DEVELOPMENT OF A NEW SENSING TECHNOLOGY FOR PLASTIC IDENTIFICATION BY USING THREE INFRARED LASER DIODES

Koji Inada
Senior Researcher
Research and Development Dept.
IDEC IZUMI Corporation
1-7-31, Nishi-miyahara, Yodogawa-ku,
Osaka 532-8550, Japan

Lanny Schuberg
Director of Product Marketing
IDEC Corporation
1175 Elko Drive
Sunnyvale, CA 94089-2211

Takeshi Takao
Manager
Research and Development Dept.
IDEC IZUMI Corporation
1-7-31, Nishi-miyahara, Yodogawa-ku,
Osaka 532-8550, Japan,

Toshihiro Fujita, Ph. D.
Vice President
R&D and Strategic Marketing
IDEC IZUMI Corporation
1-7-31, Nishi-miyahara, Yodogawa-ku,
Osaka 532-8550, Japan

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ABSTRACT

In current recycling systems, plastic identification is carried out using a spectrometer that recognizes a near-infrared spectrum of each plastic. A spectrometer is superior in accuracy but disadvantageous in terms of cost-efficiency, maintenance, etc. To solve these problems, we have studied different optical absorption peaks of plastics at wavelengths around 1700 nm and have studied alternative plastic identification technologies using InGaAsP laser diodes. We have proven the feasibility of this plastic identification technology for transparent PET, PVC, and PS using a prototype of the equipment featuring InGaAsP laser diodes using three different wavelengths. This paper describes our experimental study and verifies the effectiveness of the new plastic identification technology using InGaAsP laser diodes.

INTRODUCTION

Our society based on mass production, mass consumption, and subsequent mass waste-disposal has achieved unprecedented economic growth of the 20th century. However, this economic growth has also caused serious environmental problems on a global scale. In the past, a production system focused on improving productivity at the expense of environment, but in the future a production system must undergo a major shift in direction to also include an effective recycling process [1-4].

With only finite resources available on planet earth, the circulation of parts in arterial (manufacturing) and venous (recycling) industries as shown in FIG. 1, becomes an essential requirement to achieve a sustainable economic society. Arterial industries include production, distribution, and consumption of goods, while venous industries include recollection, disassembling, sorting, and recycling of goods for new production. In the arterial industry, parts are assembled to produce goods, while in the venous industry, goods are disassembled for recycling and salvaged to make new products.

Sensing technology is vital to both arterial and venous industries. In the arterial industry, a large variety of sensing devices have been developed and employed for assembly using robots. These range from detecting the presence of parts to measuring dimensions, colors, electric characteristics, and other physical values. For the recycling processes used in the venous industry, despite the great need to identify part materials after disassembling, few sensors have been developed. The following section describes the recycling process of plastics, which is an essential material in the modern living.

PET (polyethylene terephthalate) bottles, containers, packaging and other plastic goods are collected in various recycling methods around the world. For instance, PET bottles are recycled using the material recycling method in which the plastic is reused as plastic material. Recycling methods for other plastics include the chemical recycling method, in which plastics are chemically treated to produce oil, gas, and raw materials for blast furnaces or coke ovens. Finally, thermal recycling employs a method in which plastics are burnt to generate heat and energy.

For any of the above methods, plastic sorting is an important factor for ensuring recycling efficiency. For material recycling methods, accurate plastic sorting is essential to obtain the maximum quality of the recycled product. For chemical and thermal recycling methods, plastic sorting is also an indispensable step. PVC (polyvinyl chloride), for instance, discharges toxic hydrogen chloride when thermally decomposed, and thus must be sorted out beforehand. In addition plastics that might cause corrosion of the recycling equipment must also be sorted out.

PVC and PET plastics are in many cases separated visually by operators, by viewing the markings on plastic and their molding characteristics, as shown in FIG. 2(A). However, perfect accuracy cannot be expected with visual sorting, and plastics other than PVC and PET cannot be visually identified. Therefore an automatic plastic identification system must be employed.

The present automatic plastic identification systems generally employ near-infrared spectroscopic analysis methods [5-9], as shown in FIG. 2(B). Near-infrared spectroscopic analysis uses a spectrometer to measure the near-infrared absorption spectrum. Although this method is widely employed and highly accurate, it does also require large expensive equipment, extensive maintenance, and complicated instructions. A small-sized, low cost, corrosive resistant, and easy-to-use recycling system, such as ones found in factory automation production lines, is thus needed to achieve reliable and easy plastic recycling.

