High-Performance Photo Detector for Correlative Feeble Lighting Using Pixel-Parallel Sensing

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***Abstract*—We have developed a high-performance photo detector, which can detect a feeble projected light with pulse modulation in strong ambient light from other light sources. It is useful to expand the application field of the three-dimensional measurement system using a light-section method. A correlation circuit and a current-mode suppression circuit of constant illumination allow high sensitivity, high selectivity, and adaptive suppression of background illumination. A logarithmic-response circuit is employed to avoid saturation for wide dynamic ranges. The photo detector can quickly detect the modulated light by pixel-parallel sensing. It has advantages for some applications which require availability in various background illuminations and safe light projection for human eyes. The photo detectors have been developed and successfully tested. The high sensitivity under -18-dB signal-to-background ratio (SBR) is realized over the 47.2-dB dynamic range. The minimum SBR is -22.8 dB and the potential frame rate is 2000 fps. In addition, the photo detector shows high selectivity in a multiple-lighting system due to the suppression of orthogonally modulated light.**

***Index Terms*—High selectivity, high sensitivity, modulated lighting, photo detector, wide dynamic range.**

I. Introduction

A THREE-DIMENSIONAL (3-D) measurement system using a triangulation-based light projection method is generally more suitable for the application field, which requires high-range accuracy, range scale of several meters and simple calculation, as opposed to other methods, such as a stereo matching method, a time-of-flight method [1], [2], and an interferometric method [3]. Particularly some applications of 3-D measurement, such as a walking robot and a recognition system on vehicles, require both of availability in various background illumination and safe light projection for human eyes. Standard imagers and most of the smart position sensors [4]–[10] detect the positions of peak intensity on the sensor plane to acquire the position of the projected light in the 3-D measurement system. Therefore, these sensors require strong light projection when a target object is placed in nonideal environment such as strong background illumination. A possible method to realize the suppression of the background illumination is the interframe difference method, where the difference signals between subsequent two frames are used to detect the projected light. This method is, however, not suitable for quick detection because it takes at least a frame interval time. Color filters mounted on the sensors can suppress the background illumination and realize high-sensitivity photo detection. Sunlight has, however, distributed wavelengths with strong intensity, so that the color filters are not enough for some applications. A high-sensitivity position sensor with the capability of electronic suppression of background illumination is required in such situations.

A correlation technique, such as in [3] and [11], is a possible solution to the problems. The correlation sensor [11] can suppress background illumination to obtain high sensitivity. Its dynamic range, however, is limited by the linear difference circuit due to voltage signal saturation. It is not applicable for a strong contrast image in outdoor environment. The range finder with an electronic shutter [2] can prevent the saturation problem of [11]. Its dynamic range is decided by the limit of the shutter interval and an extremely short shutter interval can achieve wide dynamic range. It is, however, difficult to satisfy the bandwidth requirement because of the laser diode cost and to adjust an optimal shutter interval autonomously, especially in nonuniform contrast scene.

In this paper, a new sensing scheme for high-sensitivity and wide-dynamic-range photo detection is presented. For a wide dynamic range, a logarithmic-response circuit is employed to overcome the saturation problem of [2], [11]. A correlation circuit and a current-mode suppression circuit of constant illumination realize higher sensitivity than the conventional sensors [11], [12]. The photo detector can quickly detect the modulated light by the pixel-parallel sensing. In addition, it also realizes high selectivity due to the suppression of orthogonally modulated light. The photo detectors have been developed and successfully tested.

This paper is organized as follows. Section II discusses the principle of our sensing scheme for modulated lighting and its circuit implementation. Section III presents the array structure and the specifications of our designed and fabricated photo detectors. In Section IV, the measurement results of our photo detectors are shown. Its sensitivity, dynamic range, selectivity, and frame rate are evaluated. Finally, conclusions are presented in Section V.

II. Photo Detector Architecture

The architecture of the proposed photo detector is described in this section. The proposed sensing scheme, its circuit realization, and the principle of its operation are shown.

