Study on APD real time compensation methods of laser Detection system

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Abstract. With the monochromatic and the directional capability of the laser, laser detection system is confidential in anti-jamming. Detection accuracy is improved significantly as the result of laser’s good orientation ability. Sensitivity is enhanced as laser’s high-brightness characteristic. With the development of laser technology and laser devices, laser detections are developed both in civilian and military areas. In the military field, laser detection system has been widely applied in various types of tactical missiles, the technique is more mature.

Because photo detectors receive the backscattering echo signal of target in laser detection system, they are required sensitive enough to weak signal. With APD’s salient features of high sensitivity, rapid response speed, high response frequency and low noise equivalent power, etc.; PIN is replaced by APD to improve sensitivity of laser detection system in recent years. The signal magnification is inadequate in laser detection system, the detector output is usually amplified by multistage amplifiers. And then the system noise includes detector noise and latter amplifiers noise. With its high internal gain, APD becomes the primary noise source of receiving system. This point can be attested by analyzing the transfer function of laser detection system receiver. To ensure the system detecting ability, APD noise must be mitigated as low as possible. According to a large number of experiments, the power signal-to-noise (SNR) and the best multiplication factor of APD are mostly affected by background radiation and temperature. In order to make APD operate at state of the best multiplication factor, the optimum bias must be selected due to the actual operating circumstance. Therefore, APD real-time compensation must be adopted.

The existing APD compensation includes the constant false alarm rate compensation, the noise compensation and the temperature compensation. The features of these compensations are obtained by analyzing their operating principles. The constant false alarm rate compensation can’t detect the pulse signal which comes randomly. Therefore real-time performance can’t be realized. The noise compensation can meet the request of real-time performance. If it is used in the environment where background light is intense or changes acutely, there is a better effect. The temperature compensation can also achieve the real-time performance request. If it is used in the environment where temperature changes acutely, there is also a better effect. Aim at such problems, this paper presents that different APD real-time compensations should be adopt to adapt to different environments. The exiting temperature compensation adjusts output voltage by using variable resistance to regulate input voltage. Its structure is complex; the real-time performance is worse. In order to remedy these defects, a real-time temperature compensation which is based on switch on-off time of switching power supply is designed. Its feasibility and operating stability are confirmed by plate making and experiment.

At last, the comparison experiments between the real-time noise compensation and the real-time temperature compensation is carried out in the environments where temperature is almost...
invariant and background light acutely changes from 5 lux to 150 lux. The result shows that the operating effect of the real-time noise compensation is better here, the noise minifies to a sixth of original noise. The comparison experiments between the real-time noise compensation and the real-time temperature compensation is carried out in darkroom where background light is 5 lux and temperature almost rapidly changes from -20 °C to 80 °C. The result shows that the operating effect of the real-time temperature compensation is better here, the noise minifies to a seventh of original noise. Moreover, these methods can be applied to other type detection systems of weak photoelectric signal; they have high actual application value.

1. Instruction

Laser fuze has become one of the most important fuzes because of its high precision of detection, high sensitivity and strong resistibility. It is widely applied in various fields. Recently, in order to further improve the sensitivity, APD replaces PIN in laser detection system. Studies show that APD multiplication factor is the most influenced by the background radiation and the operating temperature. Selecting optimum bias based on the actual situation is its service point, so that APD always operates on the best multiplication factor state. To ensure that APD is always in the best state in laser detection system, appropriate compensatory measures must be taken. At present, APD compensation includes the constant false alarm rate compensation, the noise compensation and the temperature compensation. According to action principles of various methods, different methods have different environmental adaptability. If adopting an improper method, it cannot play its role; or even damages the device in given environment. To solve this problem, our paper presents that certain real-time measures must be taken to compensate laser detection system APD in given environment, ensuring that APD operates in the optimal gain state. In addition, the current temperature compensation adjusts output voltage by using variable resistance to regulate input voltage of switch power supply. The circuit structure is complex and the real-time performance of adjustment process is relatively poor. In order to remedy these deficiencies, a real-time temperature compensation which is based on switch on-/off-time of switching power supply is designed.

2. Analysis on APD noise model of laser detection system

The laser detection system amplifies signal inadequately. Generally, it amplifies the output of detector many times. Therefore, latter amplifiers make noise as well as detector does. If output signal is amplified n times, the overall noise coefficient is:

\[ NF = N_{F_1} + \frac{N_{F_2} - 1}{K_{s_1}} + \frac{N_{F_3} - 1}{K_{s_1}K_{s_2}} + \cdots + \frac{N_{F_{M}} - 1}{K_{s_1}K_{s_2}\cdots K_{s_{M-1}}} \]  

(1)

Where, \( NF \) is noise coefficient; \( K_x \) is amplifier power transmission function.

