Sensors and Materials, Vol. 10, No. 1 (1998) 047–061
MYU Tokyo

S & M 0313

Two-Dimensional Bar-Code Detection System Using a Complementary Laser Light Emission Method

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(Received November 27, 1996; accepted October 16, 1997)

Key words: bar code, detection system, semiconductor laser, scanner

The use of two-dimensional bar codes in practical applications, such as product management for electronic parts and motor vehicle parts, has been studied recently. A new two-dimensional bar-code detection system using two visible-light laser diodes driven by complementary light emission and pulse modulation with a bias current near the threshold has been developed for applications such as goods management in production lines requiring high-speed detection. The pulse modulation drive with a bias current near the threshold achieves a light output rise time of 300 ns, which is much shorter than the 1.3 μs it achieves without a bias current. The effective scanning speed of 950 scan/s is twice that of the conventional two-dimensional raster scanners. It has been clarified experimentally that this scanning speed is limited by the bandwidth of the photodetection amplifier.

1. Introduction

Two-dimensional (2D) bar codes are being examined for their practical use in applications such as product management for electronic parts and motor vehicle parts. To date, vericode, data code (matrix code), PDF 417, Code 49 and Code 16k (stack bar code) have been presented.(1) The detection systems used for these 2D bar codes consist of a CCD camera and raster laser scanner for applications that require relatively low-speed detection.

However, in applications such as goods management in production lines and automatic warehouses, high-speed detection ($\gtrsim$ 500 scan/s) is required. When 2D bar codes are used for these applications, the database can be greately reduced. Hence, a simplified goods management system and high-speed processing will be realized. For high-speed detection systems, the CCD camera needed to decode data in one field period (16.7 ms) according to a standard TV scanning method is not applicable; instead, the systems use a laser scanner that can decode data for each scanning period.

Laser scanners are usually composed of a laser and a photodetection mechanism that can decode one line of bar-code data for each scanning period. In simple scanners, a physical scanning period is determined by the rotation speed of the polygonal-mirror scanners or the reciprocation speed of the galvano-mirror scanners. This simple type of scanner is not sufficient for applications in which high-speed detection is necessary, since the scanning period is limited by the scanner's physical characteristics. Hence, the key to achieving a high-speed detection system is to ensure that the system can detect a large amount of bar-code information within a single scanning period.

We have devised a 2D bar-code detection system using two visible-light laser diodes (LDs) that are driven by a complementary light emission (CLE) method.[2] This system is able to read a large amount of bar-code information within one scanning period. Also, we have devised a method for pulse modulation with bias current near the threshold (PMBC). This method improves the laser light emission rising characteristics that cause problems in the detection of a range decrease in the high-frequency drive.[3] This is distinctly different from the conventional method in which the bias current is below the threshold. The conventional method has been used to suppress a time delay (< 2 or 3 ns) of 1- to 1.3-μm-wavelength laser light emission from the input current pulse, thereby reducing the pattern effect in photocommunication applications.[4]

In this paper, we describe, in detail, the new 2D bar-code detection system (BCDS) using two visible-light laser diodes driven by the CLE method and the pulse modulation method with a bias current near the threshold. We propose a decoder configuration for successive decoding of two lines of bar-code information within a scanning period as a novel decoding technique that does not require additional decoding circuits. Also, an LD suitable for simplifying the optical equipment of the BCDS is selected based on bar-code detection experiments. Furthermore, the modulation drive of the LDs and bar-code detection characteristics are investigated.

2. New System

Our new detection system is the most effective one currently available for high-speed detection. It is able to detect a stack bar code consisting of a number of lines within a scanning period without using a raster scanner. Figure 1 is a schematic outline of the new 2D detection system. The new BCDS consists of two LDs for emitting light, a single photodetection apparatus for detecting diffused reflected light from the bar code, and two sample holders in order to sample two different signals from a detected output. Use of a single photodetection apparatus keeps the size of the 2D BCDS small. Also, a polygonal mirror and signal processing circuits such as an A/D converter and a decoder, are provided. The decoder consists of a delaying circuit to delay one of the A/D output signals, a summing gate for adding one A/D output signal to the output of the delaying circuit, and a decoding circuit (Fig. 2).

Operation principle waveforms of the new BCDS are shown in Figs. 3(a) and 3(b). In this system, light emitted alternately from two LDs by drive pulses, ϕ_1 and ϕ_2 (the CLE method), is reflected on a polygonal mirror. Reflected light from the polygonal mirror scans each line of a two-line bar code alternately at an LD drive frequency. Diffused reflected lights from the two-line bar codes are detected by a single photo-detection

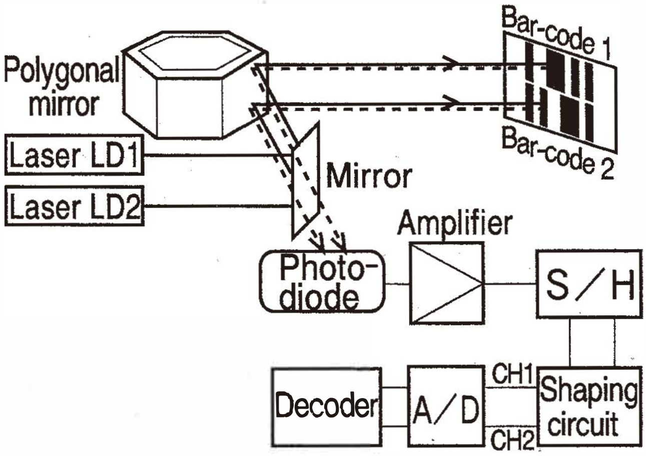

Fig. 1. Schematic outline of the new 2D BCDS.