A. New Sensing Scheme

Fig. 1 illustrates the proposed sensing scheme for high-sensitivity and wide-dynamic-range photo detection. In the range-

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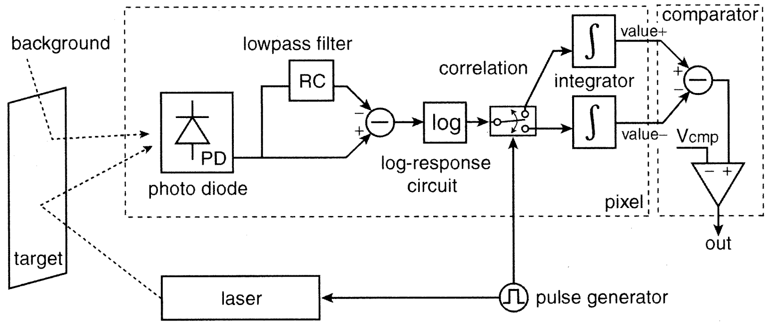

Fig. 1. Proposed sensing scheme.

finding system, a laser beam modulated by a pulse generator is projected on a target object. The photo detector receives the reflection of the projected laser beam and background illumination together. The photo current generated by the incident light is fed into a low-pass filter. The output current of the low-pass filter is subtracted from the original photo current. The subtraction is realized using the current-mode circuit instead of the voltage mode circuit [2], [11] to avoid saturation. The output current is alternating when the incident light includes a modulated light. A logarithmic-response circuit limits the amplitude of current swing to avoid a saturation problem of a correlation circuit after constant current suppression. The limited current swing is divided into two integrators by the external correlation signal. The marked difference voltage between the outputs of each integrator is acquired only when the incident light has the correlation frequency. The low-pass filter and the current-mode subtraction circuit realize adaptive suppression of constant illumination. The logarithmic-response circuit and the correlation circuit are dedicated to wide-dynamic-range and high-sensitivity photo detection.

B. Pixel Circuit Realization

Fig. 2 shows a schematic of the photo detector. The photo current $I_{\rm pd}$ is generated in proportion to the incident intensity. The photo current is copied as the current $\alpha I_{\rm pd}$, where α is a gain of the current copier circuit. Its average current $\alpha I_{\rm avg}$ is generated by a low-pass filter and it is subtracted from $\alpha I_{\rm pd}$. The low-pass filter consists of two biased transistors (M_0 and M_1) and two capacitors (C_0 and C_1). The biased transistors are used for a resistor of the low-pass filter as a simple version of the HRES circuit [13]. The drain-source current I_{M0} of the transistor M_0 is controlled by the gate voltage V_{g0}. The bias circuit keeps the gate-source voltage V_q constant in each pixel for constant resistance. The saturation current of the biased transistor M_0 is half the current of the bias current I_b controlled by V_r.

Fig. 3 shows a timing diagram of the sensing scheme. When the incident light includes a modulated light, the photo current has a constant current $I_{\rm dc}$ by background illumination and an alternating current $I_{\rm ac}$ by a modulated light

$$I_{\rm pd} = I_{\rm dc} + I_{\rm ac}. \tag{1}$$

The low-pass filter generates the average current $\alpha I_{\rm avg}$ as follows:

$$\alpha I_{\rm avg} = \alpha \overline{I_{\rm pd}} = \alpha(I_{\rm dc} + \overline{I_{\rm ac}}). \tag{2}$$

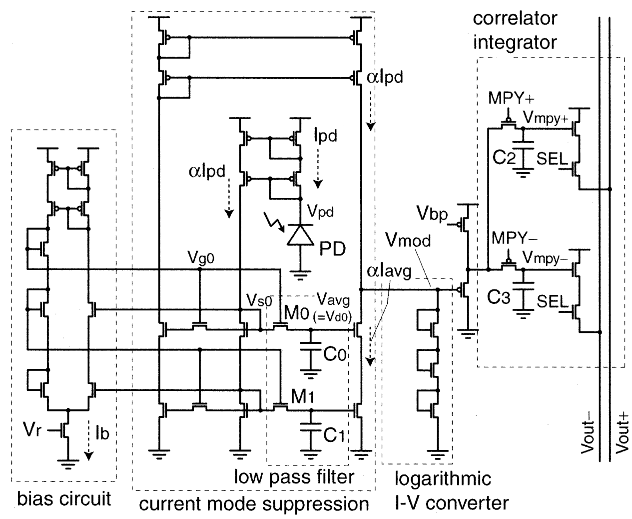

Fig. 2. Schematic of the photo detector.