Utilizing plastic’s optical absorption properties in the near-infrared region, the world’s first plastic identification technology using semiconductor laser diodes has been developed as shown in Fig.2(C). The basic theory of this technology has already been reported in previous technical papers [10-12]. The basic technology, which uses three semiconductor laser diodes with different wavelengths, has been developed to build a prototype of a plastic identification system. The evaluation and details of this development are described below.

PLASTIC IDENTIFICATION TECHNIQUE USING THREE INFRARED LASER DIODES

HDPE (high-density polyethylene), LDPE (low-density polyethylene), PP (polypropylene), PVC (polyvinyl chloride), PS (polystyrene), and PET (polyethylene terephthalate) are the top produced plastics in the world. FIG. 3 shows the optical absorption spectra of seven plastics, measured using a spectrometer. To obtain the largest possible amount of light, the samples are in the color that passes the maximum light. HDPE, LDPE, and PP are white and 2 mm thick, while PET, PVC, and PS are transparent, colorless, and 2 mm thick. As FIG. 3 shows, the optical absorption (i.e. low optical transmittance) peaks around at 1700 nm wavelength with any plastic. Optical transmittance in plastics is then measured using a spectrometer within the range of 1640 to 1740 nm. As FIG. 4 clearly shows, the wavelength dependence of optical transmittance, which is attributable to the stretching and vibration of CH bond, varies with the type of plastic [13]. This result suggests that comparing optical transmittance can identify various different plastic types.

FIG. 5 shows the emission spectra of three different InGaAsP laser diodes, which are being used in this new plastic identification technology. The emission spectra are measured using an optical spectrum analyzer, at 25°C ambient temperature. As the figure shows, emissions of LD1 (laser diode 1), LD2 (laser diode 2), and LD3 (laser diode 3) are in a longitudinal multimode and very converged, with only a 10 nm full width at half maximum. These three laser diodes were used to build the prototype of the plastic identification system, and the prototype is evaluated by its performance in identifying PET, PVC, and PS plastic samples.

EXPERIMENT

FIG. 6 shows the structure of the experimental prototype plastic identification system. As the figure shows, the light from the three laser diodes is gathered on one optical axis by half mirrors, and projected on the sample plastic. The directly reflected light from the sample plastic is received by a photo diode. The light that passes through the sample plastic is reflected from a mirror behind the sample plastic, and is also received by the same photo diode. The mirror is used in this system to obtain sufficient light, even from PET, PVC, and PS plastics, which are transparent and thus reflect only a small amount of light.

As FIG. 7 shows, three laser diodes radiate in a sequence. This sequential radiation requires only one circuit for processing photo electrics, thus a small-sized system can be developed. This system has been developed utilizing the algorithm of full-color sensor technology [14] in which the color of an object is identified by pulse-illuminating the object with red, green, and blue LEDs, and determining the intensity ratio of the reflected light. In the experiment of identifying plastics, the light signals in the photodiode were measured with an oscilloscope, and the difference of the signal levels was compared. As FIG. 8 shows, the electric current of the laser diodes was regulated to provide the same radiation energy. The result of the light signal measurement was then compared with the result of an optical transmittance measurement on a spectrometer, and the effectiveness of the plastic identification system was evaluated.

RESULTS

FIG. 9 shows the measurement results with two different plastic identification systems, one using laser diodes to measure light signals, and the other using a spectrometer to measure optical transmittance. FIG. 9(a-1) shows the result of measuring PET using the prototype laser diode system. The graph shows the waveform of light signals to the wavelengths of LD1, LD2, and LD3, and the peak voltage values as $V1_{PET}$, $V2_{PET}$, and $V3_{PET}$. FIG. 9(a-2) shows the result of measuring the optical transmittance of PET using a spectrometer. Transmittance $T1_{PET}$, $T2_{PET}$, and $T3_{PET}$ are the values of the wavelengths that are the same as the laser diode emissions of the prototype laser diode system. Similar graphs are also provided for PVC and PS.

Comparing the voltage peaks measured with the laser diode system and the optical transmittance measured with a spectrometer, the following relationships are obtained with the sample PET.

$$V1_{PET} < V2_{PET} \cong V3_{PET} \tag{1}$$
$$T1_{PET} < T2_{PET} \cong T3_{PET} \tag{2}$$

The two relationships show the same pattern.

$$V1_{PVC} \gg V2_{PVC} < V3_{PVC} \tag{3}$$
$$T1_{PVC} \gg T2_{PVC} < T3_{PVC} \tag{4}$$
$$V1_{PS} > V2_{PS} < V3_{PS} \tag{5}$$
$$T1_{PS} > T2_{PS} < T3_{PS} \tag{6}$$

PVC and PS samples also show the same relationships between using the laser diode system and spectrometer.

