第 4 卷　第 4 期
2011 年 8 月

中国光学
Chinese Optics

Vol. 4　No. 4
Aug. 2011

文章编号　1674-2915(2011)04-0404-07

Diagnosis of high-repetition-rate pulse laser with pyroelectric detector

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Abstract: Based on the working principles of a pyroelectric detector, the transient response of the detector to the pulse laser is researched. The model of pyroelectric detector is built, and the response in practical application is simulated according to the parameters of materials and structures. Signal process circuits which are suitable for a high-repetition-rate pulse laser are designed. Finally, a number of the repetition frequency laser radiation experiments on the pyroelectric detector are carried out. The experiments on frequency response and pulse width of the detector are completed, and the feasibility of applying the pyroelectric detector to the energy measurement of the high-repetition-rate and narrow pulse laser is verified.

Key words: pyroelectric detector; high-repetition-frequency pulse; pulse laser signal; circuit of signal processing

基于热释电探测器的重频脉冲激光诊断

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摘要:以热释电探测器的工作原理为基础,研究了热释电探测器对重频脉冲激光的瞬态响应特性,建立了热释电探测器对单脉冲激光辐照响应的工作模型,分析了影响探测器频率特性的主要因素。根据材料和结构参数模拟计算了实际应用中的响应模型。设计了信号检测电路并对其进行计算仿真。完成了探测器的频率响应、脉宽响应等实验测量,验证了热释电探测器用于高重频、窄脉冲激光能量测量的可行性。

关　键　词:热释电探测器;高重频脉冲;脉冲激光信号;信号检测电路
中图分类号:TN215; TN249　　**文献标识码**:A

收稿日期:2011-03-21;**修订日期**:2011-07-23
基金项目:国防预研基金资助项目(No. 22110702)

1 Introduction

The high-repetition-rate laser has wide foreground applications in the photoelectric confrontment. However, there are still series of technical difficulties in the far-field beam diagnosis of the high-repetition-rate laser. Compared with the photoconductive detector, the pyroelectric detector is characterized by non-wavelength selectivity, material uniformity in large areas and electric circuit simple for process signals, so it has been widely used in the fields of military and civilians[1-2,7]. In this paper, the diagnosis method to repetition rate pulse laser based on the pyroelectric material was investigated.

2 Theoretical model of pyroelectric detector

The pyroelectric crystal becomes slice after incision. The electrode is deposited on the two faces of a slice of pyroelectric crystal, which is upright the direction of spontaneous polarization. So the pyroelectric detector is similar to the flat capacitor. Because the free charge produced by spontaneous polarization appears on the interior face of a pyroelectric crystal, the chained charge is neutralized by the free charge on exterior face.

By setting the calorific capacity of the pyroelectric detector as H, and the heat conductivity between detector and environment as G, we assume that the ambient temperature is consistent, and the temperature of the detector ΔT is higher than the ambient temperature, then the heat flux from the detector to the environment ΔQ is

$$\Delta Q = G \cdot \Delta T. \tag{1}$$

Assuming the incidence pulse laser power received by the detector to be P, after absorbing heat radiation, the caloric received by the pyroelectric detector is αP each second, and α is detector's absorption rate. Detector's temperature rise decided by the following equation[3]:

$$\alpha P = H\frac{\mathrm{d}T}{\mathrm{d}t} + G \cdot \Delta T. \tag{2}$$

In the situation of single pulse radiation, if the temperature distribution of detector is uniformity, we carry on the modeling to the pyroelectric detector, then the pulse power expression is:

$$P = \begin{cases} P_0 & 0 \leqslant t \leqslant \tau_0 \\ 0 & t \geqslant \tau_0 \end{cases}. \tag{3}$$

Substituting Eq. (3) into Eq. (2), if the detector is under single pulse radiation, we can obtain the temperature response as follows:

$$\begin{cases} T(t) = \dfrac{\alpha P_0}{G}(1 - \mathrm{e}^{-t/\tau_T}) + T_0 & 0 \leqslant t \leqslant \tau_0 \\ T(t) = \dfrac{\alpha P_0}{G}\mathrm{e}^{-t/\tau_T}(\mathrm{e}^{\tau_0/\tau_T} - 1) + T_0 & t \geqslant \tau_0 \end{cases}. \tag{4}$$