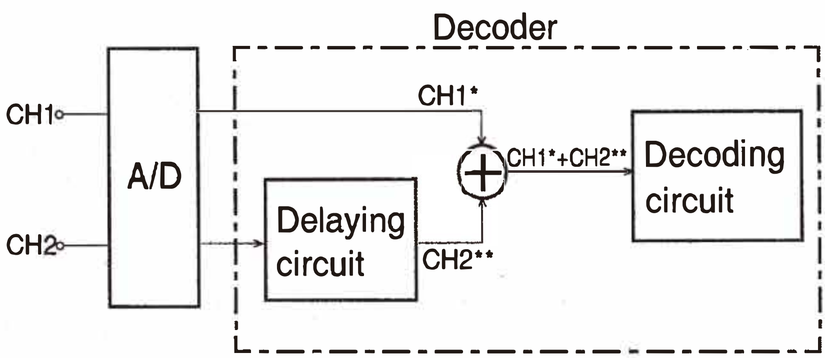

Fig. 2. Decoder configuration.

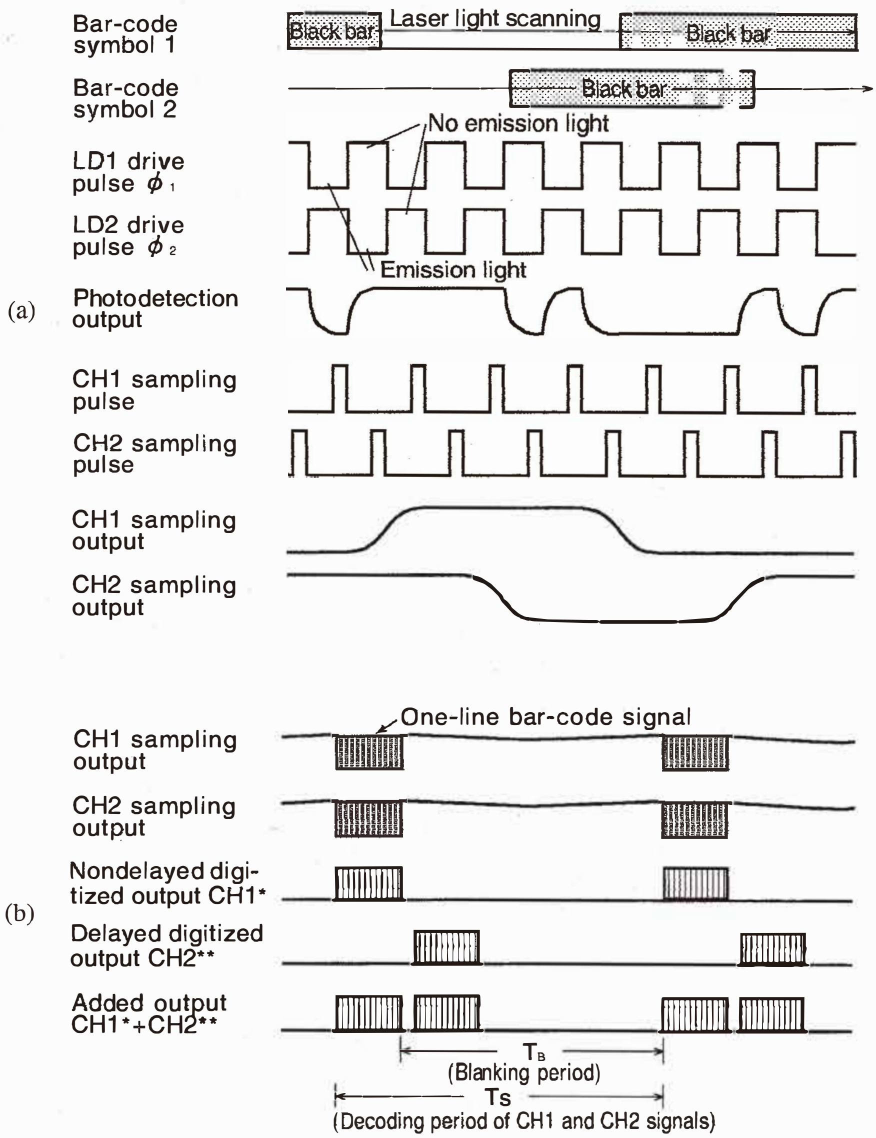

Fig. 3. Principle operation waveforms of the new 2D BCDS. (a) Light emission, photodetection and sampling operation. (b) Decoding operation.