The above results are summarized in FIG. 10. As the figure shows, the data obtained by the new plastic identification system shows the same pattern as the data obtained with the spectrometer, and the relationship varies depending on the type of plastic.

FIG. 11 shows the optical transmittance of PP, HDPE, and LDPE measured with a spectrometer, summarized in the same mode as FIG. 10. As the figure shows, the relationships of (e) HDPE and (f) LDPE are identical because these two plastics are composed of the same material. The difference of HDPE and LDPE is the pressure applied to the plastics when produced. Both HDPE and LDPE are therefore treated as PE, and these two plastics are referred to PE in the rest of this paper.

FIGs 10 and 11 reveal that the five different plastics, PET, PVC, PS, PP, and PE have different relationships of optical transmittance in the wavelengths of three laser diodes used in this prototype identification system. Although PP and PE have not been tested in the laser diode plastic identification system, the different relationships of optical transmittance show that these two plastics can also be identified by the new identification system.

CONCLUSION

The above experiment has proven that different plastics can be identified using three laser diodes of different wavelengths. FIG. 12 shows the prototype system used in this experiment, and a baseball is placed next to the system to show its relative size. TABLE 1 gives a comparison of a conventional infrared spectroscopic analysis system and the plastic identification system using laser diodes. As the table shows, the new prototype system is far superior to the conventional system in many respects. These include smaller size (1/40), faster response speed (1/20), and longer illumination life (33 times). Because this new system using laser diodes can be manufactured at a significantly lower cost, this system will be a very useful technique to achieve accurate and efficient plastic identification, and thus will contribute to efficient plastic recycling.

Utilizing the plastic's optical absorption property, a prototype of the plastic identification system has been developed for the first time in the world using three InGaAsP laser diodes with emission wavelengths in the near-infrared region. The experiment above has proven that this new system is capable of identifying plastic types. For promoting inverse manufacturing and a recycling society, the evaluation of this small plastic identification system will continue in actual applications, such as sorting lines of waste materials.

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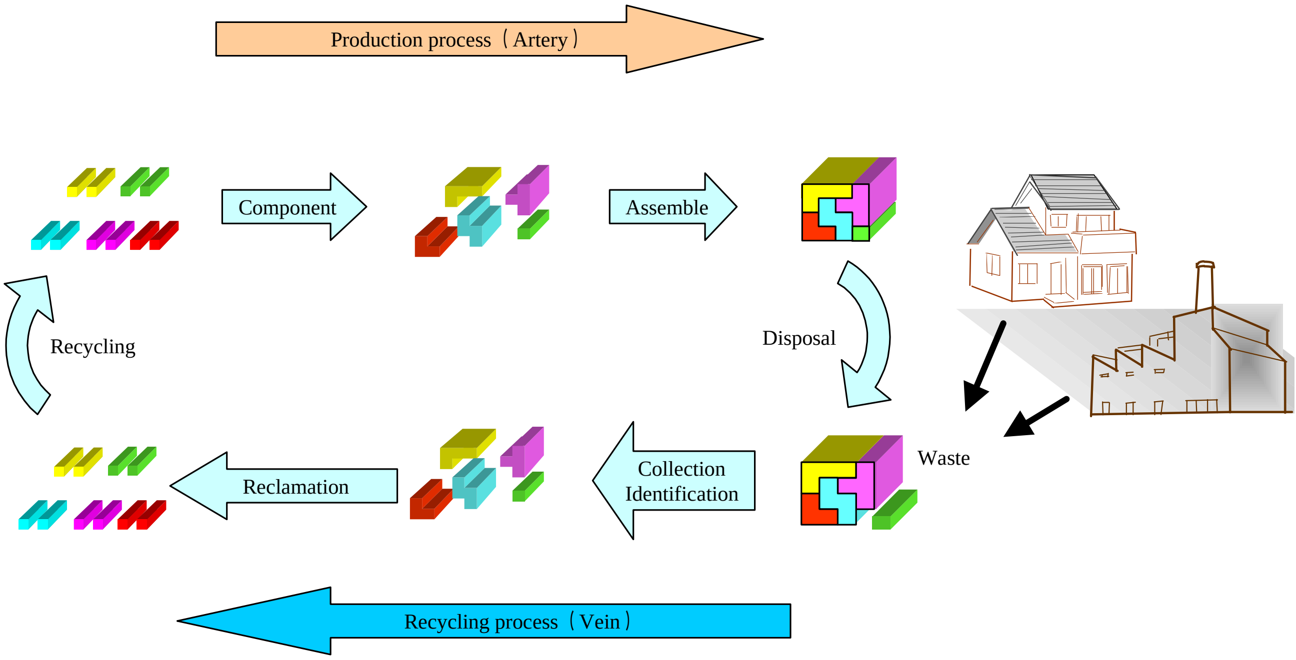
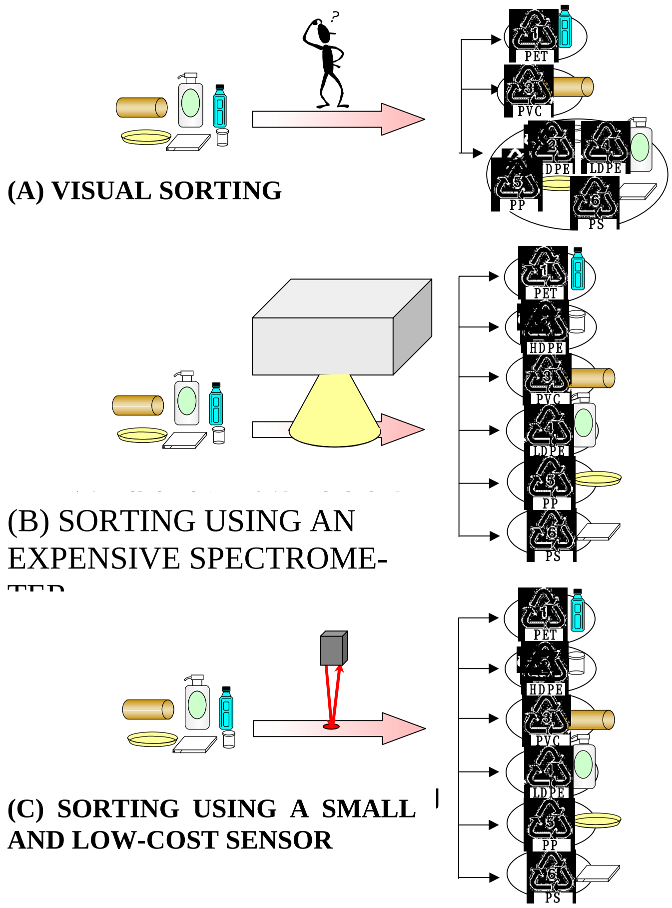