We set $\tau_T = H/G$ to be the heat time-constant, and the current across detector is:

$$i_t = Ap\frac{\mathrm{d}T(t)}{\mathrm{d}t}. \tag{5}$$

Where, A is the active area of the photosensitive unit, p is the pyroelectric coefficient, and the voltage which $i(t)$ produces on impedance Z is obtained by the following equation:

$$C\frac{\mathrm{d}V(t)}{\mathrm{d}t} + \frac{1}{R}V(t) = i(t). \tag{6}$$

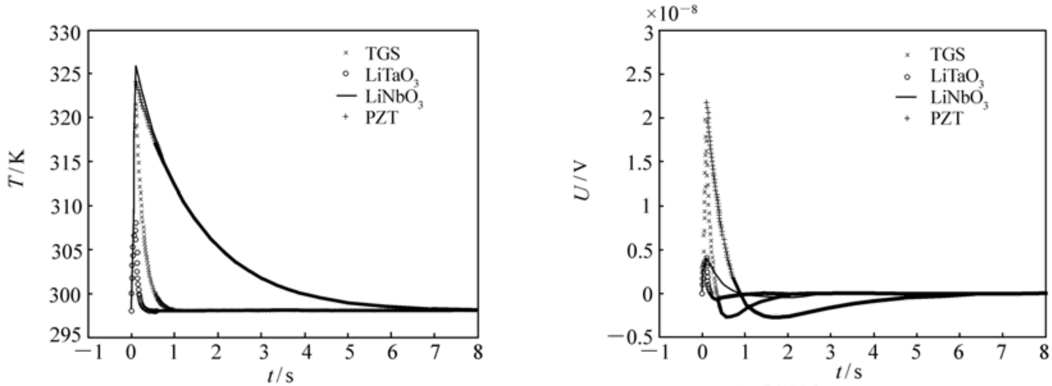
We set $\tau_e = RC$ to be an electricity time-constant. Substituting Eq. (4) into Eq. (5), the electric current expression can be obtained as follows:

$$\begin{cases} i(t) = Ap\dfrac{\alpha}{H}P_0\mathrm{e}^{-t/\tau_T} & 0 \leqslant t \leqslant \tau_0 \\ i(t) = Ap\dfrac{\alpha}{H}P_0\mathrm{e}^{-t/\tau_T}(1 - \mathrm{e}^{\tau_0/\tau_T}) & t \geqslant \tau_0 \end{cases}. \tag{7}$$

We solve the differential equation to obtain the voltage expression:

$$\begin{cases} V(t) = Ap\dfrac{\alpha}{H}P_0\dfrac{\tau_T R}{\tau_T - \tau_e}(e^{-t/\tau_T} - e^{-t/\tau_e}) & 0 \leqslant t \leqslant \tau_0 \\ V(t) = Ap\dfrac{\alpha}{H}P_0\dfrac{\tau_T R}{\tau_T - \tau_e}n\{e^{-t/\tau_T}(1 - e^{\tau_0/\tau_T}) - e^{-t/\tau_e}(1 - e^{\tau_0/\tau_e}) & t \geqslant \tau_0 \end{cases} . \quad (8)$$

We choose several typical pyroelectric materials to calculate[4], analyse, and contrast their response characteristics. The results are shown in Fig. 1.