apparatus (consisting of a lens, a photodiode and a three-stage amplifier). After conversion from light to current in the photodiode, the photocurrent is changed to a voltage signal via a current-voltage converter by means of an operational amplifier. The voltage signal is amplified as a detected output by the three-stage amplifier. Reflected light from bar-code 1 is detected during the time period when LD1 emits light. Subsequently, reflected light from bar-code 2 is detected during the time period when LD2 emits light. For example, when bar-code 1 (2) is black (white), the intensity of the reflected light from bar-code 1 (2) is weak (strong). Therefore, the output detected for such a bar-code symbol configuration represents low and high levels that correspond to the intensities of the respective reflected light. The detected output is sampled alternately using sampling pulses ϕ_{s1} and ϕ_{s2} synchronized with LD drive pulses ϕ_1 and ϕ_2. The time period for the sampling pulses (which normally have a duty ratio of 20%) is in the latter part of the laser light emission period. Two sampled outputs (i.e., signals shaped by passing through a shaping circuit), CH1 and CH2, are digitized in the A/D circuit. One of two digitized outputs is delayed in the delaying circuit. One delayed output and another nondelayed digitized output are added together in the summing gate. The added outputs are decoded successively in the decoder within a scanning period (Ts) containing its blanking period. The processor decodes the added digitized output by comparing it with the reference patterns of the bar-code symbols. Since the blanking period is usually more than six times as long as a one-line bar-code signal period, decoding is possible within one scanning period.

As mentioned above, 2D bar codes are scanned with laser light by applying emitted light alternately to each line of the bar code using the CLE method. With this method, the scanning is completed at nearly the same time, i.e., within a scanning period of one face of a polygonal mirror. Hence, effective high-speed scanning is possible.

When visible-light LDs (index-guided-type) are used in the system, a problem occurs whereby light emission increases slowly. As shown in Fig. 4, the conventional modulation drive of LDs without a bias current achieves a rise time of no less than 1.3 μs, due to its slowly rising light emission phenomenon. We measured the switching speed (rise and fall times of LD cathode terminal voltage V_L) of an LD driver, replacing the LD with a 45-Ω resistor (corresponding to the internal resistance of the LD; see Fig. 4). Since the fall time of V_L was nearly 200 ns, we believe that the LD's driver performance and packaging has absolutely no influence on its light output characteristics. Therefore, this phenomenon of slowly rising light emission is not caused by the laser drive circuit or packaging. In the new detection system, LDs are driven by the bias current near the threshold of the current-light output characteristics (PMBC method). This PMBC method enables high-speed light emission, unlike the conventional modulation drive method of LDs. Hence, it enables high-frequency driving of LDs, that is, high-speed scanning.

3. Experimental Results

We used a prototype system to investigate the basic operation of the new 2D BCDS. Since each bar code is wide (25 mm), positioning two LD beams on the bar codes is very easy. Lights emitted from two LDs are set in parallel by adjusting the LD holder manually, such that the spacing of the emitted light is equal in front of the collimator lens of LDs and bar codes. Also, focus alignment on the bar codes is done by adjusting the collimator lens position to a detection length of 15 cm. Table 1 lists the physical specifications of the prototype.

3.1 *Selection of LDs*

There are two types of visible-light lasers: the index-guided type and the gain-guided type. Comparison of bar-code detection characteristics when using these two types of LDs has not been extensively reported. Here, we investigate the difference in the detection characteristics. Figure 5 shows LD light output power P_0 versus detection length L in two types of LDs. "Detection length" means the distance between the scanner facet and the bar code. When the gain-guided LD is used, L decreases at a low light output power. In

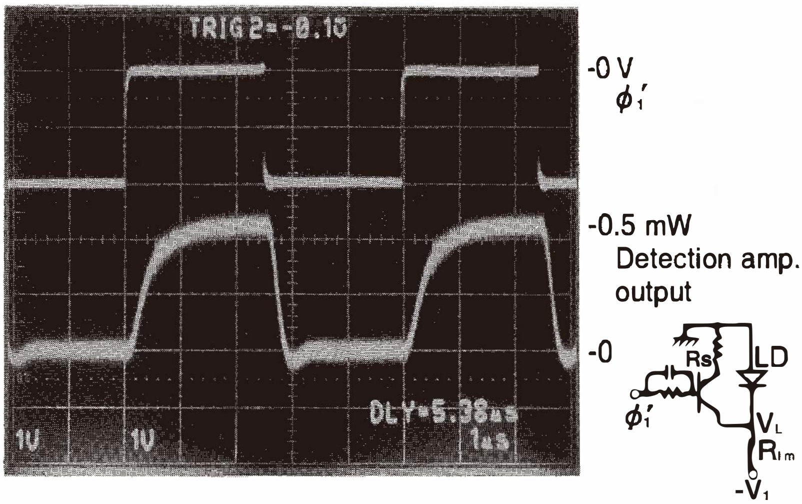

Fig. 4. Light output pulse in conventional modulation drive of LD without bias current.

