{out1} and V_{out2} will not change, so it will have no effect on distance measurement.

The background light elimination circuit automatically functions when the output voltage approaches saturation, and ON/OFF cannot be controlled.

We denote the current caused by the signal light flowing through C_{fd1} and C_{fd2} as I_{ac1} and I_{ac2} and the current caused by background light as I_{amb} . The charges caused by I_{ac1} , I_{ac2} , and I_{amb} are not distinguished and integrated simultaneously [Figure 3-6]. We denote the current caused by the incident light (signal light + background light) flowing through C_{fd1} and C_{fd2} as I_{ph1} and I_{ph2} . If V_{out1} and V_{out2} do not exceed the threshold [Figure 3-6 (a)], ΔV_{out1} (the amount of change in V_{out1}) is expressed by equation (3-5) and ΔV_{out2} (the amount of change in V_{out2}) by equation (3-6).

$$\Delta V_{out1} = (Q1 + Q_{amb})/C_{fd1} = N \times [\{I_{ac1} \times (T_0 - T_d)\} + (I_{amb} \times T_0)]/C_{fd1} \dots(3-5)$$

$$\Delta V_{out2} = (Q2 + Q_{amb})/C_{fd2} = N \times \{(I_{ac2} \times T_d) + (I_{amb} \times T_0)\}/C_{fd2} \dots(3-6)$$

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

$$\Delta V_{out} = \Delta V_{out1} - \Delta V_{out2} = N \times [\{I_{ac1} \times (T_0 - T_d)\} - (I_{ac2} \times T_d)]/(C_{fd1} \text{ or } C_{fd2}) \dots(3-7)$$

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).

$$\begin{aligned} \Delta V_{out1} &= \{(Q1 + Q_{amb}) - (Q2 + Q_{amb})\}/C_{fd1} = (Q1 - Q2)/C_{fd1} \\ &= N \times [\{I_{ac1} \times (T_0 - T_d) + I_{amb} \times T_0\} - \{(I_{ac2} \times T_d) + (I_{amb} \times T_0)\}]/C_{fd1} \\ &= N \times [\{I_{ac1} \times (T_0 - T_d)\} - (I_{ac2} \times T_d)]/C_{fd1} \end{aligned} \dots(3-8)$$

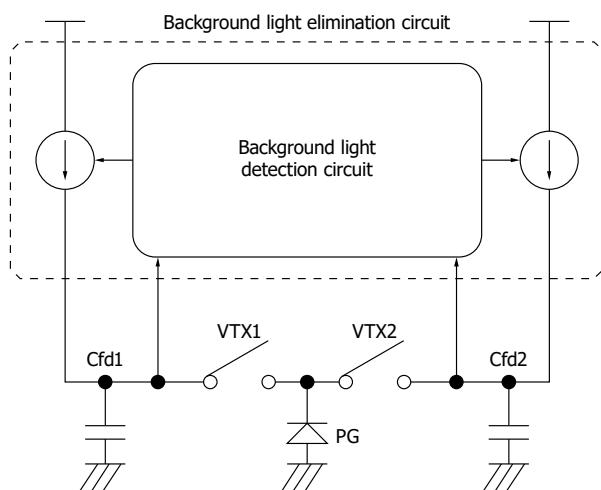
$$\Delta V_{out2} = \{(Q2 + Q_{amb}) - (Q2 + Q_{amb})\}/C_{fd2} = 0 \dots (3-9)$$

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

$$\Delta V_{out} = \Delta V_{out1} - \Delta V_{out2} = N \times [\{I_{ac1} \times (T_0 - T_d)\} - (I_{ac2} \times T_d)]/(C_{fd1} \text{ or } C_{fd2}) \dots(3-10)$$

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).

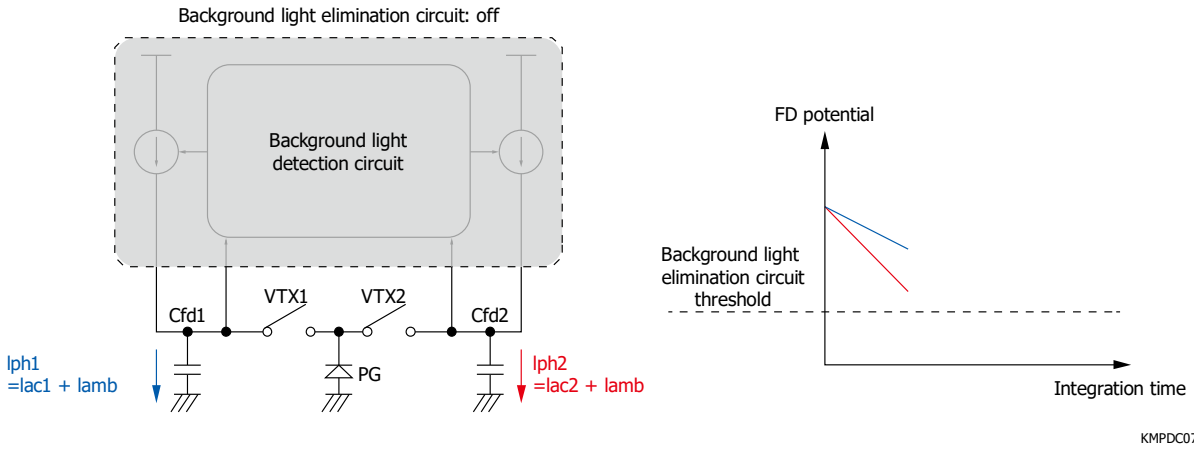
[Figure 3-5] Background light elimination circuit



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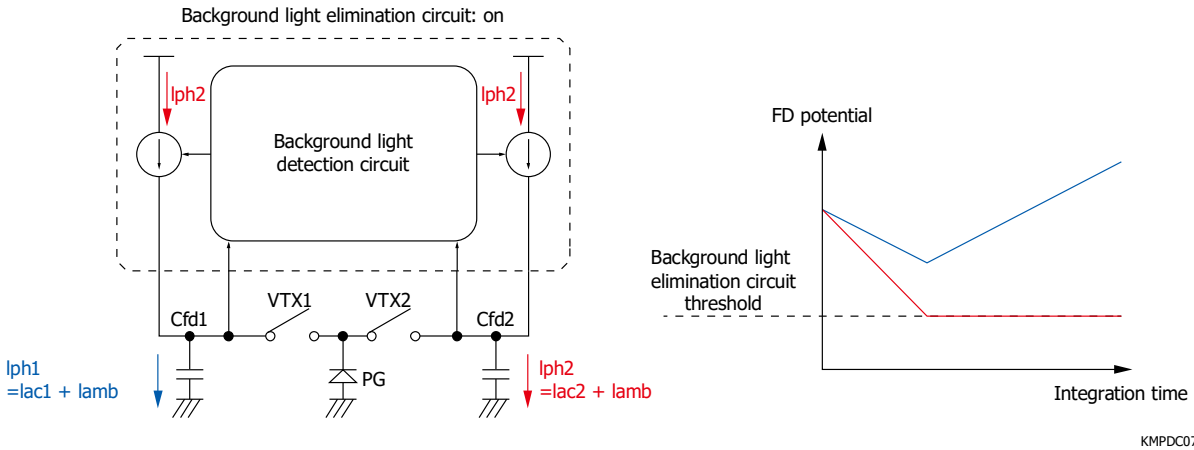
[Figure 3-6] Operation of background light elimination circuit