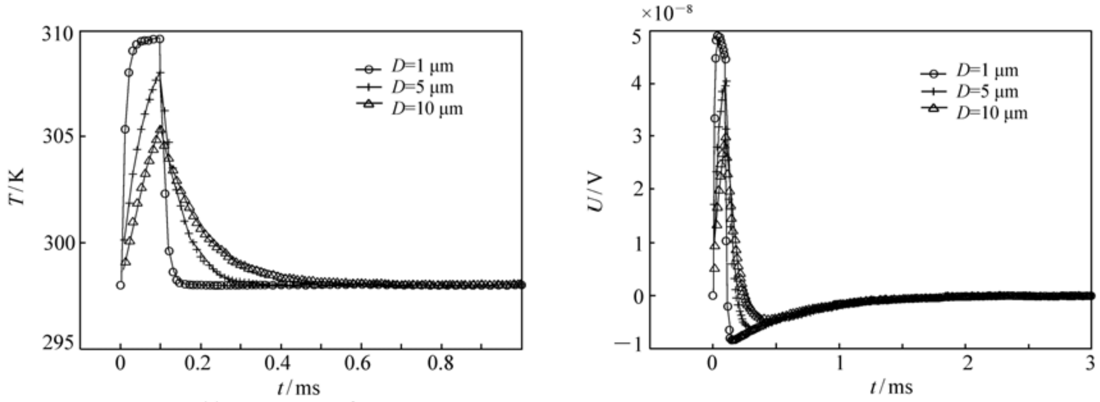
(a) Temperature change (b) Voltage response

Fig. 1 Response curves of different pyroelectric materials

Fig. 1 indicates when the photosensitive units have the same area and thickness, it takes the shortest time for the pyroelectric detector of $LiTaO_3$ material to come back to thermal equilibrium, and the speed of response is the quickest.

When the detector receives the pulse radiation, we can see that from temperature rise and the voltage expressions, the most main parameters which affect performance are the pyroelectric detector's heat time-constant τ_T and the electricity time-constant τ_e.

Seen from $\tau_T = H/G$, the heat time-constant is determined by detector's calorific capacity and the heat conductivity, but calorific capacity $H = C_v AD$ is determined by the material volume specific heat capacity C_v, the area of detector photosurface A as well as the detector's thickness D. Under the situation that the pyroelectric material has been chosen and the detector's area of photosurface is



(a) Temperature change (b) Voltage response

Fig. 2 Response curves of different detector thicknesses

1 mm^2, the temperature rise and voltage response curve of different detector with different thicknesses are shown in Fig. 2.

In Fig. 2(a), it is observed that the reduction of thickness conduce detector's calorific capacity to minish, so the pulse laser radiation of similar power cause the temperature to increase, simultaneously radiation to speed up, and response frequency to improve. However, regarding the small thickness, the calorific capacity which is excessively low causes detector's saturated threshold value to reduce. Fig. 2 (b) indicates that before the detector is saturated, detector's voltage responsivity increases gradually along with the reduction of thickness, however, the downward overswing also increases, therefore recuperating electric circuit's design should be considered to reduce the overswing.