Table 1
Physical specifications of the prototype system.

LDs	Index-guided type, 680 nm
Lens	20 mmϕ
Space between lights emitted from two LDs	16 mm
Bar codes	Two-line Code 39 symbols arranged in parallel
Photodetection apparatus	Si PIN photodiode (S1722-02) and 3-stage amplifier with a bandwidth of 1.7 MHz and a gain of 51 dB

contrast, the detection length shows minimal decrease in P_0 from 0.4 mW to 1.0 mW in the index-guided LD. Meanwhile, the astigmatism in this LD is less than half of that in the gain-guided type, as shown in Fig. 6. For simplicity, a collimator lens was used in the prototype system without compensating for the astigmatism. Hence, it is thought that the flat characteristics of the detection length versus P_0 in the index-guided LD are a result of its small astigmatism. Thus, we used the index-guided LD with a small astigmatism in subsequent experiments.

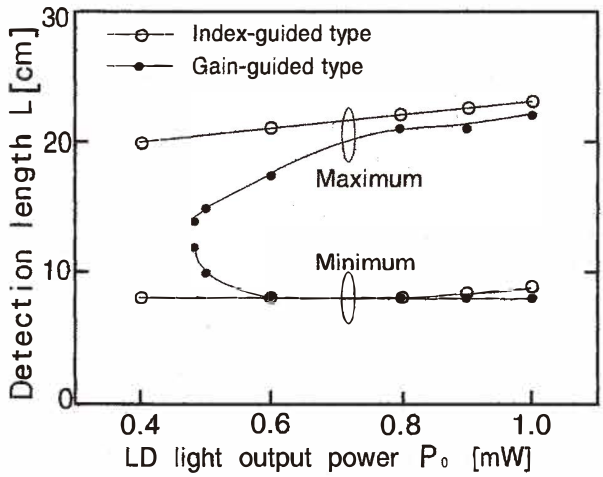

Fig. 5. LD light output power vs detection length.

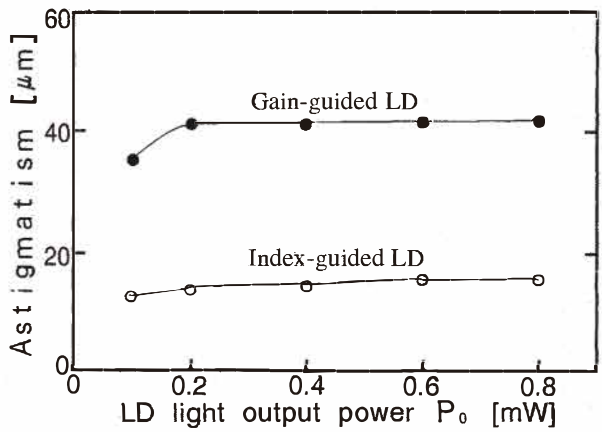

Fig. 6. LD light output power vs astigmatism.

3.2 *Modulation drive of LDs*

In the new system, LDs emit high-frequency light output pulses. The conventional LD modulation drive, with an amplitude from nearly 0 to the current level above the threshold, exhibited slowly rising light emission (a light output rise time of about 1.3 μs). However, a pulse modulation drive with an LD bias current near the threshold (PMBC drive) of visible-light LDs can considerably improve the light output rise time *tr* (Figs. 7(a) and 7(b)). As shown in Fig. 8, high-speed light emission of a rise time *tr* of 300 ns is achieved using this PMBC drive. With this drive method, a high-frequency-drive LD is expected.

3.3 *Bar-code detection ability*

Figure 9 shows two sample outputs achieved when two-line Code 39 bar-code symbols are detected. This shows that two-line detection within a scanning period is possible. One of two sample outputs was digitized and delayed. This delayed output was added to the other nondelayed one. The added output was then successively decoded.

A bar-code detection system's ability to reveal bar codes is important. Figures 10(a) and 10(b) show detection length (*L*) versus LD drive frequency (*fc*) for a conventional LD drive without bias current and the PMBC drive, respectively. The range of the detection length for 1 to 1.5 MHz drive frequency is sufficient (nearly 12 cm) in both drives. For drive frequencies below 1 MHz, the range decreases with a decrease in the LD drive frequency due to the sampling effect, since the number of sampling points for the detection output signal decreases as *fc* decreases. At high drive frequencies equal to or above 1.6