(a) Background light elimination circuit: before operation



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(b) Background light elimination circuit: after operation ($I_{ph1} < I_{ph2}$)



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3-3. Distance calculation

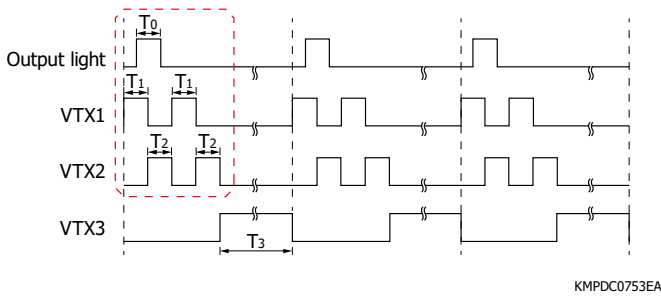
This section explains how to calculate distances by using ΔV_{out} , which is the difference between output voltages V_{out1} and V_{out2} of Cfd1 and Cfd2. Four outputs $V_{out1}(F1)$, $V_{out2}(F1)$, $V_{out1}(F2)$, and $V_{out2}(F2)$ for two gate drive timings (F1 and F2) are used to calculate a distance [Figure 3-7]. 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, ΔV_{out} is equal to zero when V_{out1} and V_{out2} 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 $\Delta V_{out}(F1)$ or $\Delta V_{out}(F2)$ 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 3-8 shows the difference signal levels for delay time T_d of the reflected light for gate drive timings F1 and F2 and Figure 3-9 the absolute values of the difference signal levels. Total charge 1 can be calculated by adding $|\Delta V_{out}(F1)|$ and $|\Delta V_{out}(F2)|$. Figure 3-10 shows a calculation example of total charge ($T_d = 1/3T_0$, $T_d = 13/8T_0$). Total charge 1 is used to determine delay time T_d , and the distance is calculated.

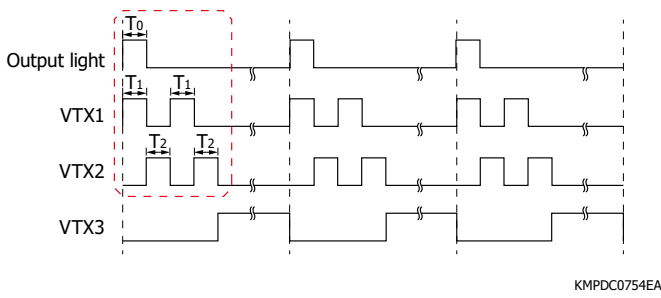
[Figure 3-7] Gate drive timing

(a) F1



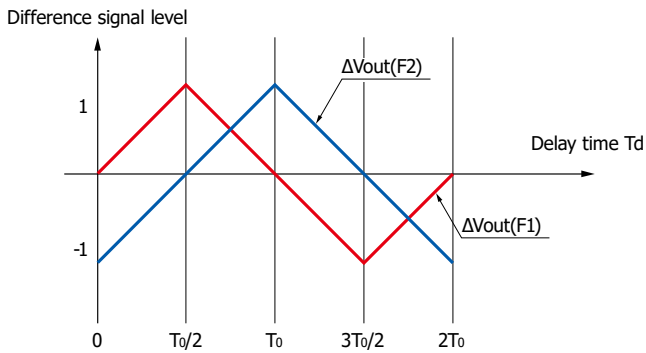
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(b) F2



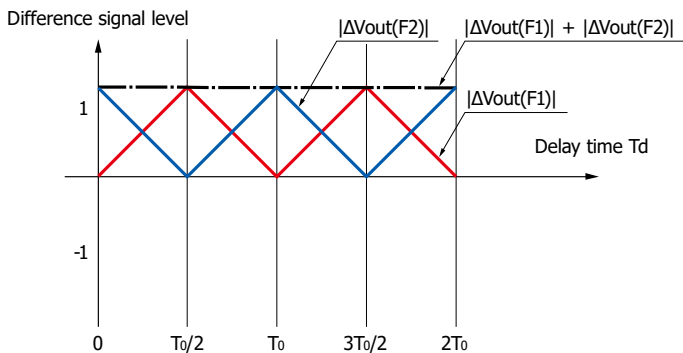
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[Figure 3-8] Difference signal level vs. delay time



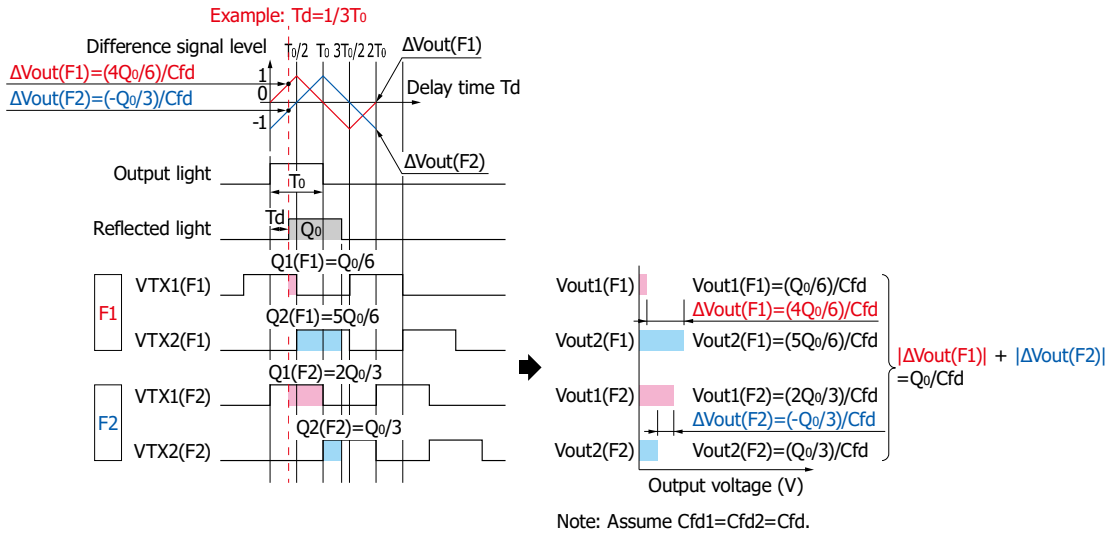
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[Figure 3-9] Difference signal level (absolute value) vs. delay time