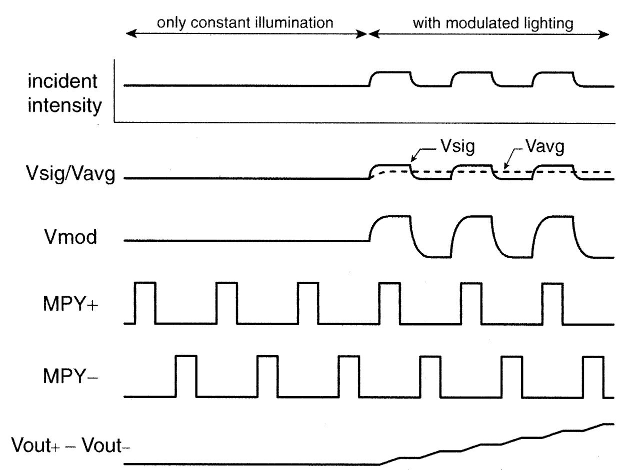

Fig. 3. Timing diagram of the sensing scheme.

The constant current $I_{\rm dc}$ is suppressed adaptively by the current-mode suppression circuit. The output current $I_{\rm mod}$ of the suppression circuit is given by

$$I_{\rm mod} = \alpha I_{\rm pd} - \alpha I_{\rm avg} = \alpha(I_{\rm ac} - \overline{I_{\rm ac}}). \tag{3}$$

The current $I_{\rm mod}$ is converted to the voltage $V_{\rm mod}$ by a logarithmic-response circuit

$$V_{\rm mod} = \beta \log(I_0 + I_{\rm mod}) \tag{4}$$

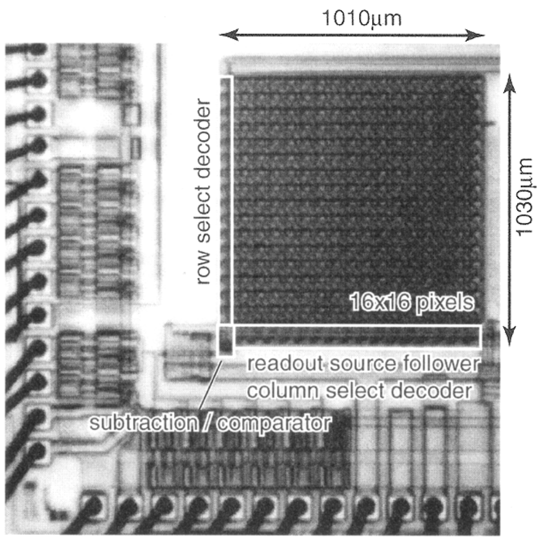

Fig. 4. Microphotograph of the fabricated chip.

where β is a gain factor of the logarithmic-response circuit and I_0 is an offset current. The output is divided into two capacitors C_2 and C_3 by the external signals $\mathrm{MPY}+$ and $\mathrm{MPY}-$ synchronized with the correlation frequency. The voltages $V_{\mathrm{mpy}+}$ and $V_{\mathrm{mpy}-}$ at C_2 and C_3 are read out as $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ by a source follower circuit, respectively.

When the incident light is only background illumination, the photo current is constant and I_{mod} is zero. In this case, the difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is zero and the pixel is decided not to be activated. On the other hand, the marked difference between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is acquired only when the incident light has the frequency synchronized with the correlation frequency. The pixel is decided to be activated when the difference voltage is above the reference voltage V_{cmp} of the comparator as follows:

$$V_{\mathrm{out}+} - V_{\mathrm{out}-} \geq V_{\mathrm{cmp}}. \tag{5}$$

Our circuit implementation using a cascode current mirror is redundant from the view point of the number of transistors in pixel. A circuit design using a single current mirror operates correctly; however, it is not able to achieve higher sensitivity of correlation than that which uses a cascode current mirror in our experiments, since our standard CMOS process has large dc leakage current at the current mirror. Therefore, we have chosen the circuit design using a cascode current mirror as shown in Fig. 2.