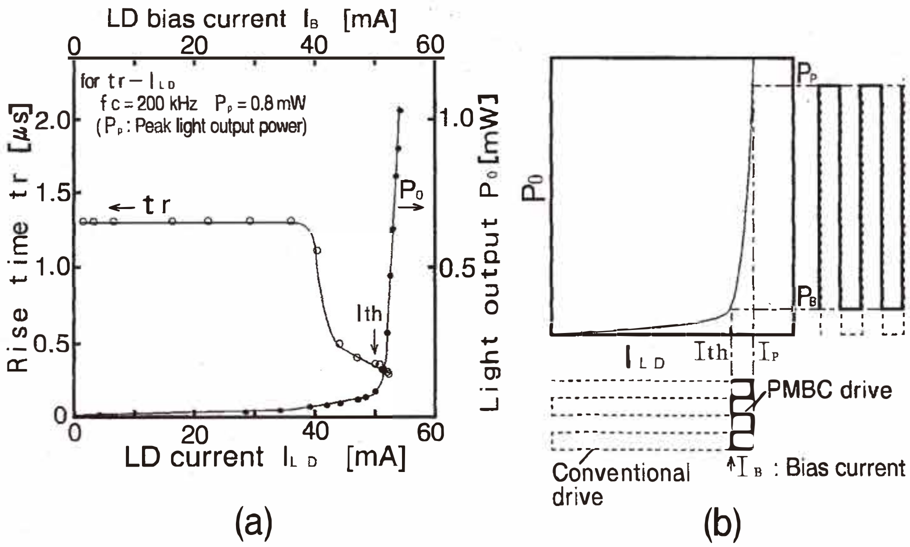

Fig. 7 (a) Light output rise time vs LD bias current and LD current vs light output characteristics. (b) Light output pulse in relation to the magnitude of LD bias current.

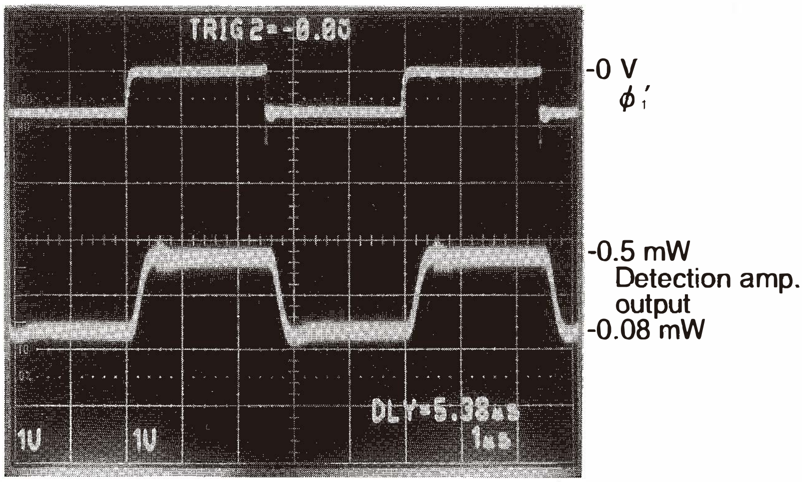

Fig. 8. Light output pulse in LD drive with bias current near the threshold (PMBC).

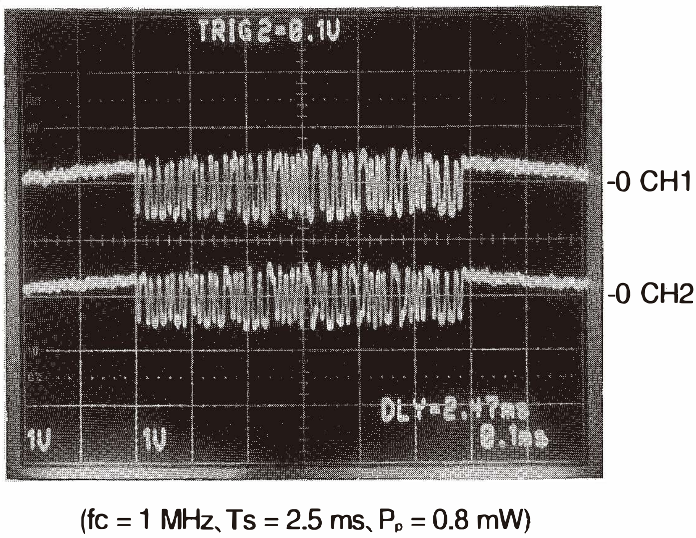

Fig. 9. Two sample outputs.

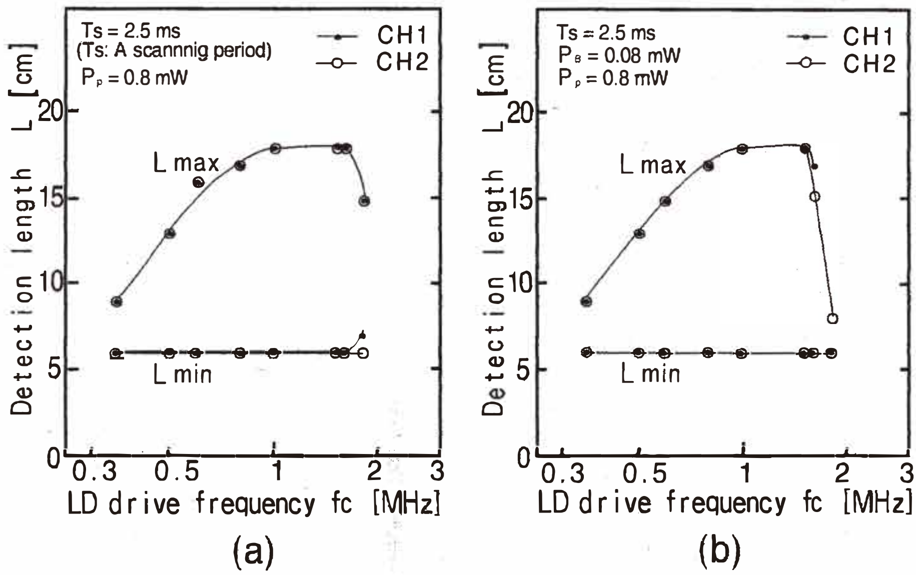

Fig. 10. Detection length vs LD drive frequency. (a) Conventional LD drive without bias current. (b) LD drive with bias current near the threshold (PMBC).