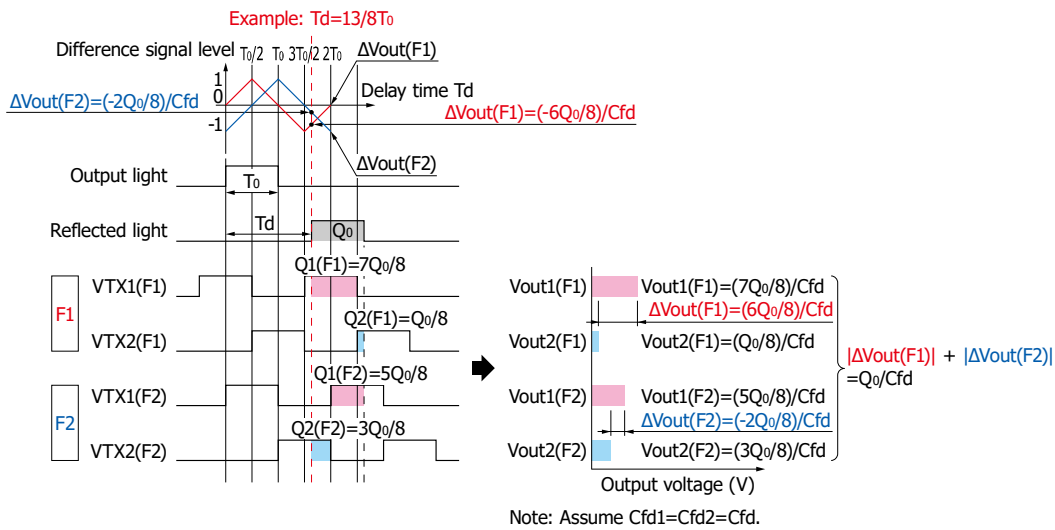


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[Figure 3-10] Calculation examples of total charge
 (a) $T_d=1/3T_0$



(b) $T_d=13/8T_0$

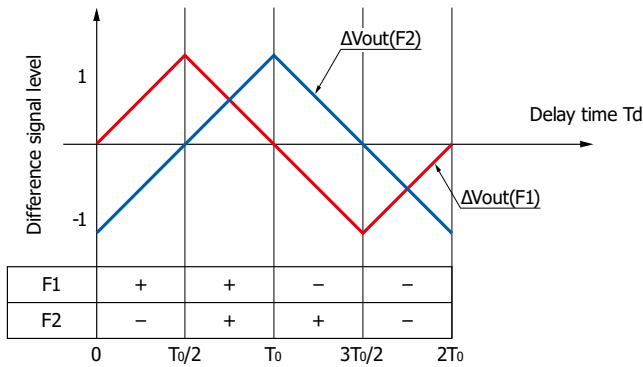


Distance D can be calculated from the ratio of the total charge and the charge caused by the reflected light [equation (3-11)]. For delay time 0 to $2T_0$, correct the charge so that it changes linearly from 0 to 1, and calculate the distance.

$$D = \{(Charge\ after\ delay\ time\ T_d)/(Total\ charge)\} \times CT_0 \dots(3-11)$$

The delay time of light reception timing is determined to be greater than or less than T_0 based on whether $\Delta V_{out}(F1)$ is positive or negative. Correct $\Delta V_{out}(F2)$, and determine the amount of change in the delay time with respect to the total charge [Figure 3-11].

[Figure 3-11] Polarity of difference signal level



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Distance is calculated by correcting $\Delta V_{out}(F2)$ separately for the cases when $\Delta V_{out}(F1)$ is positive and negative. Correct $\Delta V_{out}(F2)$ so that it changes from 0 to 1 in response to T_d changing from 0 to $2T_0$.

(1) When $\Delta V_{out}(F1)$ is positive

When $\Delta V_{out}(F1)$ is positive, delay time T_d is less than T_0 [Figure 3-11]. $\Delta V_{out}(F2)$ is corrected so that it changes from 0 to 0.5 in response to T_d changing from 0 to T_0 . When T_d is less than T_0 , $\Delta V_{out}(F2)$ 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 $\Delta V_{out}(F2)$. To make the amount of change start from zero, add an offset of 1/4. Distance D when $\Delta V_{out}(F1)$ is positive is expressed by equation (3-12).

$$D = \left[\frac{\{\Delta V_{out}(F2)/4\}}{\{|\Delta V_{out}(F1)| + |\Delta V_{out}(F2)|\}} + 1/4 \right] \times CT_0$$

$$= \left[\frac{\Delta V_{out}(F2)}{\{|\Delta V_{out}(F1)| + |\Delta V_{out}(F2)|\}} + 1 \right] \times (CT_0/4) \quad \dots (3-12)$$

(2) When $\Delta V_{out}(F1)$ is negative

When $\Delta V_{out}(F1)$ is negative, delay time T_d is greater than T_0 [Figure 3-11]. Correct $\Delta V_{out}(F2)$ so that it changes from 0.5 to 1 in response to T_d changing from T_0 to $2T_0$. When delay time T_d is greater than T_0 , $\Delta V_{out}(F2)$ changes from 1 to -1 [Figure 3-11]. If we multiply this by a factor of -1 to invert the slope, $\Delta V_{out}(F2)$ 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 $\Delta V_{out}(F2)$. Then, add an offset of 3/4 so that $\Delta V_{out}(F2)$ changes from 0.5 to 1. Distance D when $\Delta V_{out}(F1)$ is negative is expressed by equation (3-13).

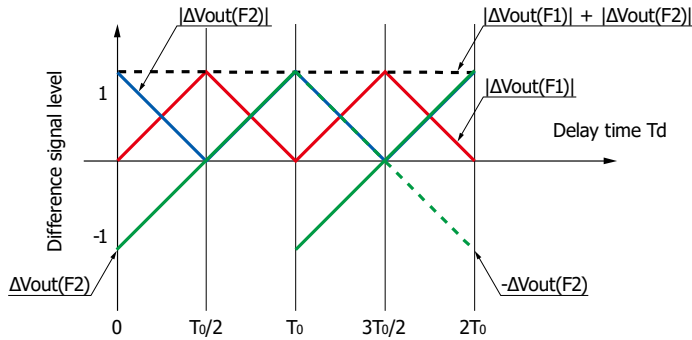
$$D = \left[\frac{\{-\Delta V_{out}(F2)/4\}}{\{|\Delta V_{out}(F1)| + |\Delta V_{out}(F2)|\}} + 3/4 \right] \times CT_0$$

$$= \left[\frac{-\Delta V_{out}(F2)}{\{|\Delta V_{out}(F1)| + |\Delta V_{out}(F2)|\}} + 3 \right] \times CT_0/4 \quad \dots (3-13)$$

Figure 3-12 shows the distance calculation process of (1) and (2).

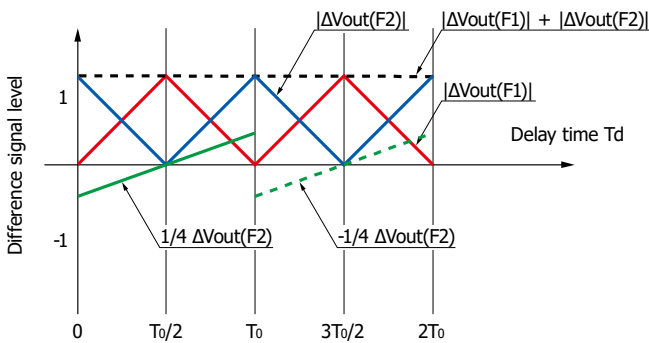
[Figure 3-12] Distance calculation process

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



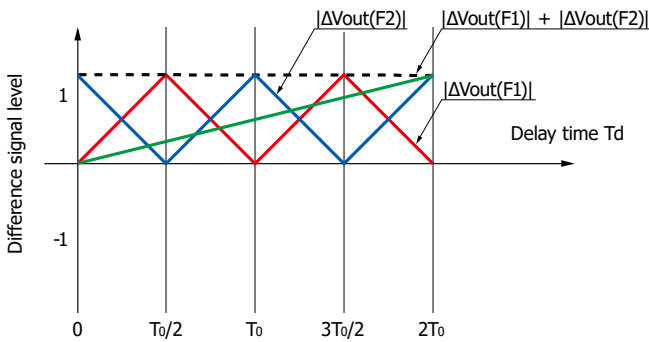
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(b) Change to the slope [multiple 1/4 to $\Delta V_{out}(F2)$]