III. Chip Implementation

The presented photo detectors have been designed and fabricated in 0.6-μm CMOS process. Figs. 4 and 5 show a microphotograph of the fabricated photo detectors and a layout of the photo detector, respectively. The chip has a 16 $\times$ 16 pixel array. The pixel area occupies 60 μm $\times$ 60 μm with 13.5% fill factor. The photo diode consists of an n^+-diffusion and a p-substrate. The pixel has 43 transistors, including 4 MOS capacitors. The capacitance of C_0, C_1 in Fig. 2 is 370 fF and that of C_2, C_3 is 150 fF. Table I shows the specification of the fabricated chip.

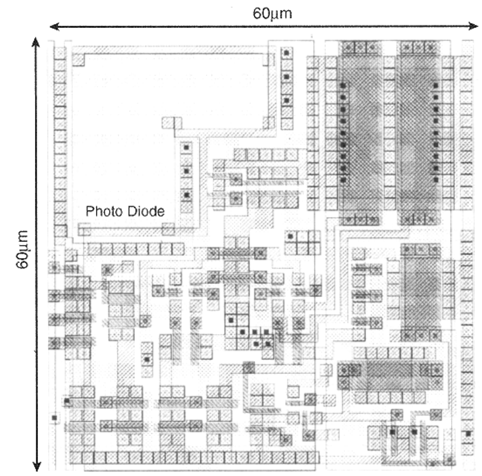

Fig. 5. Pixel layout.

TABLE I
Specification of the Photo Detectors

Process	0.6 μm CMOS 3-metal 2-poly-Si
Chip size	4.8 mm $\times$ 4.8 mm
Num. of pixels	16 $\times$ 16 pixels
Pixel size	60.0 μm $\times$ 60.0 μm
Fill-factor	13.5 %
# trans./pixel	43 trans. (including MOS capacitors)

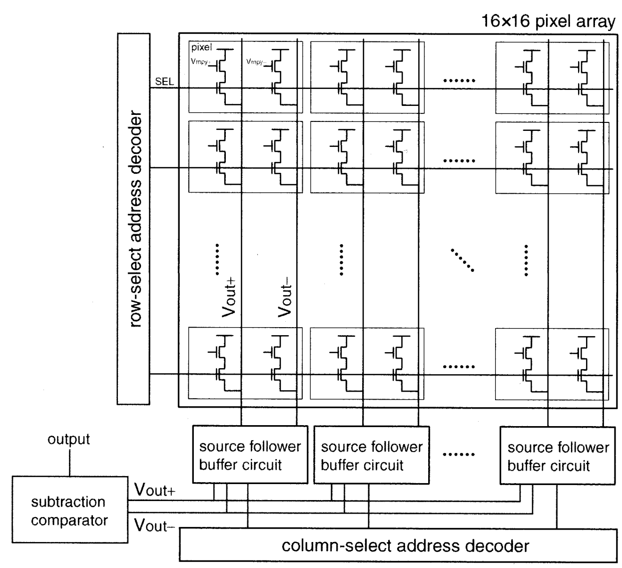

Fig. 6. Array structure of the fabricated sensor.

A. Pixel Array Structure

Fig. 6 is an array structure of the fabricated sensor. It has an array of the present photo detectors, a row-select address decoder, a column-parallel source follower buffer circuit, a column-select address decoder, and a subtraction and comparator circuit. The row-select and column-select address decoders select one pixel. Both of the output voltages $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ are read out to the subtraction and comparator circuit by a column-parallel source follower buffer circuit. At the comparator circuit, the difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is compared with the reference voltage V_{cmp} and the selected pixel is decided to be activated or not.

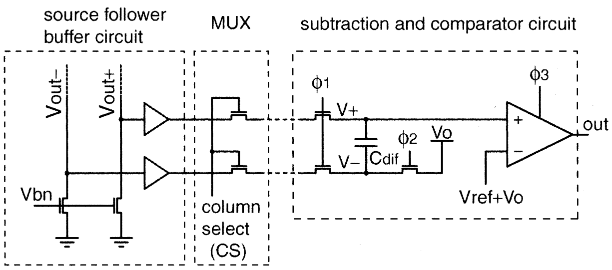

Fig. 7. Schematic of the subtraction and comparator circuit.