APD is regarded as the first stage amplifier due to its high internal gain in detection system. The latter amplifiers are regarded as the second grade, the third grade and \( \cdots \cdots \); then \( K_{s_1} = M^2 \). If \( M^2 \not\subset NF - 1, M^2 K_{s_1} \not\subset NF - 1 \) and \( \cdots \cdots \), equation (1) is approximated as:

\[ NF = NF \]  

(2)

Evidently, system noise coefficient equals with APD noise coefficient, and prime amplifier is not the main noise source which undesirably affects receiving system performances. It is the key to reduce system noise and enhance detection capabilities that restraint APD noise. APD noise equivalent model is shown in Figure 1.

Where, \( M \) is APD multiplication factor; \( i_s \) is signal photocurrent; \( \overline{i_N} = 2e(i_s + i_b + i_r) \) is shot noise power spectral density which is induced by signal light, background light and reverse saturation current; \( \overline{i_T} = 4TK_{s}/R_L \) is resistance thermal noise power spectral density. APD Power SNR is:

\[ SNR = (i_s M)^2 \left\{ \overline{2e(i_s + i_b + i_r)M^2 f + 4TK_{s}/R_L} \right\} \]  

(3)
Selecting optimum bias accounts most in APD application. Doing this will make APD works at the best multiplication factor state, and then maximize the system SNR.

by:

\[ \frac{dSNR}{dM} = 0 \]  

At this point, the best multiplication factor is defined as:

\[ M_{opt} = \left[4TK_s/(n-2)e(i_s + i_d + i_j)R_L\right]^{1/2} \]  

Evidently, \( M_{opt} \) is related to \( i_s \), \( i_d \), \( i_j \), \( T \) and \( R_L \). Any change of each, \( M_{opt} \) will result in change of \( M \). In which, \( i_s \) is inherent in the device, \( i_d \) is randomly introduced by signal, it can’t be eliminated in application process.

We can see from the experiment that when \( R \) is fixed and background noise is constant, the optimum bias is slightly less than the \( V_B \). \( V_B \) is closely related to temperature. The relationship is shown in Figure 2. At this point, it is the main factor that \( T \) affect \( M_{opt} \). On the contrary, background brightness affects \( M_{opt} \) far beyond \( T \) when it is high or acutely change. Major determinate of \( M_{opt} \) is different in different environment; thus different compensations must be adapted to APD.

3. Laser detection system APD compensation

3.1. Laser detection system APD constant false alarm rate compensation

The operating principle of constant false alarm rate compensation is shown in Figure 3.

According to the operating principle of the constant false alarm rate compensation, the logic control circuit must reduce operating bias of APD before system operating. Although it is slightly influenced by background noise, temperature or other factors in external environment, and the application range is relatively wide; it can’t detect laser pulse random signal. And then it can’t meet the request of APD real-time compensation. Thus, it is seldom used in current laser detection system.

3.2. Laser detection system APD real-time noise compensation
The operating principle of real-time noise compensation is illustrated in Figure 4. Decision point average noise power is:

\[ N = eR/2\pi \left[ \frac{1}{1 - (-KV_{\text{M}L}/255V_{\text{M}})^2} \right]^{1/2} \left[ I_r/2\pi + P_{r,H} \right] I_1 \]  

(6)

Although \( N \) is related to \( P_r, T \) and \( N_b \), the base of \( V_{\text{M}L} \) is larger, \( 1 - (-KV_{\text{M}L}/255V_{\text{M}})^2 \) change caused by the change of \( T \) is relatively small. If \( P_r \) greatly changes, the influence that \( V_{\text{M}L} \) impacts on \( N \) is much smaller than the influence that \( P_r \) impacts on \( N \). So noise compensation will achieve better results when background light is intense or greatly changes. As the noise compensation doesn’t need to be adjusted to bias before detection, it can achieve APD real-time compensation.

3.3 Laser detection system APD real-time temperature compensation based on switching on-off time

If the background illuminance is low or constant in laser detection system operating environment, the influence that \( T \) change acts on \( M_{\text{M}L} \) will be highlighted. At this point, the noise compensation can’t meet the \( M_{\text{M}L} \) requirements; or even PN junction is broken down. So the bias should be adjusted by temperature variation in relation to \( V_{\text{M}L} \). Considering the miniaturization of laser detection system, the non-isolated counterattack type transformer switch power is usually applied to supply high operating voltage for APD.