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



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3-4. Charge drain function

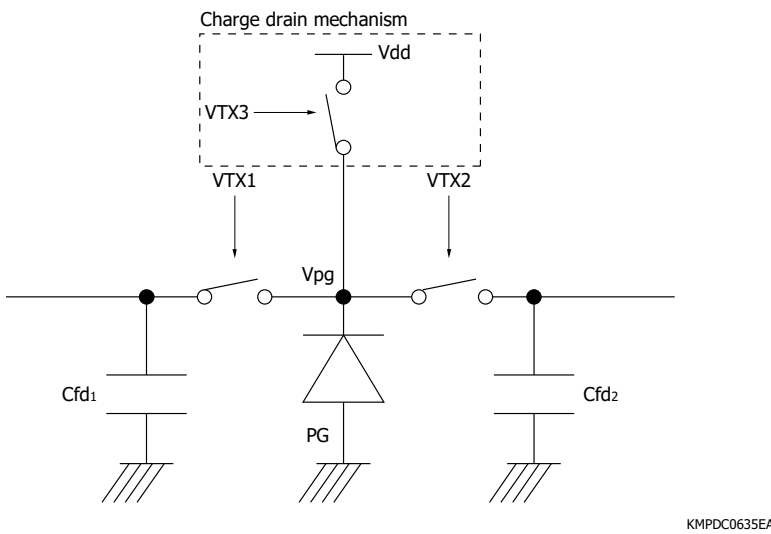
A distance image sensor has charge transfer gates VTX1, VTX2, which transfer the charges that are generated at the photosensitive area, and a charge drain gate VTX3, which discharges unneeded charges. When VTX1 and VTX2 are off and VTX3 is on, the charge drain function is turned on without the accumulation of signal charges. This makes it possible to drain unneeded charges caused by background light during the non-emission period. The charge drain function enables the following:

① Detection of high-speed pulses

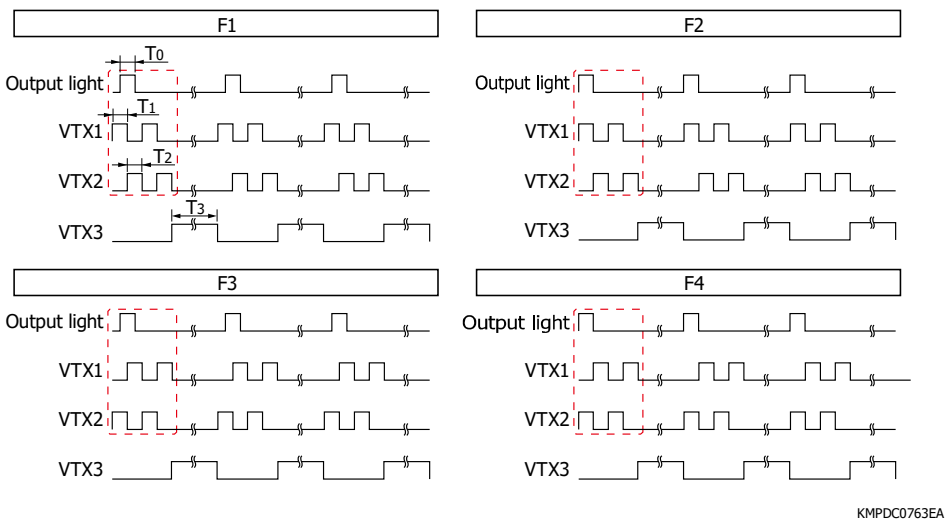
Signal charges from pulse laser diodes and other high-speed pulse light sources can be integrated efficiently.

② Shutter operation

[Figure 3-13] Structure of photosensitive area



[Figure 3-14] Timing chart of photosensitive area

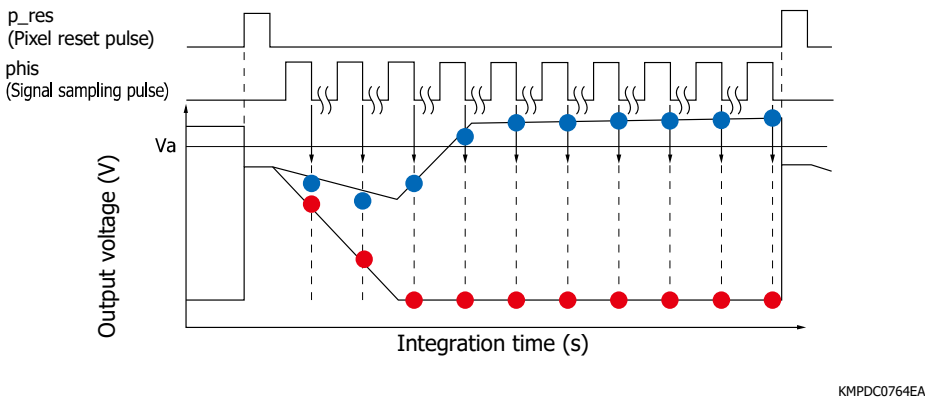


3-5. Non-destructive readout

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 3-15 shows a schematic diagram of non-destructive readout (relationship between output voltage and integration time). Set the threshold voltage V_a lower than the saturation voltage. The output voltage immediately before exceeding V_a 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.

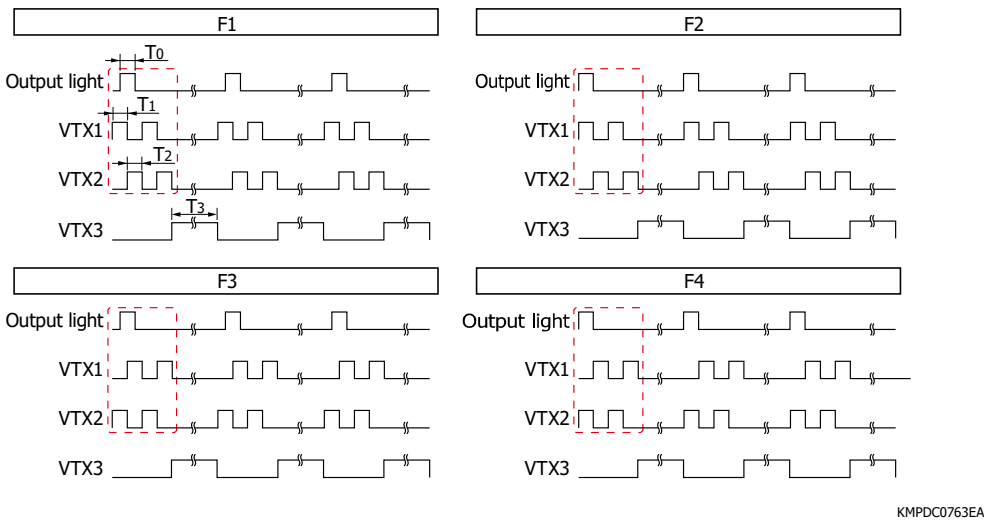
[Figure 3-15] Schematic diagram of non-destructive readout



3-6. Drive timing

In the ideal case, distance measurement is possible by using the gate drive timings of F1 and F2. However, V_{out1} and V_{out2} have intrinsic variation components (V_{err}), 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 V_{err} [Figure 3-16].