Fig. 1 - THE CIRCULATION OF PRODUCTION AND RECYCLING PROCESSES IN A RECYCLING ECONOMIC SOCIETY.

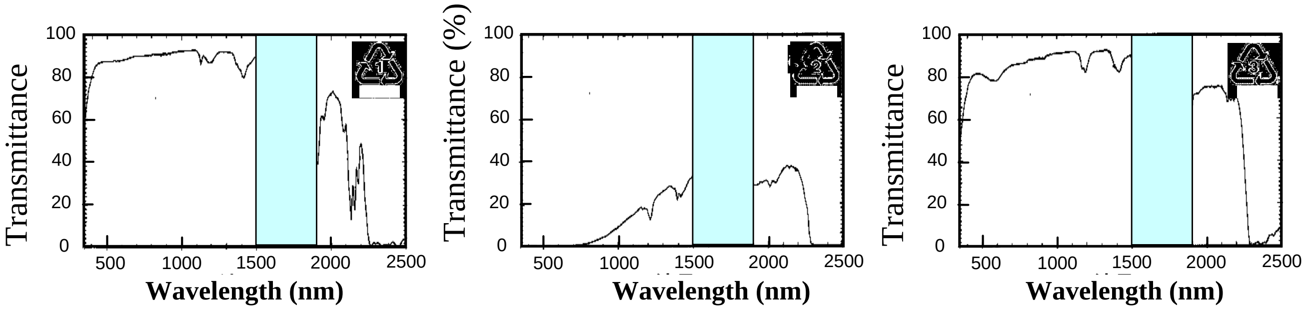


(A) VISUAL SORTING

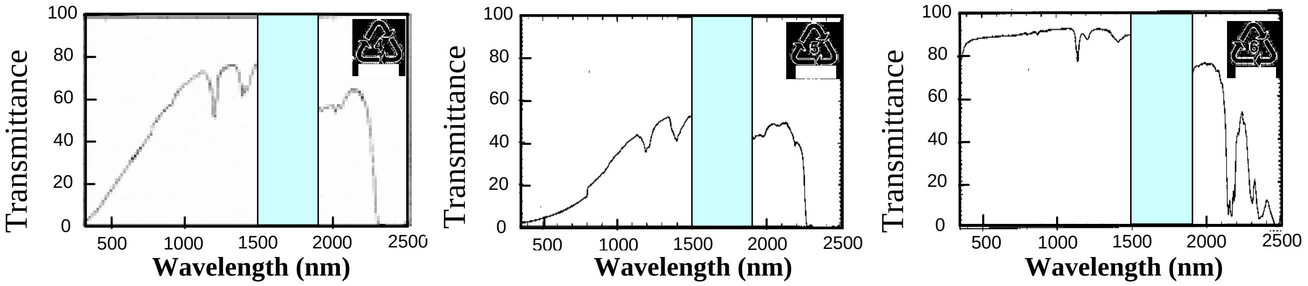
(B) SORTING USING AN EXPENSIVE SPECTROMETER

(C) SORTING USING A SMALL AND LOW-COST SENSOR

FIG. 2 – CONVENTIONAL AND FUTURE PLASTIC IDENTIFICATION SYSTEMS



(a) Polyethylene Terephthalate (PET) **(b) Low Density Polyethylene (LDPE)** **(c) Polyvinyl Chloride (PVC)**



(d) High Density Polyethylene (HDPE) **(e) Polypropylene (PP)** **(f) Polystyrene (PS)**