When \( 0 \leq t < t_1 \), the power switch turns on, the equivalent circuit is shown in Figure 5. \( R_i \) is equivalent resistance of all components in the circuit. According to Kirchhoff’s voltage theorem, when \( 0 \leq t < t_1 \), the voltage and current equations are:

\[
\begin{align*}
\frac{I_{i_1}}{R_i} &= U \left( 1 - e^{-\tau t} \right) / R_i \\
\frac{U_{i_1}}{R_i} &= U e^{-\tau t}
\end{align*}
\]

\( 0 \leq t < t_1 \)  

(7)

Where, \( \tau = L_2/R_i \) is the time constant. The magnetic flux Changes in inductor is \( \Delta \Phi \), thus:

\[ \Delta \Phi = U_\text{t}/NS \]  

(8)

Where, \( N \) is the turn of \( L \); \( S \) is the magnetic core sectional area of \( L \).

When \( t_1 \leq t \leq t_2 \), power switch cuts off, the equivalent circuit is shown in Figure 6. Where, \( R_i \) and \( C_2 \) are equivalent resistance and equivalent capacitance of all elements during the power
switching off. According to Kirchhoff’s voltage theorem, when \( t_1 \leq t \leq t_2 \), the voltage and current equations are:

\[
\begin{align*}
\text{current:} & \quad i_{t_2} = I_{t_2}(t_1)e^{-\delta t} (\cos \omega t + \frac{\delta}{\omega} \sin \omega t) \\
\text{voltage:} & \quad u_{t_2} = -\frac{I_{t_2}(t_1)}{\omega C_2} e^{-\delta t} \sin \omega t \\
\text{voltage:} & \quad u_{C_2} = U - R_i I_{t_2}(t_1)e^{-\delta t} (\cos \omega t + \frac{\delta}{\omega} \sin \omega t) + \frac{I_{t_2}(t_1)}{\omega C_2} e^{-\delta t} \sin \omega t
\end{align*}
\] (9)

Where, \( \delta = R_i/2L_2 \), \( \omega = \sqrt{\omega_0^2 - \delta^2} \), \( \omega_0 = 1/\sqrt{L_2 C_2} \).

The magnetic flux Changes in inductor is \( \Delta B_i \), thus:

\[
\Delta B_i = \left[ (u_{\text{out}} - U) (t_2 - t_1) \right] / \eta \Omega
\] (10)

Because \( \Delta B_i \) and \( \Delta B_j \) are equal, the joint equation of (8) and (10) is:

\[
u_{\text{out}} = U / (t_2 - t_1)
\] (11)

According to equation (9):

\[
u_{C_2} = U - R_i I_{t_2} - L_2 d_{t_2} / dt
\] (12)

When \( i_{t_2} \) is constant, \( u_{C_2} \) (namely \( u_{\text{out}} \)) is decided by \( \Delta t \) which is the off-time of switch element, \( \Delta t = t_2 - t_1 \). Once switch element is selected, and \( \Delta t \) is constant, thus, any \( u_{\text{out}} \) corresponds to a certain \( t_2(t_1) \), and \( t \) can be obtained, \( t_1 \) can be obtained by equation(11).

Evidently, if the input voltage is constant and the background radiation is low or constant. To complete switch on and off-time real-time adjustment can ensure that APD reverse bias is always close to \( V_B \) at any temperature of any. SNR is maximum. The laser detection system APD real-time temperature compensation principle which is based on the power switch on-off time is shown in Figure 7.

4. Experiment results and analysis

4.1. Laser detection system real-time compensation experiment when the background light acutely changes

Based on the analysis of laser detection system real-time noise compensation principle, and according to Figure 4; the matching circuit board has been designed. AD7524 is used as 8-bit D/A converter, the reference voltage is -5V. AT89CXXXX is used as a control chip, the D/A circuit output is controlled by programming. C30707 is used as photosensitive tube. Its operating temperature range is -20 °C to
80 °C, corresponding to the reverse bias voltage range of 120V to 200V, with a temperature coefficient of 0.6V/°C.