[Figure 3-16] Timing chart



F3 is F1 with the timings of VTX1 and VTX2 swapped. Ideally, $V_{out1}(F1)$ is equal to $V_{out2}(F3)$ and $V_{out2}(F1)$ is equal to $V_{out1}(F3)$. If intrinsic variation components V_{err1} and V_{err2} exist in V_{out1} and V_{out2} , $\Delta V_{out}(F1)$ is expressed by equation (3-14) and $\Delta V_{out}(F3)$ by equation (3-15).

$$\Delta V_{out}(F1) = \{V_{out2}(F1) + V_{err2}\} - \{V_{out1}(F1) + V_{err1}\} \dots(3-14)$$

$$\Delta V_{out}(F3) = \{V_{out2}(F3) + V_{err2}\} - \{V_{out1}(F3) + V_{err1}\} \dots(3-15)$$

Assuming $V_{out1}(F1)$ is equal to $V_{out2}(F3)$ and $V_{out2}(F1)$ is equal to $V_{out1}(F3)$, subtracting equation (3-14) from equation (3-15) produces equation (3-16). By using F3 along with F1, V_{err1} and V_{err2} can be eliminated.

$$\begin{aligned}
& \Delta V_{out}(F1) - \Delta V_{out}(F3) \\
&= [\{V_{out2}(F1) + V_{err2}\} - \{V_{out1}(F1) + V_{err1}\}] - [\{V_{out2}(F3) + V_{err2}\} - \{V_{out1}(F3) + V_{err1}\}] \\
&= 2\{V_{out2}(F1) - V_{out1}(F1)\} \quad \dots (3-16)
\end{aligned}$$

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)].

$$\begin{aligned}
& \Delta V_{out}(F2) - \Delta V_{out}(F4) \\
&= [\{V_{out2}(F2) + V_{err2}\} - \{V_{out1}(F2) + V_{err1}\}] - [\{V_{out2}(F4) + V_{err2}\} - \{V_{out1}(F4) + V_{err1}\}] \\
&= 2\{V_{out2}(F2) - V_{out1}(F2)\} \quad \dots (3-17)
\end{aligned}$$

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

(1) When $\Delta V_{out}(F1) - \Delta V_{out}(F3)$ is positive

$$\begin{aligned}
D &= [\{(\Delta V_{out}(F2) - \Delta V_{out}(F4))/4\} / \{|\Delta V_{out}(F1) - \Delta V_{out}(F3)| + |\Delta V_{out}(F2) - \Delta V_{out}(F4)|\} + 1/4] \times CT_0 \\
&= [\{\Delta V_{out}(F2) - \Delta V_{out}(F4)\} / \{|\Delta V_{out}(F1) - \Delta V_{out}(F3)| + |\Delta V_{out}(F2) - \Delta V_{out}(F4)|\} + 1] \times CT_0/4 \\
&\quad \dots(3-18)
\end{aligned}$$

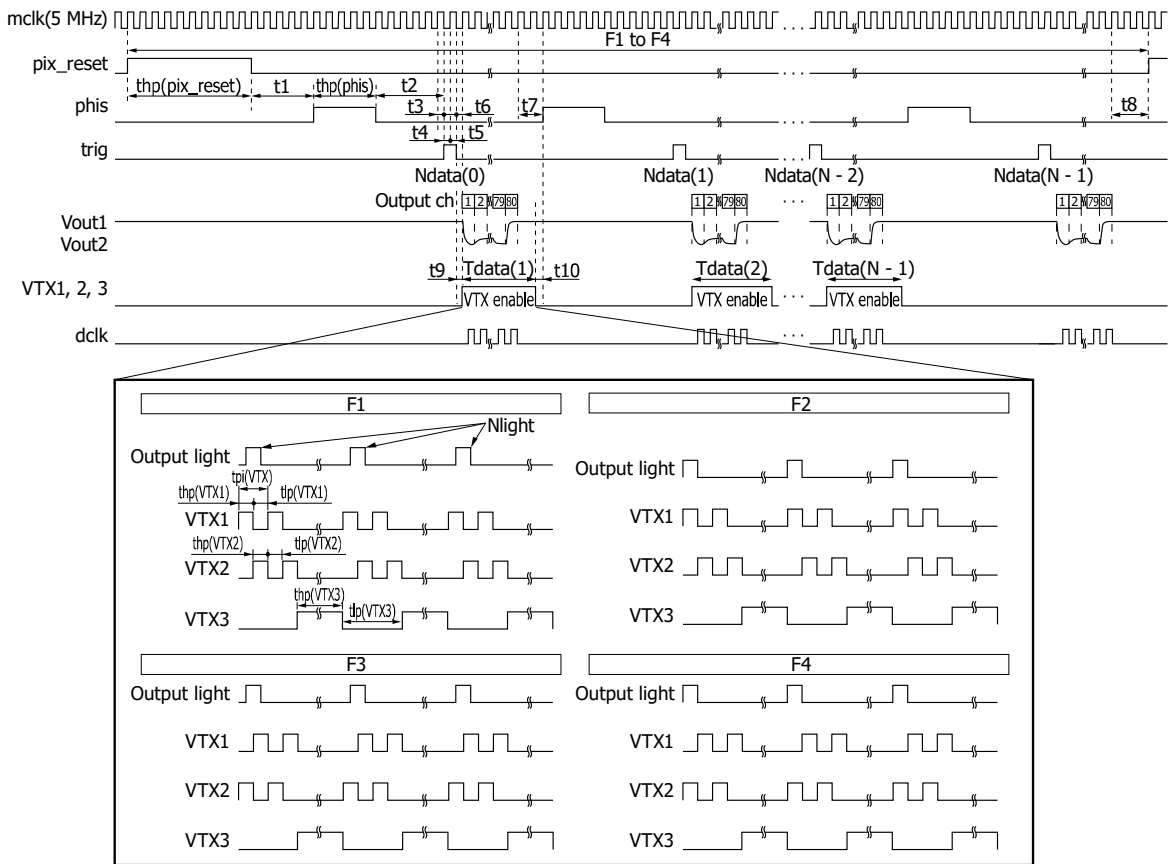
(2) When $\Delta V_{out}(F1) - \Delta V_{out}(F3)$ is negative

$$\begin{aligned}
D &= [-(\Delta V_{out}(F2) - \Delta V_{out}(F4))/4] / \{|\Delta V_{out}(F1) - \Delta V_{out}(F3)| + |\Delta V_{out}(F2) - \Delta V_{out}(F4)|\} + 3/4] \times CT_0 \\
&= [-\{\Delta V_{out}(F2) - \Delta V_{out}(F4)\} / \{|\Delta V_{out}(F1) - \Delta V_{out}(F3)| + |\Delta V_{out}(F2) - \Delta V_{out}(F4)|\} + 3] \times CT_0/4 \\
&\quad \dots (3-19)
\end{aligned}$$