FIG. 3 – OPTICAL ABSORPTION SPECTRA OF PLASTICS

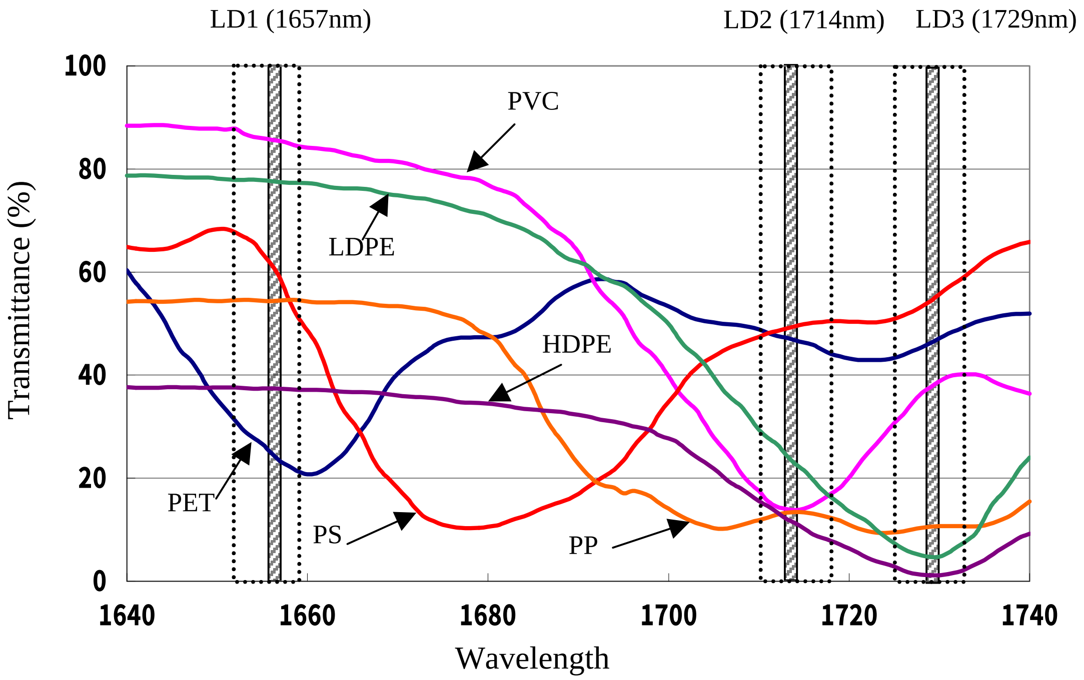


FIG. 4 – OPTICAL ABSORPTION SPECTRA OF PLASTICS IN 1640 TO 1740 nm WAVELENGTH

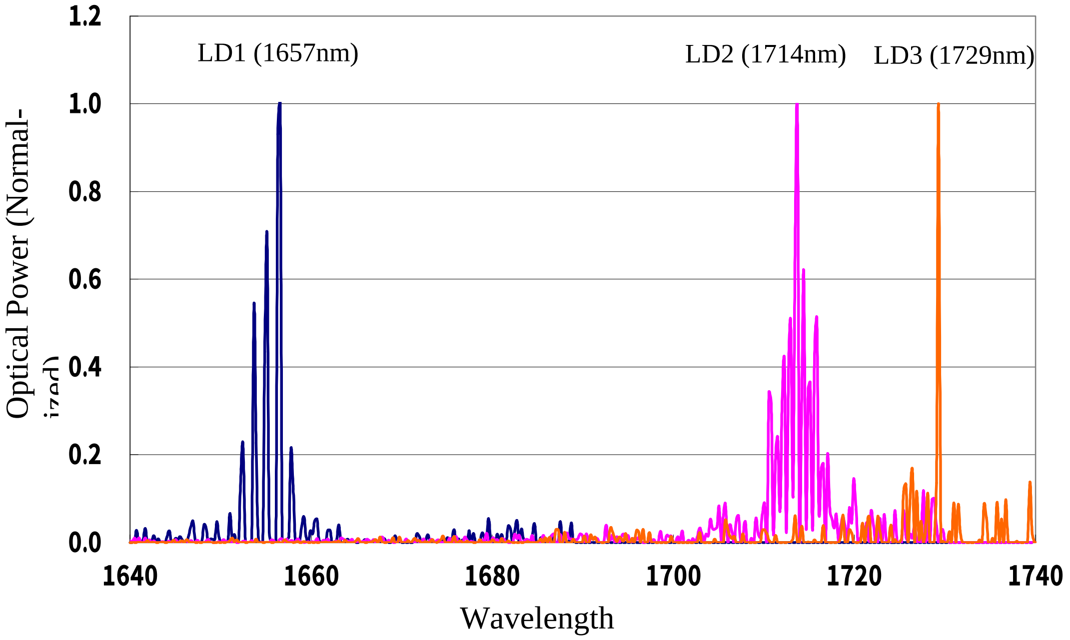


FIG. 5 – EMISSION SPECTRA OF LASER DIODES MEASURED USING AN OPTICAL SPECTRUM ANALYZER