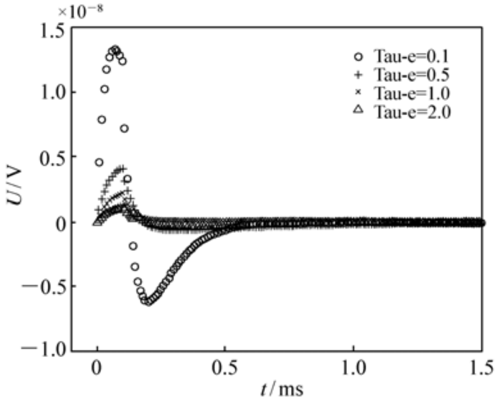


Fig. 3　Voltage response curves of different electricity time-constants

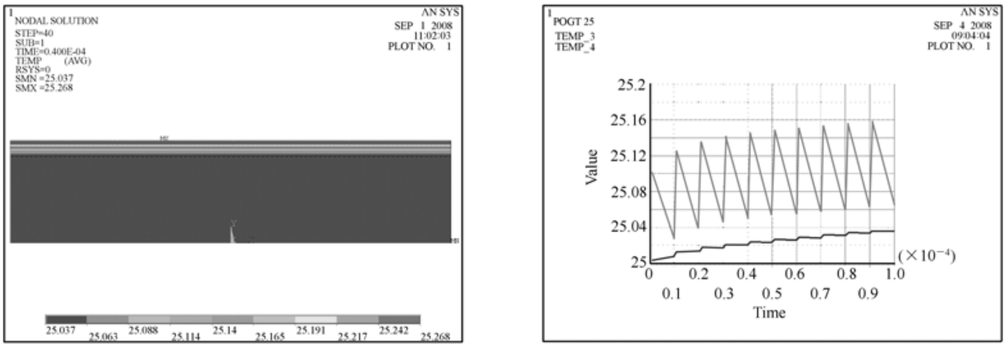
The electricity time-constant is another key parameter that affects the detector performance, and voltage response curves of different electricity time-constants are shown in Fig. 3.

The simulation result indicates that regarding the voltage response characteristic, when the electricity time-constant reduces, the time that signal returns to the baseline may be reduced, and simultaneously the responsivity is increased, but the scope of the overswing will also be increased. In the situation that pyroelectric detector's interface resistance and self-capacitance are certain, the electricity time-constant may be adjusted by changing pre-amplification electric circuit's input resistance and the input capacity.

3　Heat transfer theory of pyroelectric detector

We take the thin film as the sensitive unit to design the pyroelectric detector, which consists of a silicon substrate, an insulating layer, an electrode below, a pyroelectric level, a electrode up and a absorption film from bottom to top[5,6].

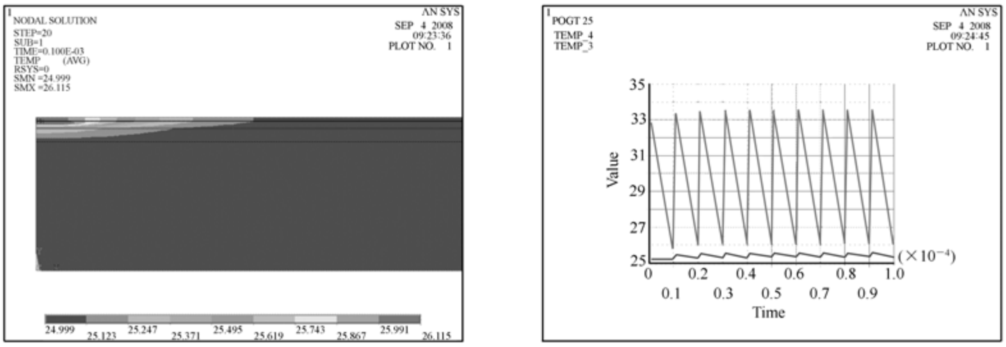
The detector worked under the room temperature of 25 ℃, and we calculate the temperature field with 10 pulse radiation. Under the radiation by the big area beam and the small one , the temperature



(a) Various film temperature fields of detector

(b) Around surface of sensitive component temperature variation along with time

Fig. 4　One-dimensional thermal analysis



(a) Various film temperature fields of pyroelectric

(b) Around surface of sensitive component temperature variation with time

Fig. 5 Two-dimensional thermal analysis

field distribution of the detector is shown in Fig. 4 and Fig. 5.

Regarding the former, the sensitive unit temperature is assumed in periodic variation along with the incident pulse light. Because the pulse optical frequency rate is high, the heat of detector can not disperse promptly, therefore the photosensitive unit temperature rise increases along with the pulse number. When the heat change between the detector and external environment reaches the balance, the temperature of detector rise tends to be stable, and this time around the superficial temperature difference really respondes the single pulse energy of incident light. Under the situation of beam incidence, it may regard the surface of detector which receive ray radiation as to be big infinitely, at the same time the thermo diffusion carries on along crosswise and longitudinal. As shown in Fig. 5, the thermal equilibrium time is established to reduce.

4 Experimental verification

The pyroelectric detector is a kind of high impedance[8]. It must be matched with the preamplifier with a quick speed and a low noise. The performance of the detector is affected by the preamplifier. So it is significant to improve the performance of the amplifier.