3-7. Timing chart

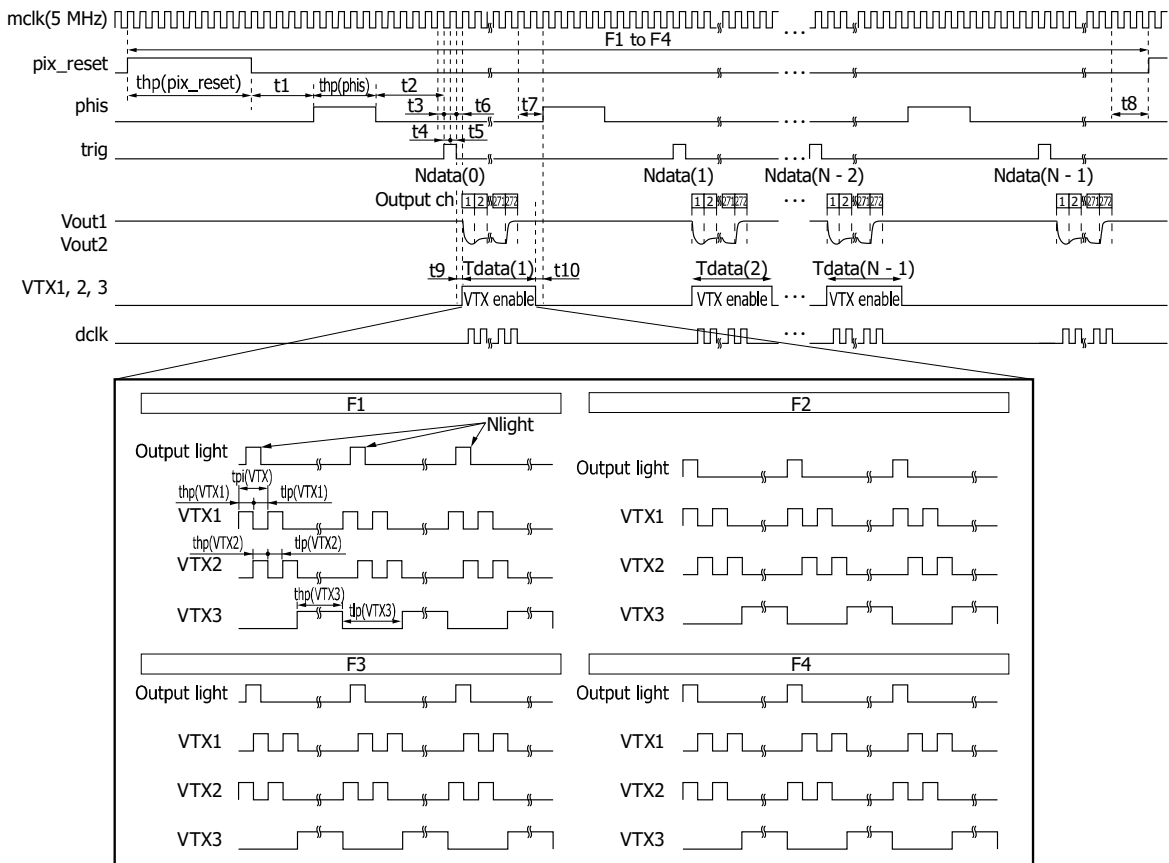
Figure 3-17 shows the signal readout timing chart. When the distance is measured once, readout is performed four times using different gate timings. F3 and F4 are gate drive timings of F1 and F2 but with the VTX1 and VTX2 timings swapped.

[Figure 3-17] Timing chart
(a) Linear image sensor (S15452-01WT)



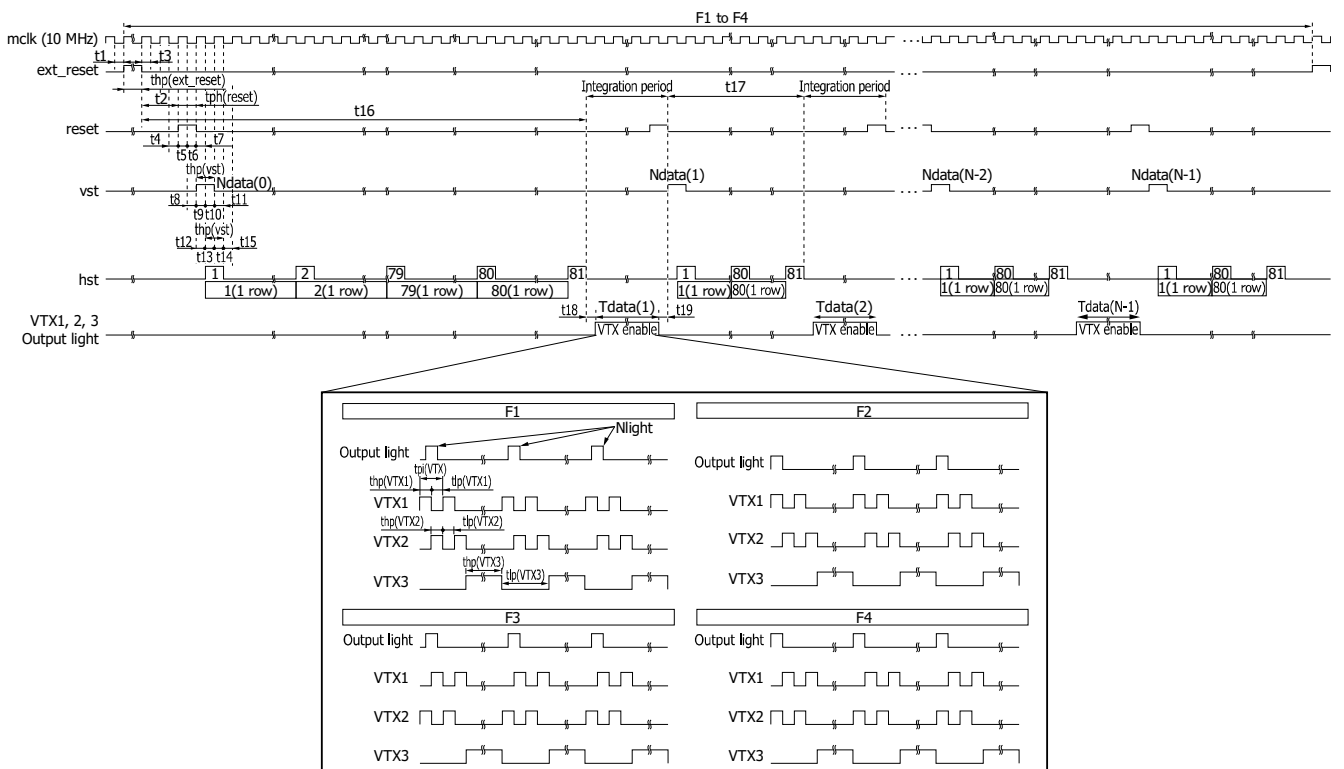
KMPDC0739EB

(b) Linear image sensor (S15453-01WT)



KMPDC0743EB

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



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3-8. Calculating the frame rate

$$\begin{aligned}\text{Frame rate} &= 1/\{4 (\text{Time per subframe})\} \\ &= 1/\{(\text{Integration time} + \text{Readout time}) \times 4\} \quad \dots(3-20)\end{aligned}$$