MHz, the range decreases. The following three factors are thought to play a part in this detection range limitation factor:

(1) Slowly rising light emission phenomenon of LDs,
(2) Narrow bandwidth of the photodetection amplifier, and
(3) Constant small crosstalk between detection signals corresponding to two-line bar codes by LD bias current.

Factor (1) causes detection output to decrease. Factor (2) also causes detection output to decrease and the crosstalk to increase due to the fall time limit of the detection of the output signals.

3.4 *Detection range limitation factor*

We investigated the detection range limitation factor for high drive frequencies. First, we investigated the bar-code detection ability of a single-line scanning operation that did not include an interference problem between two-line detection signals. This detection length versus the LD drive frequency in the single-line scanning operation is shown in Fig. 11. In the PMBC drive, the range does not decrease as long as *fc* is 2 MHz, while the frequency at which the range decreases in the conventional drive is the same as that in the two-line scanning operation. The upper limit of *fc* (2 MHz) in the PMBC drive is determined by factor (2). In the PMBC drive, the detectable LD drive frequency in the two-

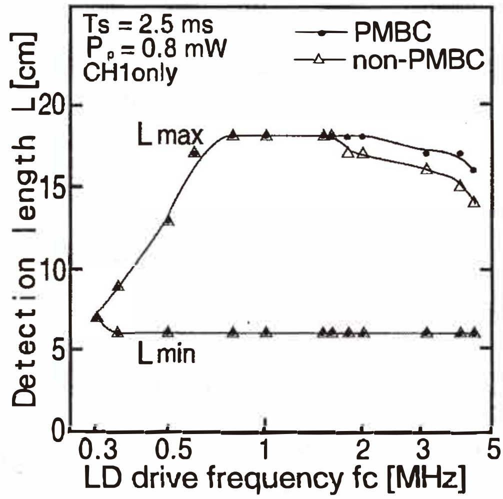

Fig. 11. Detection length vs LD drive frequency in a single-line scanning operation.

line scanning operation (1.6 MHz) is smaller than that in the single-line scanning operation (2 MHz). The difference between the two scanning operations in the PMBC drive lies in the detection of either a single bar code or two bar codes. We believe that the interference problem between the two line signals causes this decrease in the two-line scanning operation. Therefore, it seems that in the PMBC drive, the upper limit of the detectable frequency is reduced due to the interference between the two detection output signals. On the other hand, the upper limit of *fc* in the conventional non-PMBC drive is determined by factor (1).

Second, we checked the influence of adjacent bar-code line patterns, taking into consideration interference between two-line detection signals. Figures 12(a) and 12(b) show the detection output voltage of channel 2 (CH2) in relation to channel 1 (CH1) bar-code patterns versus LD drive frequency for the conventional LD drive without bias current and the PMBC drive, respectively. Here, V_{2w} shows the detection output corresponding to a black-white symbol change. ΔV_2 shows the detection output change of CH2 for the black symbol in relation to the black-white symbol change of CH1. In the conventional LD drive without bias current, V_{2w} from 400 kHz decreases with an increase in drive frequency due to factor (1) (see also Fig. 13), since light outputs of LDs have a long rise time (1.3 μs). Also, ΔV_2 increases from a drive frequency of 1.5 MHz due to factor (2), that is, the fall time limit of the detection output (see also Fig. 13). At this time, a signal slightly distorted by the white symbol of the CH1 bar code, that is, a crosstalk signal from another channel, is seen in the detection output of CH2. Consequently, without an LD bias current, the detection output decreases due to the slowly rising light emission phenomenon of LDs and the crosstalk between two channels increases from an *fc* of 1.5 MHz due to the bandwidth