In order to verify operating effect of laser detection system real-time noise compensation in the environment where background radiation is high or acutely changes, APD output signal is tested. The peak current of power transmitter is 15A. The rising edge is 8ns. The frequency is 10 kHz. When the APD operating background illuminance abruptly changes from 5lux to 150lux, the output signal of receiver module without any compensation is showed in Figure 8 (a). The target echo signal is 4.5V, and then the noise is up to 2.5V. The output signal of receiver module with real-time temperature compensation is showed in Figure 8 (b). There is no obvious change. The output signal of receiver module with real-time noise compensation is showed in Figure 8 (c). The noise value is about 0.4V, reduced to one sixth of the original noise. Comprehensively, the APD output noise suppression effect of noise compensation is remarkable due to a drastic change in background light in the laser detection system where the temperature is almost constant. According to the measured value of APD reverse bias, the fitting curve is shown in Figure 9. And then theoretical K is 40. The Figure demonstrates that the measured value fairly well accords with the theoretical control curve. Calculating according to the measured bias, the real average K value is 39.8. When background illuminance changes from 3lux to 200lux, the APD reverse bias of each interval 50lux is shown in Table 1. Visibly, MCU output control signal changes with the background light changing, different output voltages are obtained.

![Figure 8. Laser receiving module output](image)

![Figure 9. Measured reverse bias fitting curve of APD schematic diagram](image)

| Illuminance | V_r / V | V_i / V |
|------------|---------|---------|
| 3          | 3.3     | 132     |
| 50         | 3.6     | 144     |
| 100        | 3.8     | 153     |
| 150        | 4.1     | 165     |
| 200        | 4.5     | 178     |

Table 1. Output of D/A and bias of noise compensation under different illuminances
4.2. Laser detection system real-time compensation experiment when the environment temperature acutely changes

Based on the analysis of laser detection system real-time temperature compensation principle, and according to Figure 7, the matching circuit board has been designed. Temperature sensor used AD590, its rated temperature coefficient of $1 \mu A / k$. Power MOS as a switch, the maximum drain current of 6A; voltage is 200 V. C8051XXXX for the control chip. APD also use C30737.

In order to verify operating effect of Laser detection system real-time temperature compensation in the environment where temperature acutely changes, APD output signal is tested in a dark room (light intensity is 1.5lux). The peak current of power transmitter is 15A, the rising edge is 8ns; the pulse width is 15ns; the frequency is 10 kHz. The APD temperature rapidly changes from room temperature (25 °C) to 60 °C. The output signal of receiver module without any compensation is showed in Figure 10(a). The target echo signal is 4.4V, and then the noise reaches 2.2V. The output signal of receiver module with real-time noise compensation is showed in Figure 10(b), there is no significant change. The output signal of receiver module with real-time temperature compensation is showed in Figure 10(c). The noise is about 0.3V, falling to one seventh of the original noise. Comprehensively, when the background light is low and the environment temperature considerably changes, the APD output noise is better controlled by temperature compensation, but the effect of noise compensation is poor. When temperature changes from -20°C to 80°C, the APD reverse bias of each interval 20°C is shown in Table 2. Hence, MCU output control signals of different frequency and different duty cycle changes when the temperature changes, and different output voltages are obtained.

![Figure10. Laser receiving module output](image)

### Table 2. Changes of MCU controls Signal and output voltage temperature

| Temperature /°C | -20 | 0  | 25  | 40  | 60  | 80  |
|-----------------|-----|----|-----|-----|-----|-----|
| Switching on-time | 41.6 | 46.6 | 52.8 | 60.3 | 68.7 | 78.9 |
| Switching off-time | 16.6 | 17.2 | 17.3 | 18.7 | 19.7 | 21.0 |
| Output voltage /V | 131 | 144 | 160 | 173 | 185 | 198 |

5. Conclusion

By analyzing the operating noise characteristics of laser detection system transceiver and APD basic application circuit noise model; the relationships between best multiplication factor and dark current, signal power, background power, temperature, load resistance are obtained. By analyzing principles of constant false alarm rate compensation, real-time noise compensation and real-time temperature compensation of laser detection system; this paper presents that laser detection APD system must take different compensations in different environments. A real-time temperature compensation which is based on switch on-/off-time of switching power supply is designed. The method can achieve real-time adjustment of APD operating bias, and the structure is relatively simple, stable and reliable; thus it can fill the shortages of current real-time temperature compensations. Meanwhile, the comparison experiments between laser detection system APD noise compensation and temperature compensation
are carried out in different environments. Results show that adopting appropriate compensation in different environments can make APD operate in the optimal state. If the background illuminance and the temperature of the laser detection system operating environment change dramatically, the composite compensation of noise and temperature in the system can be taken into account. It is certain that the volume and complexity of the system will be correspondingly increased. Additionally, it is necessary to consider the power consumption and electromagnetic interference in the fuse system which is strictly limited in size. Moreover, in the basis of the application effect of APD real-time compensation in the laser detection system, these methods can be applied to other type detection systems of weak optical signal. Therefore, they are of high actual value.

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