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)]

$$\begin{aligned}\text{Readout time} &= \frac{1}{\text{Clock pulse frequency}} \times \text{Number of horizontal pixels} \\ &= \text{Time per clock (Readout time per pixel)} \times \text{Number of horizontal pixels} \dots (3-21)\end{aligned}$$

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

$$\begin{aligned}\text{Readout time} &= \frac{1}{5 \times 10^6 [\text{Hz}]} \times 272 \\ &= 200 [\text{ns}] \times 272 \\ &= 0.0544 [\text{ms}] \dots(3-22)\end{aligned}$$

When operating in non-destructive readout mode:

$$\text{Time per subframe} = \text{Integration time} + (\text{Readout time} \times \text{Non-destructive readout count}) \dots (3-23)$$

[Area image sensor (S15454-01WT)]

$$\begin{aligned}\text{Readout time} &= \frac{1}{\text{Clock pulse frequency}} \times \text{Horizontal timing clock} \times \text{Number of vertical pixels} \\ &= \text{Time per clock (Readout time per pixel)} \times \text{Horizontal timing clocks} \times \text{Number of vertical pixels} \dots (3-24)\end{aligned}$$

Calculation example of readout time

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

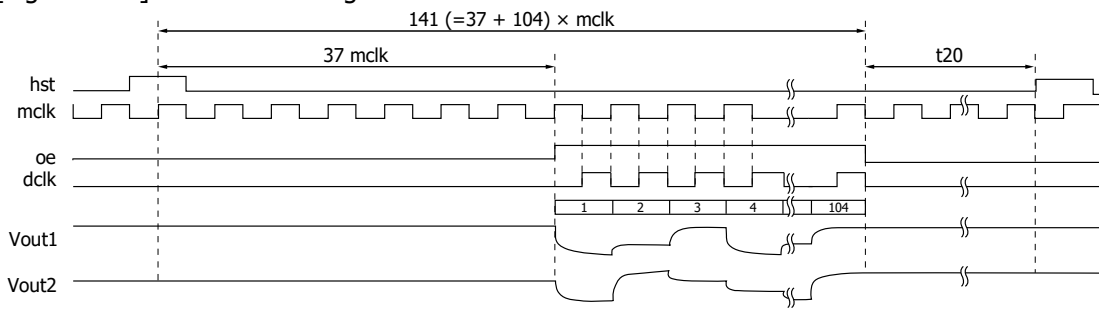
$$\begin{aligned}\text{Readout time} &= \frac{1}{10 \times 10^6 [\text{Hz}]} \times 141 \times 80 \\ &= 100 [\text{ns}] \times 141 \times 80 \\ &= 1.128 [\text{ms}]\end{aligned}$$

When operating in non-destructive readout mode:

$$\text{Time per subframe} = \text{Integration time} + (\text{Readout time} \times \text{Non-destructive readout count}) \dots (3-25)$$

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 3-18] Horizontal timing



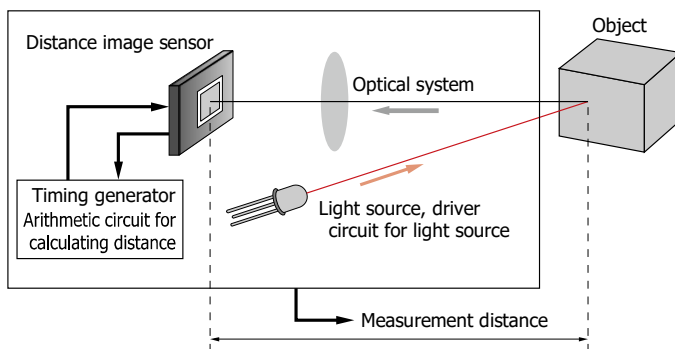
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4. How to use

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



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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 distance area image sensor, 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. The reasons why calibration is necessary are shown below.

[Reasons why calibration is necessary]

- 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
- Peripheral circuits

The following shows an example of the calibration method.

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

(1) When $T_d \leq T_0$

$$D = a \left(\frac{V_{outB}}{|V_{outA}| + |V_{outB}|} + 1 \right) \times \frac{CT_0}{4} - Dofs \quad \dots (5-1)$$

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

$$D = a \left(\frac{-V_{outB}}{|V_{outA}| + |V_{outB}|} + 3 \right) \times \frac{CT_0}{4} - Dofs \quad \dots (5-2)$$

a: 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 (a).

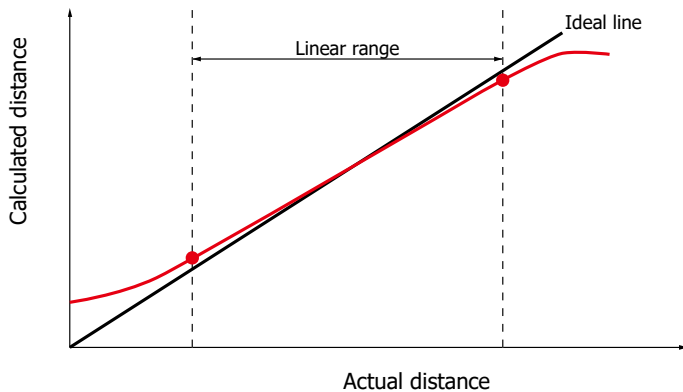
Setting the light emission timing delay, distance offset, and Dofs

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 a

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

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



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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 T_{acc} [s]
- Light emitter's angle at half maximum θ_{source} [V]
- Light projection angle (horizontal, vertical) θ_H , θ_V [°]

(3) Background light

- Sunlight intensity P_{amb} [W/m²]
- Band-pass filter's transmission wavelength range (short-wavelength side, long-wavelength side) λ_{short} , λ_{long} [nm]