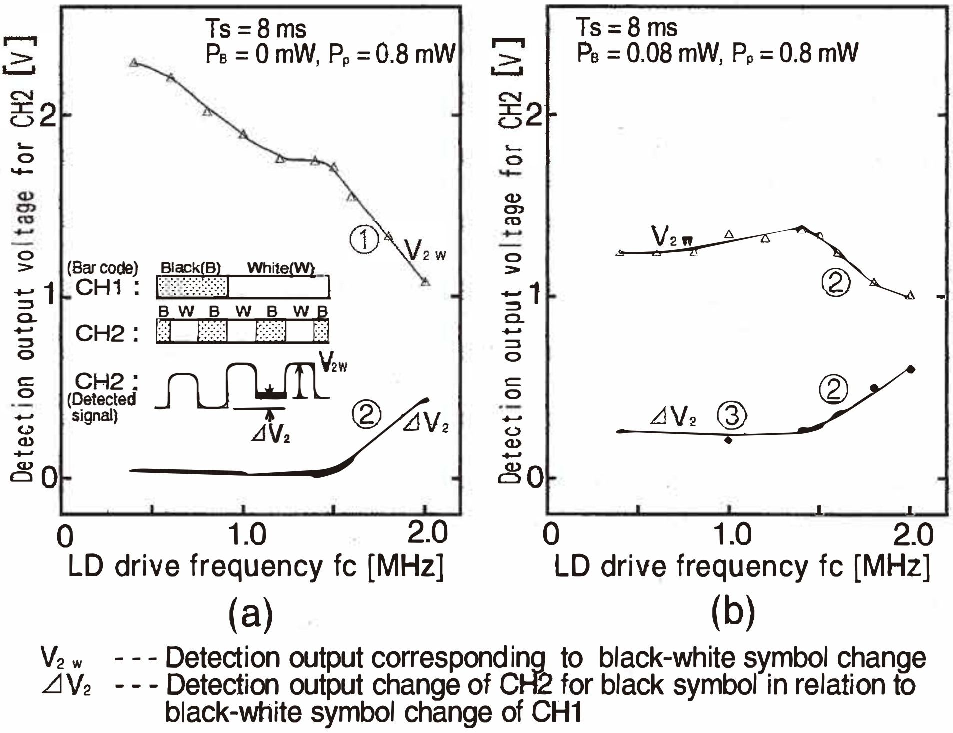

Fig. 12. Detection output of channel 2 in relation to channel 1 bar-code patterns. (a) Conventional LD drive without bias current. (b) LD drive with bias current near the threshold (PMBC).

limit of the photodetection amplifier. These two factors lower the detection ability at high drive frequencies, especially above a drive frequency of 1.5 MHz.

However, in the PMBC drive, V_{2w} decreases from a drive frequency of 1.5 MHz due to factor (2), that is, the rise time limit of the detection output (see also Fig. 13). ΔV_2 has a constant offset due to factor (3) and increases from a drive frequency of 1.5 MHz due to factor (2), that is, the fall time limit of the detection output (see also Fig. 13). Then, the above-mentioned crosstalk signal from another channel is seen in the detection output of CH2. As a result, with an LD bias current, the detection output decreases from an *fc* of 1.5 MHz due to the bandwidth of the photodetection amplifier. The crosstalk between two channels added to the constant small crosstalk due to the bias current increases from an *fc* of 1.5 MHz due to the bandwidth limit of the photodetection amplifier at high drive frequencies. These two factors lower the detection ability at high drive frequencies greater than 1.5 MHz.

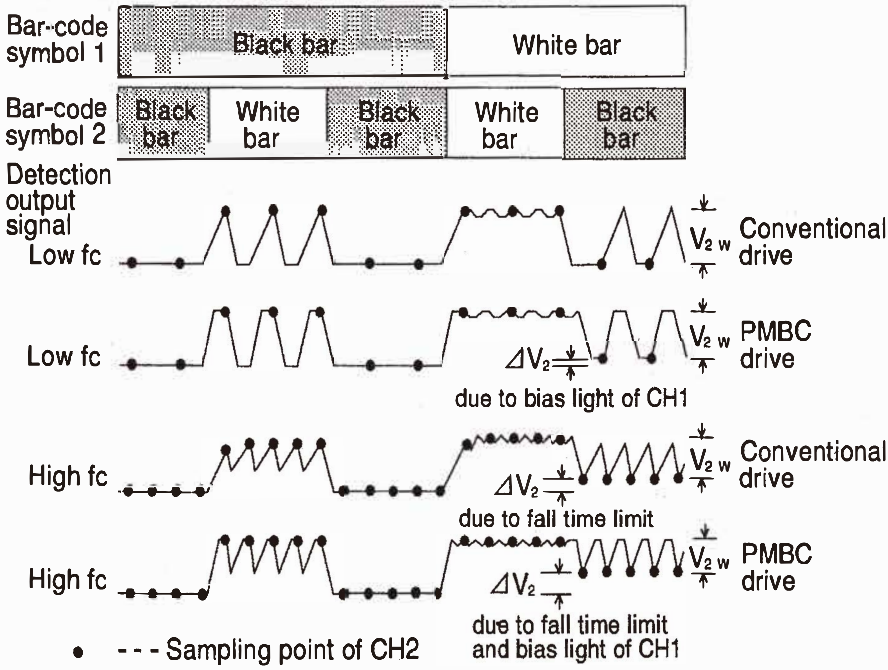

Fig. 13. Detection output dependence on LD drive frequency.