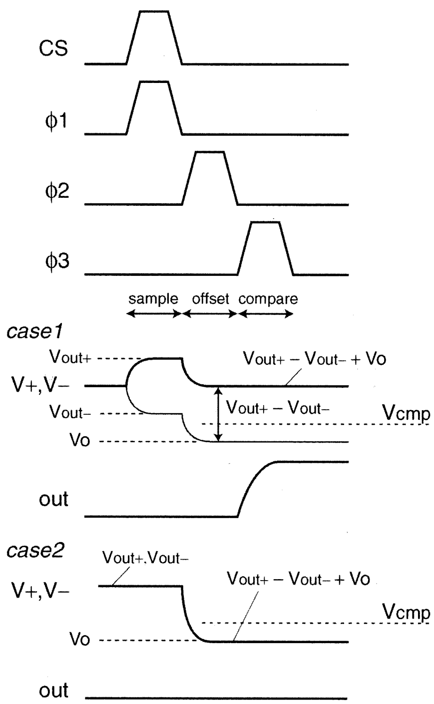

Fig. 8. Timing diagram of the subtraction and comparator circuit.

B. Subtraction and Comparator Circuit

Fig. 7 shows a schematic of the subtraction and comparator circuit and Fig. 8 shows its timing diagram. A pixel is selected by the column-select address decoder and its output voltages $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ are sampled at each node of C_{dif} by ϕ_1. When ϕ_2 is thrown ON, the voltage V_+ at the node of C_{dif} is given by

$$V_+ = V_{\mathrm{out}+} - V_{\mathrm{out}-} + V_o \quad (6)$$

where V_o is an offset voltage for adjusting to the input range of the comparator. The reference voltage V_{cmp} of the comparator is given by

$$V_{\mathrm{cmp}} = V_{\mathrm{ref}} + V_o. \quad (7)$$

The comparator is realized by a latched sense amplifier. The voltage V_+ is compared with V_{cmp} when ϕ_3 is thrown ON. The pixel is decided to be activated when the difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is over the threshold voltage V_{ref}

$$V_{\mathrm{out}+} - V_{\mathrm{out}-} \geq V_{\mathrm{ref}}. \quad (8)$$

When the incident light of the selected pixel includes a modulated light synchronized with the correlation frequency, the difference voltage becomes large, as shown in case 1 of Fig. 8. On the other hand, the difference voltage is zero or small, as shown in case 2 of Fig. 8, when the incident light does not include the correlation frequency.

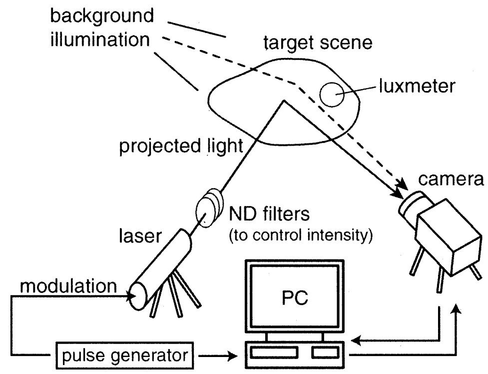

Fig. 9. Measurement system structure.

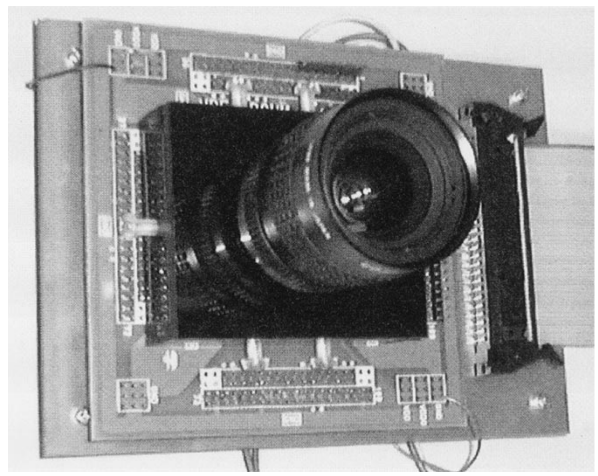

Fig. 10. Photograph of the sensor on a test board.