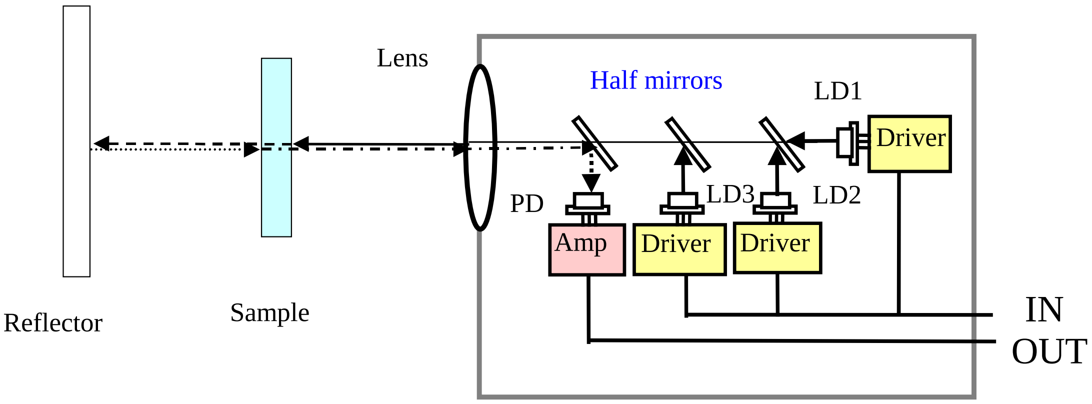


FIG. 6 – STRUCTURE OF EXPERIMENTING PROTOTYPE PLASTIC IDENTIFICATION SYSTEM

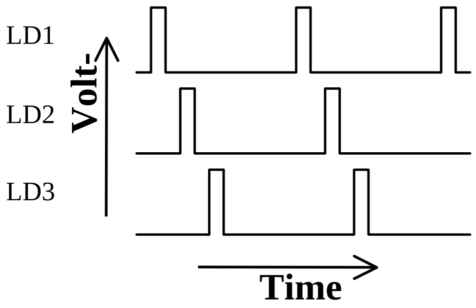


FIG. 7 – TIME-DIVIDED DRIVING PULSES OF THREE LASER DIODES

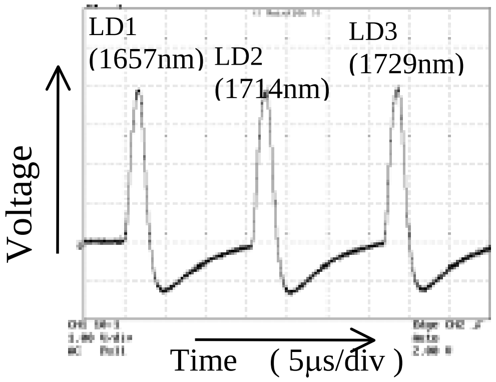
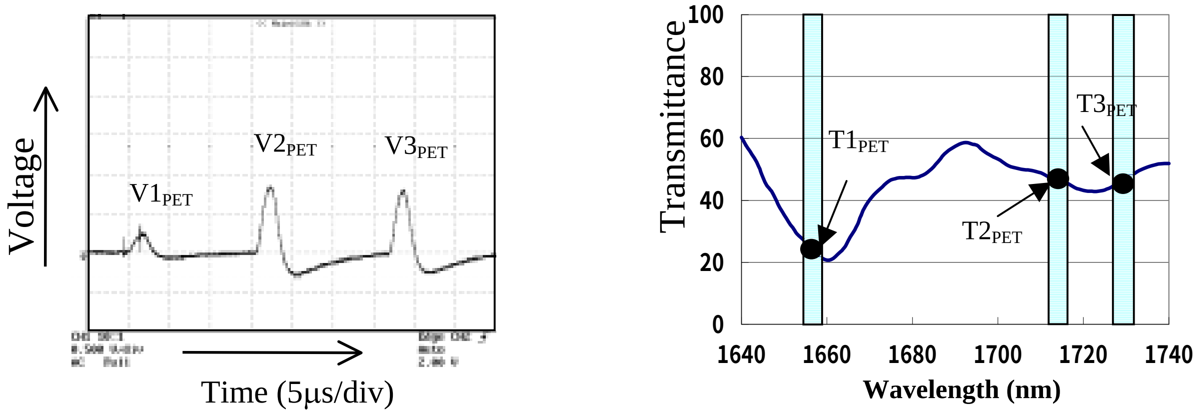