In order to raise the responsivity, we must reduce the speed of response advisably. The current amplifier[9] shown in Fig. 6 transforms the electric current produced by the pyroelectric detector into the

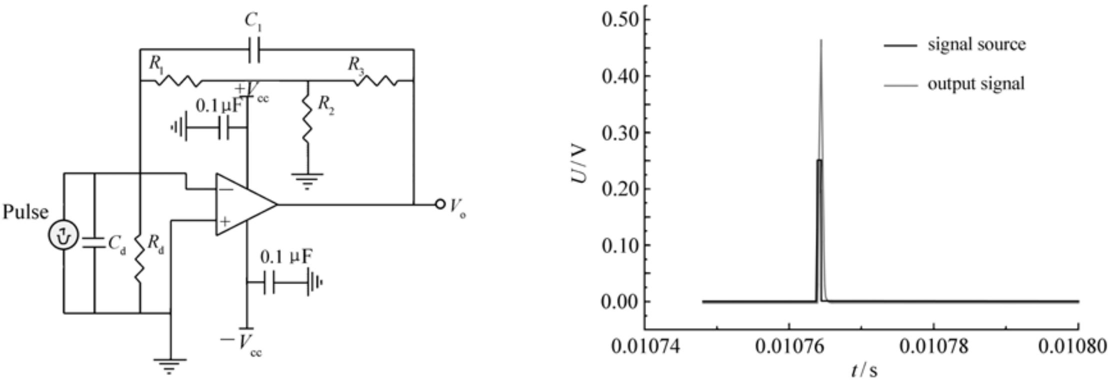


Fig. 6 Current amplifying circuit and simulation result

voltage signal directly, and its merit is that the input resistance is low, even approximate zero, which can satisfy the request of the quick response.

By using the green light pulse laser to radiate the pyroelectric detector with the current amplifier separately, detector′s output voltage response is shown as Fig. 7.

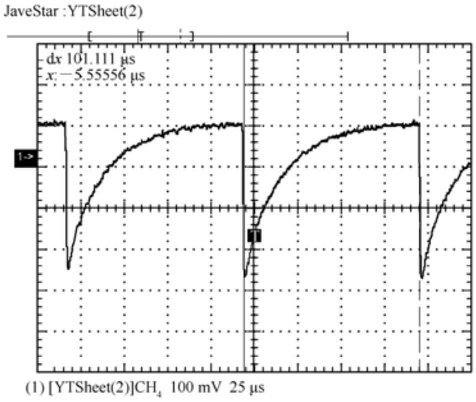


Fig. 7 Output waveform of detector with current amplifying circuit (the repetition frequency is 10 kHz)

As shown in Fig. 7, the repetition frequency of the signal measured with the pulse width of 100 μs can reach 10 kHz.

Based on the theory analysis and experiment validation above, the detector unit is demarcated in laboratory. The responsivity measured can reach 2.5 V/nJ. At present, the detector unit can measure the signal with the frequency of 10 kHz. The linear dynamic range of the detector unit is possible to reach 110, which has the linearity of 0.999 27. The imitating curve is shown in Fig. 8.

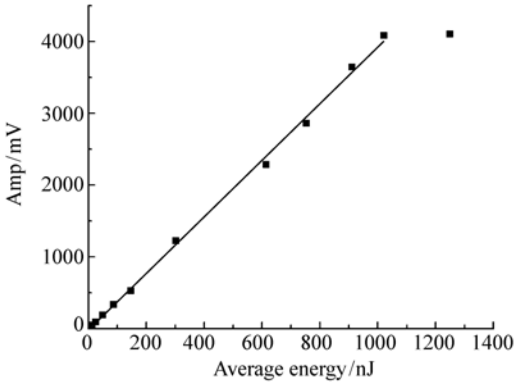


Fig. 8 Measurement of linear dynamic range of detector unit

5 Conclusions

A pyroelectric detector unit with a current amplifier to diagnose far-field beams is investigated, which can measure the laser signal with the frequency of 10 kHz. The responsivity measured can reach 2.5 V/nJ. It validates the feasibility to measure the laser energy of high-repetition-frequency pulse laser by adopting the pyroeletric detector.

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