IV. Experimental Results

For performance evaluation, the measurement system of the fabricated sensor has been constructed as shown in Fig. 9. It consists of the fabricated sensor with a lens mounted on a test board, a laser pointer (wavelength 635 nm), a pulse generator, a light projector for background illumination, and a luxmeter. Fig. 10 shows a photograph of the camera on a test board. The sensitivity, the dynamic range, the selectivity, and the potential frame rate of the present sensor are evaluated by the measurement system. The range data of a target object can be acquired by triangulation when the projected laser beam is scanning on a target scene and the sensor detects the position of the projected laser beam on the sensor plane.

A. Sensitivity and Dynamic Range

Fig. 11 shows the relationship between the background intensity and the minimum projected light intensity to be detected. In the measurement of the sensitivity and the dynamic range, the modulation frequency is 1 kHz and the frame interval is 5 ms. To evaluate the sensitivity of the photo detection, the intensities of the projected light and the background illumination are measured by the photo current I_{pd} generated by each incident light.

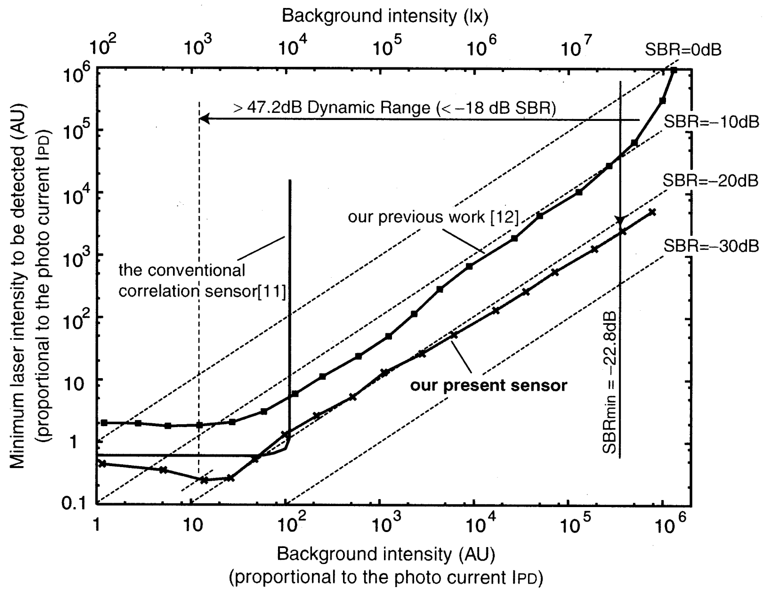

Fig. 11. Sensitivity and dynamic range.

The illuminance corresponding to the background photo current is shown in Fig. 11 (in the upper axis) for reference.

The experimental results of the present sensor are shown in Fig. 11. The present sensor can suppress the background illumination. In other word, the projected light can be weaker than the background illumination. The minimum signal-to-background ratio (SBR), which stands for the sensitivity of the photo detection, is -22.8 dB. In addition, high-sensitivity photo detection without saturation is possible over a wide range of background illumination. The high sensitivity under -18 dB is realized in dynamic range of 47.2 dB in terms of background illumination. For example, the projected light intensity can be equivalent to about 1.2×10^3 lx in an outdoor environment, where the background intensity is about 1.1×10^5 lx in the summer season. It can be equivalent to about 22 lx in a room, where the background intensity is about 1.0×10^3 lx in general.

For comparison, the capabilities of our previous work [12] and the conventional correlation sensor [11] are shown in Fig. 11. The present sensor has advantages of both high sensitivity and wide dynamic range.

B. Modulated Light Selectivity in Ambient Light From Other Light Sources

Fig. 12 shows the difference voltage of the correlation outputs, which is $V_{\text{out}+} - V_{\text{out}-}$, at various incident light frequencies. In this measurement, the correlation frequency f_0 is 1 kHz and the frame interval is 5 ms. The incident light without the correlation frequency f_0 is suppressed. Particularly, the suppression ratios to even harmonics of f_0 are less than 0.05. Therefore, the incident light with each even-harmonics frequency can be detected independently. The bandpass width is 40 Hz at 1 kHz correlation frequency. The present sensing scheme has high selectivity for a multiple light projection system by using a set of the frequencies such as 1, 2, 4, and 8 kHz.