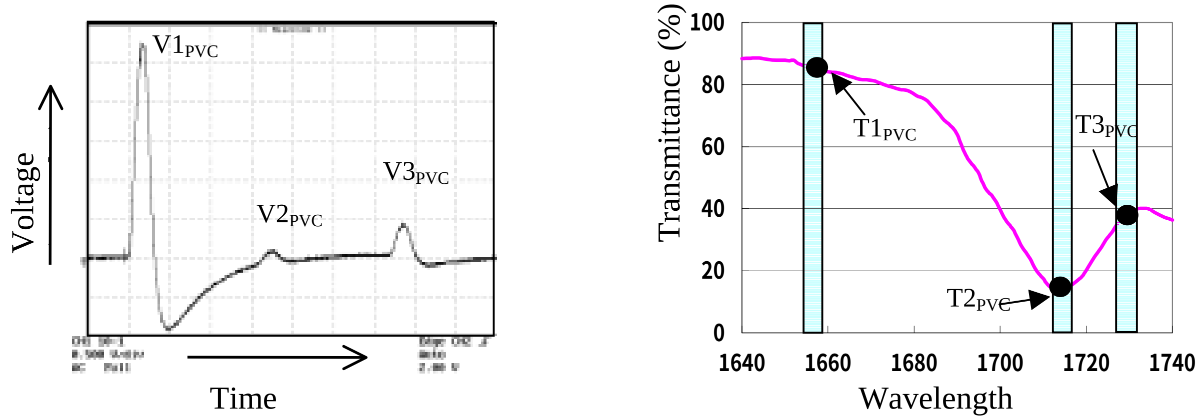


FIG. 8 – VOLTAGE LEVELS OF LASER DIODES WITHOUT SAMPLE PLASTICS, MEASURED BY AN OSCILLOSCOPE



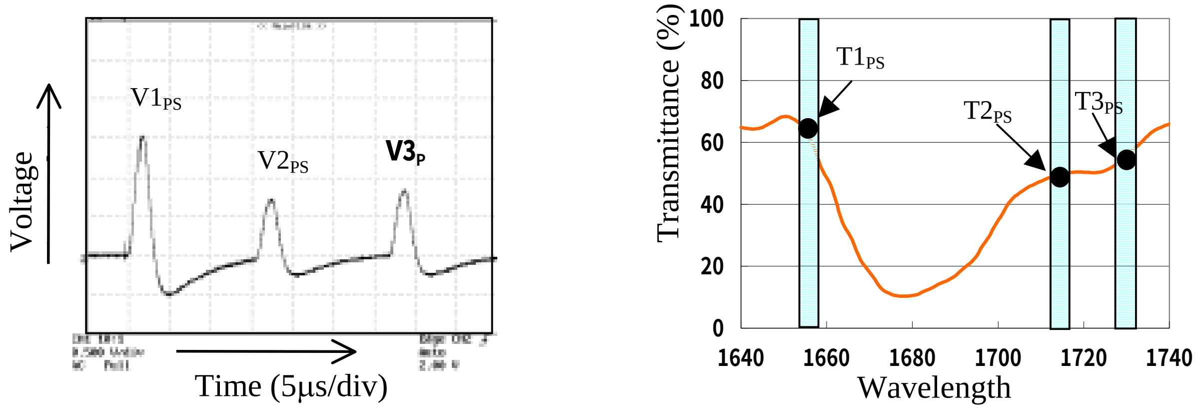
(A-1) LIGHT SIGNALS TO LASER DIODE PLASTIC IDENTIFICATION SYSTEM, MEASURED BY AN OSCILLOSCOPE (PET)