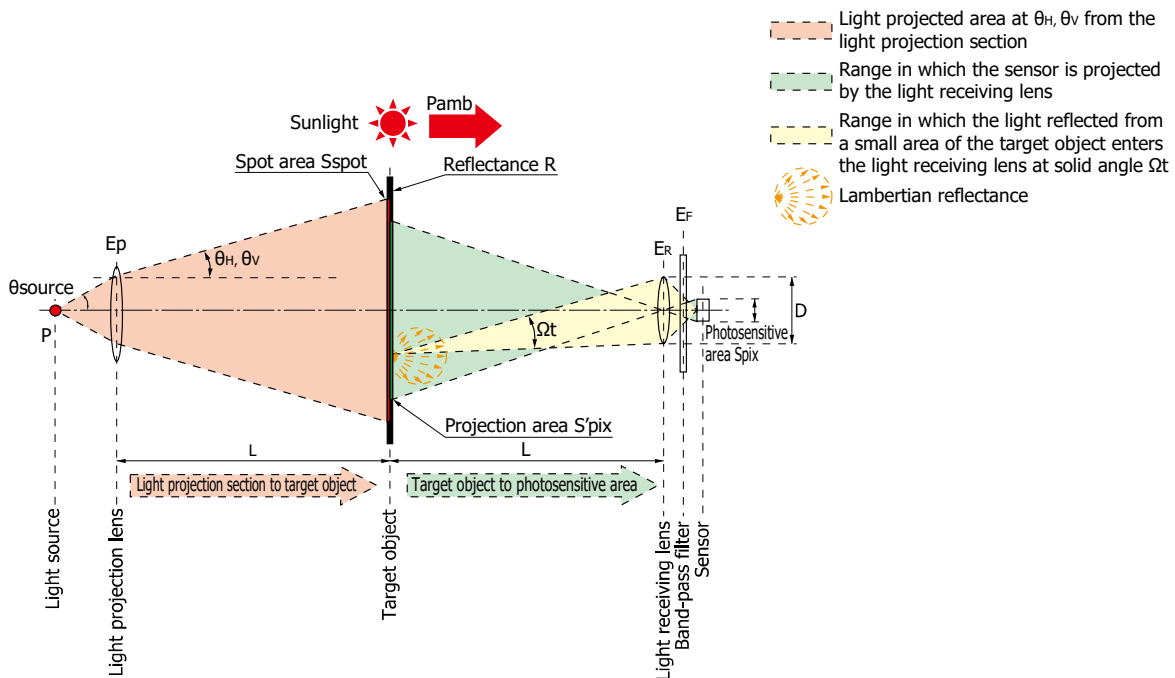
(4) Photosensitive area

- 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) H_{pix}, V_{pix} [m] (area S_{pix})
- Fill factor FF [%]
- Photosensitivity S_{sens} [A/W]
- Pixel capacitance C_{fd} [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



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Calculation method

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

$$P_{spot} = P \times \frac{A}{L^2} \times E_p \times \frac{1}{S_{spot}} \dots(6-1)$$

P : Light source output [W/sr]

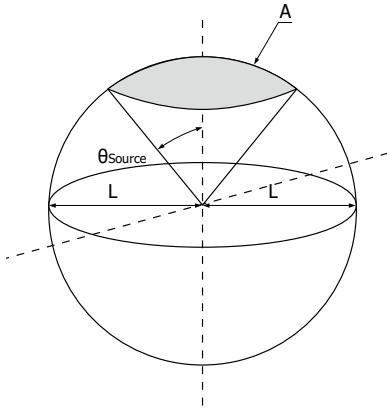
A : Area of a spherical surface obtained by cutting a sphere with radius L at an angle of θ_{source}

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

E_p : light projection efficiency [%]

S_{spot} : area of the light spot projected on the target object [m²]

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



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Sspot is given by equation (6-2).

$$S_{spot} = 2L \tan \theta_H \times 2L \tan \theta_V \dots (6-2)$$

A is given by equation (6-3).

$$A = 2\pi \{1 - \cos(\theta_{source})\} \times L^2 \dots (6-3)$$

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).

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

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

$$\Omega_t = 4\pi \sin^2 \frac{\theta_R}{2} \dots (6-5)$$

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 Ω_t 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 S_{pix} and the pixel projection area S'_{pix} on the target object is given by equation (6-6).

$$S'_{pix} = \left(\frac{L}{f} \right)^2 S_{pix} \dots (6-6)$$

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 P_{pix} [W] entering a single pixel is given by equation (6-7).

$$P_{pix} = P_{spot} \times R \times \frac{1}{\pi} \times \Omega_t \times S'_{pix} \times E_R \times E_F(\text{sig}) \times FF \dots (6-7)$$

The background light level $P_{pix}(\text{amb})$ [W] entering a single pixel is given by equation (6-8).

$$P_{pix}(\text{amb}) = P_{amp} \times R \times 1 \times \Omega_t \times S'_{pix} \times E_R \times E_F(\text{amb}) \times FF \dots (6-8)$$

$E_F(\text{sig})$: band-pass filter transmittance for signal light

$E_F(\text{amb})$: band-pass filter transmittance for background light

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

$$V_{pix} = P_{pix} \times T_{acc} \times \text{duty} \times (S_{sens}/C_{fd}) \dots (6-9)$$

T_{acc} : integration time [s]

duty: duty ratio

S_{sens} : photosensitivity [A/W]

C_{fd} : pixel capacitance [F]

Output voltage $V_{pix}(\text{amb})$ [V] generated from the background light is given by equation (6-10). Because background light is incident at the two gate drive timings, we double $V_{pix}(\text{amb})$.

$$V_{pix}(\text{amb}) = P_{pix}(\text{amb}) \times T_{acc} \times \text{duty} \times (S_{sens}/C_{fd}) \times 2 \dots (6-10)$$

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 I_{pix} [A] per pixel generated by the signal light is given by equation (6-11).

$$I_{pix} = P_{pix} \times S_{sens} \dots (6-11)$$

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

$$\begin{aligned} Q_{pix} &= I_{pix} \times T_{acc} \times \text{duty}/e \dots (6-12) \\ &= P_{pix} \times S_{sens} \times T_{acc} \times \text{duty}/e \end{aligned}$$

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

The number of electrons $Q_{pix}(\text{amb})$ [e^-] per pixel generated by the background light is given by equation (6-13).

$$Q_{pix}(\text{amb}) = P_{pix}(\text{amb}) \times S_{sens} \times T_{acc} \times \text{duty}/e \times 2 \dots (6-13)$$

Next, noise components are described. The amplitudes of light shot noise N_L , random noise N_R , dark current shot noise N_D are given by the following equations [unit: e^-].

$$N_L = \sqrt{Q_{pix} + Q_{pix}(\text{amb})} \dots (6-14)$$

$$NR = 2 \times RN \times Cfd/e \dots (6-15)$$

RN: random noise [V]

$$ND = \sqrt{2 \times V_D \times T_{acc} \times Cfd/e} \dots (6-16)$$

V_D: dark output [V]

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

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

The S/N is the ratio of the number of signal electrons Q_{pix} to N.

Distance accuracy σ [m] is given by equation (6-18).

$$\sigma = \frac{N}{Q_{pix}} \times \frac{cT_0}{2} \dots (6-18)$$

c: speed of light

T₀: light emission pulse width

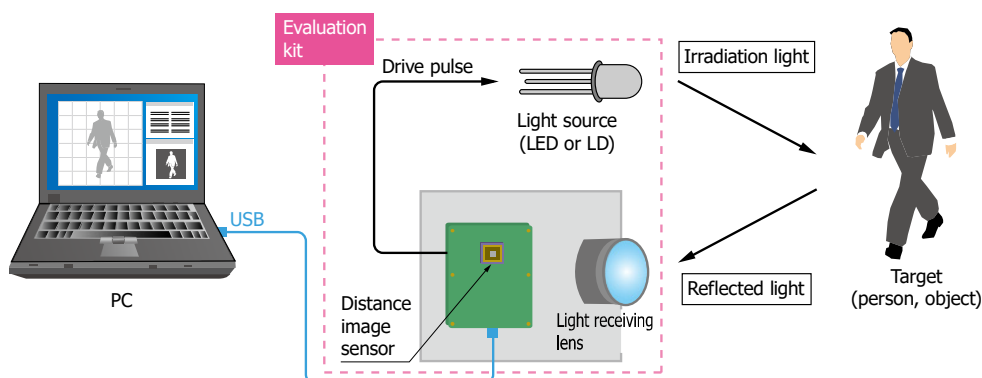
Increasing the incident signal level helps to improve the distance accuracy. As the temperature rises, dark current shot noise increases and distance accuracy worsens, so it is necessary to consider the heat dissipation design of the distance image sensor.

7. Evaluation kit

Figure 8-1 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, and S15454-01WT.

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



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[Figure 7-2] Evaluation kit examples
(a) For linear image sensors



(b) For area image sensor

