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Frequency sensitivity analysis of series photodetector frequency circuit system using circuit parameters of quartz crystal

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ABSTRACT

The 48 MHz series photodetector frequency circuit systems matched with different quartz crystals were developed for frequency sensitivity analysis. In accordance with derived theory of series photodetector frequency circuit system, the circuit parameters of quartz crystal such as R_q and C_q can be applied to improve the frequency sensitivity. On the basis of parameter adjustment, the quartz crystal with proper R_q and C_q was selected to improve the frequency sensitivity of fluorescence detection. In the optimal conditions of R_q and C_q, the detection limit of U1392-Hex fluorescence dye concentration 3.3 pmol/L can be measured by 48 MHz sensor system. Moreover, the frequency method showed that the detection limit of U1392-Hex fluorescence dye concentration was lower than the conventional fluorescence technique by 2–3 orders. The result also indicated that the frequency shift ΔF was linearly related to the logarithm of fluorescence dye concentration in the range 3.3 pmol/L–3.3 μmol/L.

1. Introduction

On the basis of fluorescence detection theorem [1,2], the series photodetector frequency circuit system has been proposed for detection of fluorescence dye concentration. While emissive fluorescence irradiated on the photodetector, the photocurrent of photodetector was produced to influence the frequency response of series photodetector frequency circuit system. The detection system can transduce the fluorescence signal to frequency response for detection of fluorescence dye concentration. The previous study presented that frequency response can be influenced during emissive fluorescence irradiating on the photodetector of series photodetector frequency circuit system. The fluorescence dye concentration can be appropriately estimated by the frequency shift. In accordance with the fluorescence detection experiment of 100 MHz sensor system, the detection limit of U1392-HEX fluorescence dye concentration 3.3 pmol/L can be measured. Although the 100 MHz sensor system has higher frequency sensitivity for fluorescence detection, the 100 MHz quartz crystal with stable frequency response cannot be manufactured easily. Therefore, the lower resonance frequency of series photodetector frequency circuit system which has high frequency sensitivity was developed and analyzed. From previous study, the frequency shift of 48 MHz series photodetector frequency circuit system matched with photodetector APT, PDMS focusing lens of diameter 10 mm, and supply voltage 5.8 V increased linearly from 3.3 pmol/L to 333.3 nmol/L [3]. The result had the same detection limit of fluorescence dye concentration as 100 MHz sensor system. It meant that the 48 MHz sensor system with effect of PDMS focusing lens and enhanced bias of photodetector had higher frequency sensitivity to detect lower fluorescence dye concentration.

Based on 48 MHz series photodetector frequency circuit system matched with proper circuit parameter of quartz crystal, the improvement method of frequency sensitivity was proposed in this research. According to the theory analysis of frequency sensitivity, the circuit parameters such as R_q and C_q were discussed in the improvement experiment of frequency sensitivity. The 48 MHz sensor system was utilized to analyze the fluorescence detection characteristics and to evaluate the practicability of DNA hybridization with fluorescence label. The frequency method was also compared with conventional fluorescence techniques in terms of detection limit of fluorescence dye concentration.

2. Experiment

2.1. Apparatus

The diagram of series photodetector frequency circuit system is shown in Fig. 1. The green laser light source (optical power 5 mW, wavelength 532 nm, Green Laser GLM Module, M&T OPTICS, Taiwan) was used to irradiate fluorescence sample on the detection region. The optical filter (FSQ-OG550, 50.8 mm square, lens thickness 3 mm, NEWPORT, Taiwan) was used to filter the light wavelength under 550 nm. The home-made 48 MHz oscillators

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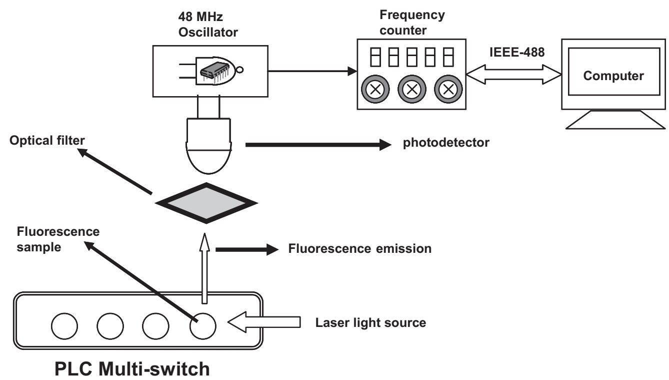

Fig. 1. The diagram of series photodetector frequency circuit system.

with different quartz crystals were based on the principle of Barkhausen criterion and the frequency circuits were constructed with quartz crystals (AT-cut 48 MHz type, Light-Tech Electronics, Taiwan), logic IC and photodetector APT (Phototransistor TK123PT, Tyntek, Taiwan) in series to make up the feedback network (Fig. 2). The PLC Multi-switch (Programmable Logic Controller, FX2N32MR, MITSUBISHI, Japan) matched with DC transmission motor was used to select different U1392-Hex fluorescence dye concentration for fluorescence experiment. A frequency counter (Agilent 53131A, valid frequency range: 1 Hz–255 MHz, USA) was used to measure frequency response. The computer with GPIB card was applied here to read the frequency data of frequency counter by Agilent VEE program. An impedance analyzer (Agilent 4294A, USA) and a semiconductor parameter analyzer (Agilent 4156C, USA) were utilized to measure the impedance parameter of photodetector. All devices of series photodetector frequency circuit system were installed in a dark room at a constant temperature 25 °C for fluorescence experiment.