3.5 *Scanning speed*

Scanning speed in the new BCDS depends on drive frequency. Figure 14 shows LD drive frequency versus maximum effective scanning speed. The highest drive frequency is 1.5 MHz, since it is limited by detection amplifier characteristics in the prototype system. The maximum effective scanning speed *V*smax was 950 scan/s. This was due to the detection amplifier characteristics limitation. Therefore, it is possible that faster scanning can be achieved by improving the detection amplifier's bandwidth. The scanning speed was twice that of conventional 2D raster scanners.

However, *V*smax in the new 2D BCDS without bias current is limited to 910 scan/s, due to the slowly rising light emission of LDs. In this case, it is not possible to achieve a faster scanning speed.

4. Discussion

Let us consider the limits of the effective scanning speed of the 2D BCDS. The conventional 2D BCDS uses a single laser (laser diode or He-Ne laser) driven in a

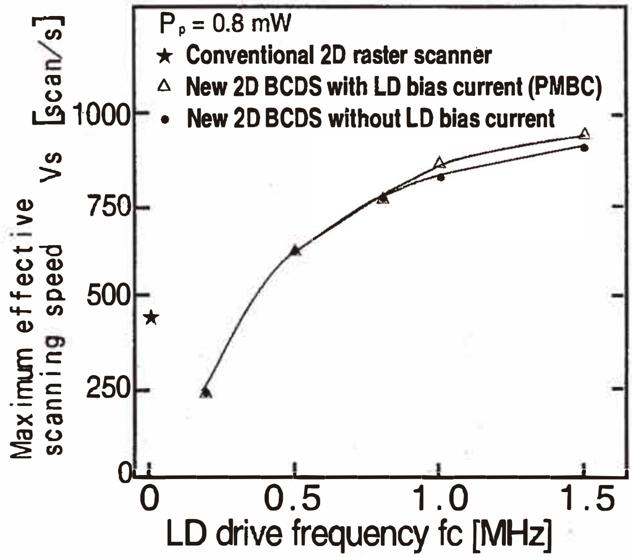

Fig. 14. LD drive frequency vs maximum effective scanning speed.

continuous light-emission mode. In this system, scanning speed is determined by the speed of the raster scanner's rotation and of the decoder, since one-line bar-code data decoding is performed during each scanning period. A raster scanner that has a tilted axis is currently available. In general, however, the rotation speed of the ordinary raster scanner is limited to approximately 500 scan/s due to its low stability during high-speed rotation. Also, it has been confirmed that the decoder can scan at a high speed of over 1000 scan/s when a nonraster scanner, without a tilted axis, is used to permit stable rotation. Therefore, the limit of the scanning speed in the conventional 2D BCDS is determined by the rotation speed of the raster scanner, which is nearly 500 scan/s.

However, in the new 2D BCDS with LDs driven by the CLE method, two laser diodes are used in a pulse light emission mode. In this system, the effective scanning speed is determined by the speed of the scanner's rotation and that of the decoder, the LD drive method and frequency, and the bandwidth of the detection amplifier. As mentioned above, the detectable drive frequency has been limited to approximately 1.5 MHz by the characteristics of the detection amplifier using the PMBC drive. In the following discussion, we assume that the detection amplifier has a bandwidth wide enough to clarify the limits of the effective scanning speed.

Using the PMBC drive, we can expect a maximum detectable drive frequency above 2 MHz since the crosstalk between two channels will be reduced if the detection amplifier has sufficient bandwidth. Since the CLE method decodes two-line bar codes within a single-line-scanning period, the effective scanning speed is double the conventional speed.

With the PMBC drive using the CLE method for LDs, a maximum detectable effective scanning speed of above approximately 1700 scan/s can be expected. This is determined from the LD drive frequency of above 2 MHz, when we deduce from the data (in Fig. 14) that a scanning speed at the LD drive frequency of 1 MHz (not influenced by low detection-amplifier bandwidth) is 870 scan/s. In the new 2D BCDS, the nonraster scanner without a tilted axis, which permits high-speed rotation, can be used instead of a raster scanner with a tilted axis. Since the conventional nonraster scanner without a tilted axis can be operated at a scanning speed of 1300 scan/s, the maximum effective scanning speed will be a value that is limited by either the decoding speed (> 1000 scan/s) or the scanner's rotation speed (1300 scan/s).

5. Conclusions

After developing a new high-speed 2D BCDS with two visible-light LDs driven by the CLE and PMBC drive schemes, the following were concluded:

1) Since an index-guided LD shows desirable detection characteristics that do not depend on light output power due to its small astigmatism, this type of LD is suitable for the BCDS.
2) A pulse modulation drive with bias current near the threshold of visible-light LDs achieves a light output rise time of 300 ns, which is much shorter than the 1.3 μs achieved by a drive without bias current.
3) An effective scanning speed of 950 scan/s was achieved using the prototype system.
4) The effective scanning speed of the BCDS with the PMBC drive is twice that of conventional 2D raster scanners.
5) Since this scanning speed is presently limited by the bandwidth of the photodetection amplifier, it may be possible to increase the scanning speed by improving the amplifier's bandwidth in the BCDS with the PMBC drive.

Acknowledgements

The authors would like to thank Mr. O. Hayashiguchi for helpful discussions and comments provided throughout the course of this research.

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