(A-2) OPTICAL TRAMSMITTANCE MEASURED BY A SPECTROMETER (PET)



(B-1) LIGHT SIGNALS TO LASER DIODE PLASTIC IDENTIFICATION SYSTEM, MEASURED BY AN OSCILLOSCOPE (PVC)

(B-2) OPTICAL TRAMSMITTANCE MEASURED BY A SPECTROMETER (PVC)



(C-1) LIGHT SIGNALS TO LASER DIODE PLASTIC IDENTIFICATION SYSTEM, MEASURED BY AN OSCILLOSCOPE (PS)

(C-2) OPTICAL TRAMSMITTANCE MEASURED BY A SPECTROMETER (PS)

FIG. 9 – (A-1), (B-1), (C-1): LIGHT SIGNALS TO A LASER DIODE PLASTIC IDENTIFICATION SYSTEM, MESURED BY AN OSCILLOSCOPE
(A-2), (B-2), (C-2): OPTICAL TRANSMITTANCE MEASURED BY A SPECTROMETER

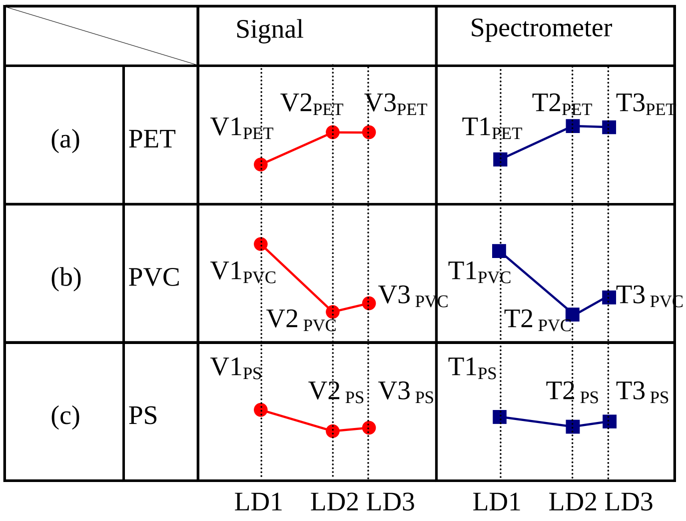


FIG. 10 – COMPARISON OF LIGHT SIGNALS AND OPTICAL TRANSMITTANCE ON PET, PVC, AND PS

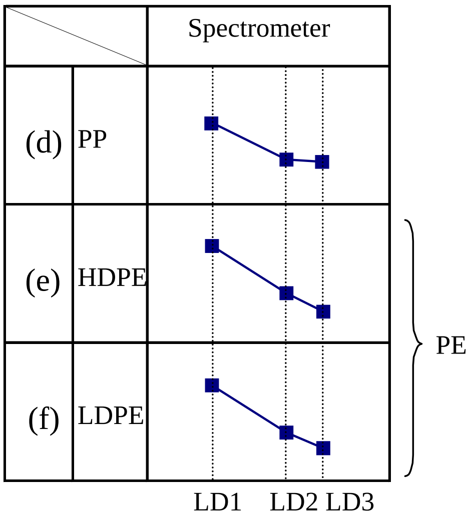


FIG. 11 – OPTICAL TRANSMITTANCE OF PP, HDPE, AND LDPE

TABLE 1 – COMPARISON OF CONVENTIONAL INFRARED SPECTROSCOPIC ANALYSIS SYSTEM AND LASER DIODE PLASTIC IDENTIFICATION SYSTEM

Method	(a) Infrared Spectrometer	(b) LD absorption	Ratio (b)/(a)
Size W x L x H (mm)	350 x 300 x 200 ~ 3500 x 2000 x 4000	50 x 100 x 100	Volume ≤ 1/40
Response speed (msec)	1	0.05	1/20
Lifetime of light source	about 3,000 hr (Incandescence lamp)	about 100,000 hr (Laser diode)	33
Dissipation power	200 W	5 W	1/30
Price ($)	50,000 ~ 300,000	5,000 ~ 10,000	1/10 ~ 1/30

FIG. 12 – PROTOTOTYPE OF SMALL PLASTIC IDENTIFICATION SYSTEM