2.2. Materials and samples

The fluorescence dye U1392-Hex (DNA probe U1392, PURIGO, Taiwan) with best absorption spectrum 535 nm and best emission spectrum 556 nm was diluted by TE3 buffers (TRIS/pH 8.0 10 mM + EDTA 1 mM, BIO BASIC, Taiwan). The following concentrations of fluorescence dye were prepared by tenfold dilution from 33.3 μmol/L to 333.3 fmol/L.

2.3. Measurement steps of photodetector responsivity

The different wavelengths of light sources were produced by the xenon light source with temperature 5600 K (175 W, Model ASB-XE-175-BF, SPECTRAL PRODUCTS, Taiwan) and were filtered by using bandpass filters with central wavelengths 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm and 694 nm. The luminous flux of filtered light source was measured by standard modules of optical power measurement which includes detector (Model 818-UV, NEWPORT, USA) and optical power meter (Model 1815C, NEWPORT, Taiwan). Afterward, the responsivity of photodetector was calculated by photocurrent, luminous flux, and irradiated area of photodetector.

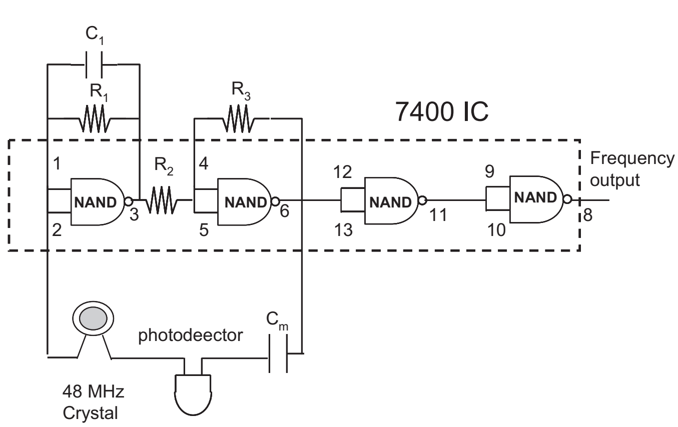

Fig. 2. The frequency circuit of series photodetector frequency circuit system.

2.4. Detection steps of series photodetector frequency circuit system

In the experiment of fluorescence detection, the dilute U1392-Hex fluorescence sample was put on the detection region and then moved to the detection platform under the optical filter. The fluorescence sample was irradiated by using green laser light source of 532 nm (side illumination type). Then, the emissive fluorescence of 556 nm was produced for fluorescence detection. Further, the emissive fluorescence of 556 nm passed through the optical filter and irradiated on the photodetector which was installed above the optical filter. Afterward, the photocurrent of photodetector was produced to influence the frequency response of series photodetector frequency circuit system while emissive fluorescence irradiating on the photodetector. The frequency data of the sensor system were recorded by Agilent 53131A counter and later on transmitted to computer by using GPIB interface. The series photodetector frequency circuit system was applied to detect the different fluorescence dye concentrations. The frequency data was read every second, and the frequency responses of different fluorescence dye concentrations were recorded in interval of 5 s.

3. Theory analysis of frequency sensitivity based on circuit parameters of quartz crystal

While alternate voltage applies on the quartz crystal, it begins to change shape producing the characteristics known as the piezoelectric effect and mechanical deformation. The characteristics of piezoelectric effect and mechanical deformation of quartz crystal are widely used in precise frequency control. The series photodetector frequency circuit system is based on the principle of Barkhausen oscillation criterion and the frequency circuit is constructed with AT-cut quartz crystal, logic IC and photodetector in series to make up the feedback network. The relevant optical experiment can be analyzed by photodetector based on the transduction function of optical signal and electrical signal, such as fluorescence detection or DNA hybridization with fluorescence label. Photodetector absorbs photons, and then converts light energy into electric current. That is, the photons strike, then the electrons and holes of semiconductor material have sufficient energy to jump the gap, and make up the current flow for conduction. According to the bias theory of photodetector, the higher photocurrent can be produced due to higher bias of photodetector. And the higher photocurrent can be obtained due to lower impedance of photodetector. In other words, the frequency response of series photodetector frequency circuit system is related to the impedance of photodetector.

The electronic behavior of a piezoelectric quartz crystal can be described by the equivalent circuit shown in Fig. 3(a). And it can be demonstrated by connecting the motional inductance L_q, motional resistance R_q, motional capacitance C_q, and static capacitance C_o. The equivalent circuit of photodetector is shown in Fig. 3(b) and it can be explained as parallel connection of resistance and capacitance, equivalently. R_p is the resistance of photodetector and C_p is the capacitance of photodetector. The equivalent circuit of series photodetector frequency circuit system can be obtained by