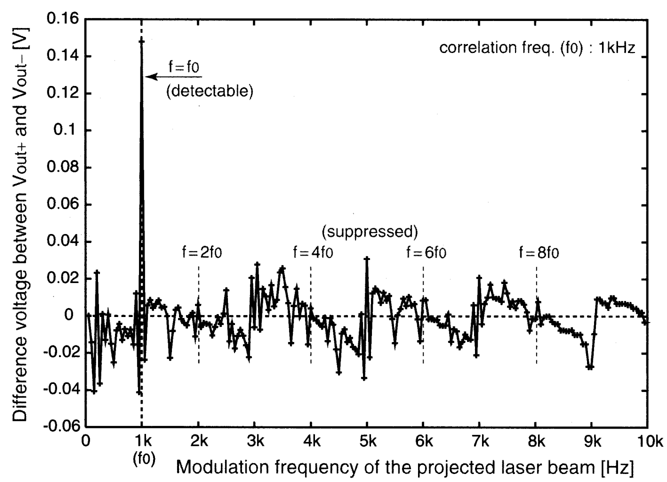

Fig. 12. Selectivity: the correlation outputs at various incident light frequencies.

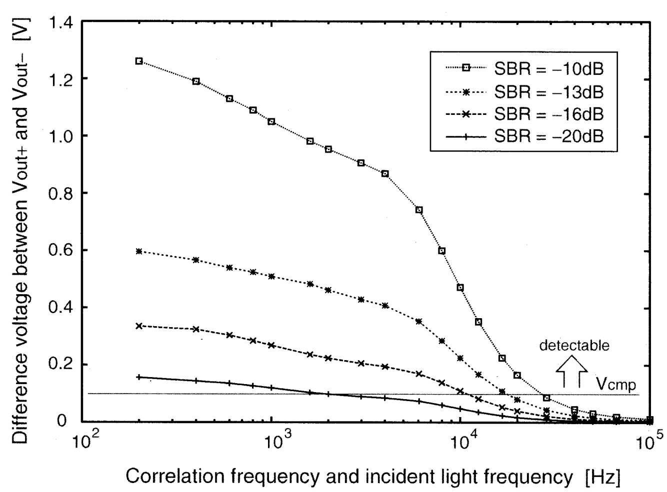

Fig. 13. Relationship between the correlation frequency and the sensitivity.

C. Frame Rate

Fig. 13 shows the relationship between the correlation frequency and the sensitivity. X axis is a correlation frequency. The modulated light frequency is the same as the correlation frequency in this measurement. Y axis is a difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$. In 22 klx background illuminance, the projected light intensity is varied in order to measure the difference voltage at various sensitivities, such as -10, -13, -16, and -20 dB SBR. The higher the correlation frequency is, the smaller the gain of correlation is due to the parasitic capacitance of the photo diode. The maximum correlation frequency is 10 kHz at -16 dB SBR and the correlation interval is 0.5 ms in this situation, that is, the potential frame rate is 2000 fps at -16 dB SBR.

V. Conclusion

A new sensing scheme for high-sensitivity and wide-dynamic-range photo detection has been proposed. A correlation circuit and a current-mode suppression circuit of constant illumination realize high sensitivity, high selectivity, and adaptive suppression of a background illumination. A logarithmic-response circuit is employed to avoid saturation for wide dynamic range. The photo detector can quickly detect the modulated light by the pixel-parallel sensing. The present photo detectors have been developed and successfully tested. Measurement results show the high sensitivity under -18 dB SBR is realized in dynamic range of over 47.2 dB in terms of background illumination. The minimum SBR is -22.8 dB and the potential frame rate is 2000 fps at -16 dB SBR. In addition, the photo detector realizes highly selective photo detection for a multiple-lighting system due to the suppression of orthogonally modulated light. The present sensor has advantages to applications which require both of availability in various background illumination and safe light projection for human eyes. Our future work is the development of a range finder with the present photo detector array for advanced 3-D measurement applications.

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